Scaling 60 GHz WLANs: Creating and Identifying Opportunities for Multi-User Transmission

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A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree

Master’s Thesis

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October 2016
ABSTRACT

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The millimeter scale carrier wavelength of the 60 GHz spectrum makes it feasible to pack two order of magnitudes more antennas into the same form factor compared to legacy bands (i.e. 2.4 and 5 GHz band). Prior works in 60 GHz have exploited this large antenna arrays to enhance the link budget of a single user transmission, which suffers from high path loss in 60 GHz. We are proposing a scalable multi-user scheme in 60 GHz WLANs in order to serve multiple clients with multi-Gbps data rate simultaneously in the same environment using the same frequency channel. To this end, we first propose a scalable beam training protocol, which tracks the users for directional transmissions. Then we have designed and evaluated incremental policies that add clients to a transmission sequentially until the AP’s resources are exhausted or client link budgets, including interference, are exceeded. We further target polarization diversity and non-uniform antenna partitioning as mechanisms to dramatically reduce inter-stream interference enabling vastly improved aggregate rate. At lower bands, multi-user aggregation is typically achieved by zero-forcing inter-user interference via sender-side digital pre-coding using channel state information at the source. Unfortunately, such techniques
do not scale to 60 GHz since (i) 60 GHz transmission is highly directional and lacks the rich scattering propagation environment assumed for most prior work; (ii) even efficient mechanisms for CSIT collection do not scale to large antenna arrays; (iii) prior techniques employ a large number of radio frequency chains (up to one per antenna) which are not feasible in our scenario. Our experiments through over-the-air testbed built over WARP platform and trace-driven simulations show that our methodology can achieve performance near to that of exhaustive search of all possible client combinations, yet with substantially less overhead.
ACKNOWLEDGEMENTS

I would like to extend my sincere thanks to my advisor Prof. Edward W. Knightly for letting me dictate the pace of my research, giving me freedom to choose my favorite research topic, his encouragement and insight into my research.

I am grateful to my committee members, Professor Behnaam Aazhang and Assistant Professor Aydin Babakhani for their valuable inputs. I am also thankful to them for being gracious enough to accommodate me and making the final oral defense possible on the day of my choice.

I would like to thank my group-mates and my friends, Dr. Adriana Flores, Sharan Naribole, Kumail Haidar, Ryan Guerra, Xu Zhang, Peshal Nayak, Joe Chen and David Ramirez for helping me with oral defense and giving me great feedbacks.

Finally, I would like to thank my parents who have always encouraged me in my quest for higher education and especially my husband for supporting me in this path.
To all courageous girls around the world who go beyond the traditional norms and become the leaders of their own lives.
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Chapter 1

Introduction

Current commercial 60 GHz systems [1–3] exploit codebook-based analog beamforming techniques to provide sufficient link budget to a single-user transmission which is exposed to the higher path loss and reflection loss compared to legacy bands (i.e. 2.4 and 5 GHz). The millimeter scale carrier wavelength of 60 GHz spectrum makes it feasible to pack two order of magnitude more antenna elements into relatively small form factors enabling analog beamforming to get advantage of antenna directivity to overcome aforementioned losses and provide multi-Gbps data rate for a single point-to-point transmission. The next generation of mobile systems, being standardized via IEEE 802.11ay, may support concurrent spatial streams by transmitting independent and parallel data streams to a group of users in dense 60 GHz WLANs. In this thesis, we target a scalable multi-user design in which the AP can simultaneously transmit to a group of clients.

The multi-user multi-antenna downlink transmission has been well studied in literature for legacy bands [4, 5] where multi-user aggregation is typically achieved by zero-forcing inter-user interference via sender-side digital precoding using channel state information at the transmitter. Such techniques do not scale to 60 GHz with large antenna arrays since i) 60 GHz transmission is highly directional and lacks the
rich scattering propagation environment assumed for most prior work; (ii) even efficient mechanisms for CSIT collection (e.g., implicit CSI collection [6–8]) do not scale to two order of magnitude larger antenna arrays; (iii) prior techniques employ a large number of radio frequency (RF) chains (up to one per antenna) which are not feasible in our scenario.

To address these practical challenges, recent work has considered the use of hybrid digital/analog beamforming to take advantage of large number of antennas without having an equally large number of RF chains [9]. In hybrid beamforming, analog and digital precoding are designed in two stages. First, the analog beamforming vectors are selected based on user’s individual channels (no interference) and then the digital pre-coder employs zero-forcing on the effective channels of a pre-selected users [10]. Similar to traditional digital beamforming (MU-MIMO) systems where user selection is a major challenge, hybrid digital/analog beamforming systems require an efficient protocol to jointly configure the analog beamforming and select the users to be served.

We initially hypothesized that high directivity at 60 GHz enables concurrent transmissions to (nearly) any set of clients, provided that they have sufficient angular separation. Unfortunately, our preliminary experiments at 60 GHz indicate that this is not the case as artifacts such as spurious reflections and side lobes can create sufficient interference to preclude simultaneous reception, even with inter-client angular separation that significantly exceeds beamwidth.

In this thesis, we present Scalable USer and beAms eNter (SUSAN) to maximize the sum rate achieved via multi-user transmission while ensuring the limited sounding overhead in 60 GHz WLANs. SUSAN jointly selects user-beam tuples in the context of analog beam forming with finite number of predetermined beam patterns. The key features of SUSAN are: (i) Joint user-beam selection (ii) Scalability to large antenna arrays and dense user population, and (iii) Compatibility with SINR boost
techniques like non-uniform antenna partitioning and polarization diversity.

**Joint user-beam selection.** The problem of analog beam selection is not isolated from user grouping. The conventional analog beamforming is suggested by IEEE 802.11ad standard which selects the beam providing the highest signal strength from a predefined set of beam patterns [11]. This mechanism may result in selecting the best analog beam in a single stream transmissions; however, the interference of co-scheduled users in a multi-stream scenario has not been considered in such analog beamforming mechanisms.

Instead of exhaustive search over all user-beam combinations, SUSAN suggests an incremental mechanism, where in each round the user-beam tuple with the highest gain when grouped with already scheduled user-beams is selected.

**Scalability and limited overhead time.** In order to guarantee a scalable multi-user scheme, the sounding overhead of user and beam selection should be limited and not growing with user population. SUSAN’s key techniques to achieve scalability are twofold: First, the user-beam addition to the group is user-driven instead of sender-side selection (AP-driven). In each round, unselected users estimate their potential to boost the network’s sum rate if grouped with existing selected users. Then, they participate in a distributed contention where the one with highest potential wins and sends feedback to the AP. The user-driven approach does not require the AP to obtain the channel information of every user in the network; thus, it saves the overhead time for sending channel information to the AP. Second, the beam training procedure operates in two different time scales. In the coarse level, the AP transmits beam training frames from all TX analog beam patterns and partially trains all existing clients simultaneously. The coarse level beam training provide necessary information for user-driven addition to the group in each round. In the fine level beam training, the analog TX and RX beams are selected for scheduled users in each round. We show
that the number of beam training frames in coarse timescale is independent from user population and the number of user-beam selection rounds is at most upper-bounded to the number of RF chains in the AP which does not scale with user population. Therefore, applying these two techniques, we are able to design a scalable user and beam selection protocol.

**Compatibility with future SINR boost techniques.** The hybrid system architecture leads to specific SINR boost techniques which can increase data rate of 60 GHz transmissions. The hybrid system architecture with shared antenna array and dual-polarized antenna elements creates the opportunity for non-uniform antenna partitioning and polarization diversity. These techniques can be exploited to boost the SINR and mitigate the inter-user interference. In this paper, we also study the compatibility of SUSAN with these SINR boost techniques.

We implement the key components of SUSAN and characteristics of 60 GHz propagation polarized channel by 3-D image-based Ray Tracing technique. To validate our simulator, we also use a steerable 60 GHZ RF-fronted combined with the software-defined radio platform WARP [12] for experimental evaluation in a typical conference room. Our testbed utilizes mechanically steerable horn antennas to emulate 802.11ad phased-array, and enables us to install antennas with different beamwidth.

The remainder of this thesis is organized as follows: Chapter 2 provides the background and Chapter 3 describes our system architecture and channel model. Our proposed scalable multi-user scheme is described in Chapter 4. Chapter 5 discusses the compatibility of proposed design with SINR boost techniques. Chapter 6 presents our implementation setup and Chapter 7 evaluates the performance of SUSAN protocol. Chapter 8 describes related work and Chapter 9 concludes this thesis.
Chapter 2

Background

2.1 Single-user transmission in 60 GHz band

In order to meet the path loss constraints and coverage requirements in 60 GHz band, large antenna arrays should be deployed at both transmitter and receiver. Fortunately, the millimeter scale wavelength of 60 GHz makes it feasible to pack around two order of magnitudes more antenna elements into the small form factors. The large antenna arrays are exploited to generate the highly directional beams. In a multi-user transmission, the AP needs to establish directional links with several users and update this information upon any nodal or environmental mobility in the environment. In this section, we first describe how a single point to point connection can be established in 60 GHz band based on 802.11ad standard.

2.1.1 802.11ad Beamforming Training (BFT)

Beamforming Training (BFT) is a bidirectional process in which two end nodes determine their optimum Tx and Rx sectors to reach each other by exchanging a sequence of training frames. BFT comprises of two phases: a mandatory Sector Level Sweep
Figure 2.1: Sector Level Sweep Phase in 802.11ad.

(SLS) phase, and an optional Beam Refinement Phase (BRP). As shown in Figure 2.1 during the SLS, a pair of stations exchanges a series of sector sweep (SSW) frames over different antenna sectors to find the one providing highest signal quality. During the SLS, each station acts once as a transmitter and once as a receiver of a sweep. However, this phase is coarse grained, and the refinement phase can be used to further divide the selected sectors to improve link budget.

In 802.11ad standard, channel time is divided into Beacon Intervals (BIs), with a structure depicted in Figure 2.2. BFT between the AP and an unassociated station cannot rely on coordination preceding to the beam training. To overcome the challenges of directional link setup, the AP uses its beacon sweep during the Beacon Transmission Interval (BTI), as an initiator sector sweep for all stations. All unassociated stations and the associated ones who see changes in the AP’s frames need to respond to the initiator sector sweep. To allow multiple stations to respond to a beacon sweep without coordination, the Association Beamforming Training (A-BFT) interval implements a contention based response period. The A-BFT reserves channel time for multiple responder sector sweeps (A-BFT slots). An overview for the association beamforming training during BTI and A-BFT is shown in the upper left part of Figure 2.2. Each A-BFT slot consists of a fixed time allocation for a number of SSW frames (transmitted by the connecting station). The contention process during an A-BFT does not apply carrier sensing. Instead, a collision is detected by a missing
SSW Feedback frame from the AP.

Once beacon header interval (BHI) is complete and before initiating a multi-user transmission, each user \( i \) knows the best receive sector ID, the received signal strength per AP’s transmit sector ID. The available information in the AP contains knowledge of the best transmit sector ID to communicate to each single user.

2.1.2 Codebook based analog beamforming

In the 802.11ad standard, sector has a virtual meaning and represents any kind of beam patterns pointing toward a direction in space.

A specific beam pattern is generated by assigning different weights to antenna array elements. The fixed set of beams is defined by a codebook whose each column specifies the beam weight vector including a combination of weights assigned to the antenna elements for that specific beam formation. The set of columns standing for the beam patterns span the entire space, which is 360°, and the number of rows
specify the size of linear array. A codebook example can be [13]:

\[ W(p, q) = j^{\text{floor}\left(\frac{p \times \text{mod}(q + (Q/2), Q)}{Q/4}\right)} \]  

(2.1)

Where \( p \in \{0, 1, ..., P-1\} \) and \( q \in \{0, 1, ..., Q-1\} \) and \( P \) and \( Q \) are total number of antenna elements and total number of beams, respectively \((Q \leq P)\).

### 2.2 Multi-user transmission in sub 6 GHz bands

Digital beamforming is the promising approach for multi-user multi-antenna systems in lower 2.4 and 5 GHz frequency bands in which beamforming vectors can be computed based on the estimated channel information from every single transmit antenna to all receive antennas. Open finishing this procedure, which is called channel sounding, the AP is capable of calculating the optimum weight vectors for its antenna elements as [4]:

\[ W = H^*(HH^*)^{-1} \]  

(2.2)

where \( H \) is the channel matrix and \( W \) is the transmit weight vector. Applying the weight vector \( W \) results in \( h_k(w_j)^T = \text{min} \) for \( k \neq j \) and \( h_k(w_j)^T = \text{max} \) for \( k = j \) which means maximum received of intended data stream and minimum inter-user interference.

In 60 GHz systems, we have to pack large antenna arrays in the transmit and receive side while the number of RF chains or D/A and A/D converters are limited and does not scale with antenna elements due to power and cost constraints. Therefore, acquiring channel state information per antenna element is regarded to be costly and high overhead. Even if the full channel information be available at the AP, designing an efficient precoding and decoding scheme consider to be complex due to large size of channel matrix. In addition, rich scattering propagation environment is a prerequisite.
for zero-forcing and similar techniques in lower bands which are built on the fact the there are multiple paths from the AP to each client. However, the high penetration loss in 60 GHz makes the channel to be sparse meaning that only one LOS path and one or two reflected path may be available in the best case scenario. Therefore, developing a multi-user scheme in 60 GHz has new challenges which have not beed addressed in prior work on multi-user transmissions.
Consider the multi-user 60 GHz WLAN where an AP with $N_{AP}$ antennas and $N_{RF}$ RF chains is assumed to communicate with $U$ mobile users. The $u$th mobile user is equipped with $N_u$ antennas as depicted in Fig. 3.1. We focus on the case in which every user has only one RF chain, hence the AP communicates with every client via only one data stream. Therefore, the total number of simultaneous data streams ($N_{SS}$) is upper-bounded to $\min(N_{RF}, U)$ for $N_{RF} < N_{AP}$. The architecture depicted in Fig. 3.1 has the following features:

(i) Multi-stream support: RF chains are connected to a separate set of phase shifters and can support simultaneous independent data streams transmission.

(ii) Antenna allocation flexibility: All $N_{AP}$ antenna elements in the AP are shared among the existing phase shifters. Hence, shared antenna array makes it feasible to assign an arbitrary portion of antennas to a specific RF chain. While the protocol and results developed in this paper can be applied to arbitrary antenna arrays, we use uniform linear arrays (ULAs) in the simulations of chapter 7.

(iii) Polarization diversity support: In case of exploiting dual-polarized antenna elements, two independent data streams can be transmitted simultaneously with orthogonal horizontal/vertical polarization modes to their intended receivers.
Figure 3.1: Hybrid beamforming architecture of AP and mobile users.

Let $L_u$ be the number of multi-path components between the AP and $u$th user. The $N_u \times N_t$ dimensional channel between the AP, transmitting with $N_t$ antennas, and $u$th user is modeled as [10]

$$H_u = \sqrt{\frac{N_u N_t}{L_u}} \sum_{l=1}^{L_u} \alpha_{u,l} a_u(\theta_{u,l}) a_{AP}(\phi_{u,l}),$$

(3.1)

where $\alpha_{u,l}$, $\theta_{u,l}$ and $\phi_{u,l}$ are the complex gain, angles of arrival and departure of $l$th path, respectively. $a_{AP}(\phi_{u,l})$ and $a_u(\theta_{u,l})$ are the antenna array response vectors of the AP and $u$th user, respectively.

Let $w_{u,tx} \in \mathbb{C}^{N_t \times 1}$ be the transmit RF beamforming vector of the AP for $u$th user and $w_{u,rx} \in \mathbb{C}^{N_u \times 1}$ be the receive RF beamforming vector of the $u$th user. Then the output signal for $u$th user can be written as

$$y_u = w_{u,rx}^T \sum_{n=1}^{U} (H_u w_{n,tx} s_n + n_u),$$

(3.2)

where $n_u$ is the additive white Gaussian noise and $s_n$ is the transmitted symbol for $n$th user.

The transmit and receive beamforming vectors, i.e. $w_{u,tx}$ and $w_{u,rx}$, were conven-
tionally computed via digital precoding using channel state information (CSI) in sub
6 GHz frequency bands [4, 5, 14, 15]. However, due to a limited number of RF chains
and a large number of antennas, acquiring the estimation of channel is regarded to
be costly and high overhead. As a result, the RF beamforming vectors are usually
selected from a predetermined codebook through a beam training procedure [13, 16].

Prior works on 60 GHz multi-user have studied the problem of user and beam
selection separately.

**Beam selection:** According to equation 3.2, the beam training procedure re-
quires to solve the following optimization problem

\[
\{ w_{u,tx}^*, w_{u,rx}^* \} = \arg \max_{\forall w_{u,tx} \in F, \forall w_{u,rx} \in W_u} \| w_{u,rx} H_u w_{u,tx} \| \tag{3.3}
\]

where \( F \) and \( W_u \) are RF beamforming codebook of the AP and user \( u \) respectively.
Equation 3.3 provide the optimal beamforming vectors for a single user transmission
which may not be optimal in existence of inter-user interference in a multi-user sce-
nario. The 802.11ad standard suggests a two-step procedure to find the suboptimal
solution of equation 3.3. First, to find the suboptimal transmit analog beam (i.e.
\( \hat{w}_{u,tx}^* \)), the AP sends beam training frames and sweeps through all beam pattern of
codebook \( F \) while the receiver adopts a quasi-omni pattern. Second, user \( u \) sweeps
through beam patterns of codebook \( W_u \) while the AP is in quasi-omni mode which
results in selecting \( \hat{w}_{u,rx}^* \). The 802.11ad standard simply train all the exiting clients
in the network; thus, the total number of beam training frames to train \( U \) users is

\[
N_{11ad} = N_{\text{user}}^{\text{omni}} \times |F| + \sum_{u=1}^{U} N_{AP}^{\text{omni}} \times |W_u| \tag{3.4}
\]

where \( N_{AP}^{\text{omni}} \), \( N_{\text{user}}^{\text{omni}} \) are the number of quasi-omni patterns at the AP and users,
respectively.
Equations 3.3 and 3.4 imply that 802.11ad beam selection procedure does not consider the interference of possible co-scheduled users and its overhead time grows with user population.

**User selection:** Several works focus on user grouping and selection based on channel state information in sub 6 GHz MU-MIMO systems [4], [5], [14]. These works require channel state information to estimate the aggregate capacities of potential user sets. While these algorithm are potentially more precise than SUSAN due to additional information they require, huge overhead time which scales which number of antenna elements and user population render these protocols impractical to deploy for 60 GHz. Very recent work has considered the problem of user selection for 60 GHz specifically [17]. The authors propose a greedy mechanism for user selection; however, their approach does not consider beam selection and does not scale to dense networks.
Chapter 4

Scalable Multi-User scheme for 60 GHz WLANs

In this chapter, we propose Scalable User and beam selectioN (SUSAN) for 60 GHz WLANs which jointly selects beam-user tuples sequentially until the AP’s resources are exhausted or client link budgets, including interference, are exceeded. In dense 60 GHz WLANs, the number of existing clients is typically greater than number of RF chain at the AP (i.e. \( U \gg N_{RF} \)). Instead of training all existing clients together with excessive overhead, SUSAN adopts a two-level training in two-different time scales.

**Coarse Level:** The goal of this stage is to partially train all existing clients and provide sufficient information for fine level user-beam selection. **Fine Level:** In each fine time subframe, SUSAN schedules up to \( N_{RF} \) user-beam tuples via a greedy method. Instead of a global user grouping strategy which requires the AP to obtain all users’ channel information, SUSAN runs distributed incremental joint user-beam selection which relies on the information obtained during partial beam training. In each round, unselected users estimate their SINR if grouped with already scheduled users and introduce the best user-beam pair candidate to the AP. This procedure removes the overhead needed for sender-side user-beam selection and considers the interference of co-scheduled user on user-beam tuple selection in SINR estimation.

Next, we describe the main components of SUSAN, multi-stream analog beam-
forming and user-beam selection.

### 4.1 Partial Analog Training

Unlike 802.11ad standard, we target joint user-beam selection in a downlink multi-user scenario. To this end, we split the beam training procedure into two phases. The first phase is a periodic mandatory partial beam training for every existing user in the network. This partial training provides the sufficient information for joint user-beam selection in the fine time scale. In the second phase, only the scheduled users to be simultaneously served complete their beam training procedure.

Similar to 802.11ad procedure, the partial beam training consists of two sector level sweeps (SLS), i.e. transmit sector sweep and receive sector sweep as depicted in Fig. 4.1.

The AP initiates the transmit beam training procedure by sending sector sweeping frames (SSW) from all beams in the codebook $|F|$. All existing clients listening in their quasi-omni mode and each user $u$ is able to compute $RSS_{i,omni}^{u}$, which is the received signal strength from $i$th transmit beam pattern ($i \in \{1,2,...,|F|\}$, $u \in \{1,2,...,U\}$ and $|F|$ is the AP’s codebook size). Next, the AP sends training frames...
on the omni-mode while every client $u$ sweeps and receives these frames from its receive sectors. Therefore, in this phase each client is able to compute $RSS_{u,j}^{omni}$, where $j \in \{1, 2, ..., |W_u|\}$ and $|W_u|$ is the codebook size of $u$th client.

The total number of SSW frames to partially train all $U$ users is

$$N_{coarse} = N_{user}^{omni} \times |F| + N_{AP}^{omni} \times \max(|W_u|)$$  \hspace{1cm} (4.1)

where $N_{user}^{omni}$ and $N_{AP}^{omni}$ are the number of quasi-omni patterns for users and AP, respectively. In contrast to $N_{11ad}$ in Equation 3.4, $N_{coarse}$ is independent from user population (i.e. $U$).

### 4.2 SUSAN’s User-Beam Selection

The SUSAN’s user selection protocol runs before the start of any data transmission using the information provided by partial multi-stream analog beam training. For an AP with $N_{RF}$ RF chains, multi-user transmission requires selecting a subset of up to $N_{RF}$ users to serve based on the channel information of all $U$ users in a network. Finding the optimal user set that maximizes the PHY-layer sum rate and ensures MAC-layer fairness is possible with full CSI knowledge of all users at the AP. As discussed earlier, obtaining the full CSI is impractical in 60 GHz networks. Nevertheless, finding the optimal user set is computationally prohibitive even with full CSI knowledge, especially in dense user populations.

Suboptimal incremental algorithm have shown to achieve approximate the optimal capacity with less computational complexity in sub 6 GHz MU-MIMO systems. SUSAN inherits the low-complexity of incremental user selection and induces a small overhead at each selection round whereby the total rounds is upper-bounded to the number of RF chains in the AP, i.e. $N_{RF}$. The AP can choose the first user based on
a fairness mechanism to ensure MAC-layer fairness. Then, it selects the next user-beam pair that provides the highest sum rate when grouped with already selected ones. This sender side greedy user selection procedure requires the partial beam training information of all users to identify the best user at each iteration.

Instead of a global greedy strategy which requires the AP to obtain all users’ beam training information, SUSAN runs distributed user selection, whereby each user evaluates its own potential contribution to boost the downlink capacity when grouped with already selected ones. Such potential is characterized with the SINR estimation. Each unselected user estimates the interference from already selected users to a subset of its receive beam pattern. The best receive beam pattern which captures the highest SINR value for that user is chosen. The user with highest SINR reports its chosen transmit beam ID to the AP in order to complete the partial analog beamforming training and enable. Therefore, the choice of receive beam ID is taken jointly with selection and the beamforming training procedure is completed for the selected user in each round.

In general, a new user can be added to the group when the following conditions are met on the MAC layer:

1. The new user’s SINR is higher than a pre-defined threshold.

2. The additional interference caused by the new user does not degrade the already selected users’ SINR below the threshold value.

3. Adding the new user improves the sum data rate.

Fig. 4.2 illustrates a typical flow of the proposed user selection operation with 4 users and one AP in the environment. In each round of greedy user grouping, the following steps take place:
1) **Next Round Announcement (NRA):** The AP announces its intention for another round of user selection though NRA packets. NRA packets are transmitted quasi-omni directionally and contains the user ID of already selected users. For instance, at the first round the ID of prime user (assumed to be user 2 in Fig. 4.2) is included in the NRA packet. The user which hears its own ID responds to the NRA packet with the beam training feedback. This feedback contains the information selected TX beam ID from partial multi-stream training (i.e. $S_{TX}^k$ for user $k$). The selected RX beam ID for the prime user is based on the maximum received signal strength; however, for all subsequent users, the received beam ID is selected considering the interference of already selected users. Therefore, the beam training procedure is completed for prime user in the first round since the AP obtains the selected TX beam ID to communicate directionally with this user and the RX beam ID has been selected at the user side. Let the subset of selected users at iteration $i$ to be $G_i$. Thus, the AP collects the TX beam ID of all selected users (i.e. $\{S_{TX}^k\}, \forall k \in G_i$).

To avoid global greedy user selection approach, users have to introduce the one with the highest potential contribution to improve the network’s downlink sum rate.
This potential contribution can be characterized with SINR estimation since it reflects both channel quality and mutual orthogonality with selected users’ channels.

2) **SINR Estimation:** To enable unselected users to measure the interference of already selected ones, the AP transmits the next packet from all transmit sectors corresponding to the already selected users, i.e. \( \{S_{TX}^k\}, \forall k \in G_i \). The unselected users is able to estimate the interference coming from already selected users to their receive antennas. Let \( B_j \) be RX beamforming vectors chosen at partial beam training phase for user \( j \). Then the SINR captured by the unselected user \( j \) using receive beamforming vector \( v \) can be modeled as follows.

\[
\varepsilon\{SINR_{j,v}\} = 10 \cdot \log_{10} \left( \frac{RSS_{j,omni}^{S_{TX}^j}}{N_0 + \sum_{k \in G} RSS_{j,v}^{S_{TX}^k}} \right), \quad \forall v \in B_j
\]

when \( RSS_{j,omni}^{S_{TX}^j} \), received power at user \( j \) from the best corresponding selected sector ID \( (S_{TX}^j) \) in the AP, was measured during partial multi-stream beamforming.

3) **Distributed Feedback Contention:** Now every client knows its estimated SINR and its potential to boost the sum rate when grouped with already selected users. To maximize the achievable sum rate, the one with the highest SINR has to be selected, however, clients do not have a full knowledge and are not coordinated. One approach can be global selection meaning that, all clients report their estimated SINR to a center unit (AP) and let the AP find the one with the highest SINR. This approach induces high overhead which scales with user population. SUSAN finds the user with the highest potential, i.e. highest estimated SINR, with a distributed contention mechanism. The unselected users with their SINR being above a threshold map their SINR to a slot number from \([0, W-1]\) where higher SINR maps to lower value. Users with SINR below a threshold (assumed to be 5.5 dB) will not participate in the contention. In addition, SUSAN enforces an upper limit to this metric,
corresponding to the maximum SINR that AP can observe in its WLAN. We choose [5.5, 25] dB as the default range based on our over-the-air measurements. Then the SINR will be quantized into W levels and every user maps its own SINR to a slot number from [0,W-1]. Every single user counts down and senses the channel until it gets zero and then starts to transmit a null data packet omni-directionally until the end of the window size. Users with higher SINR start the transmission earlier. The winner of the contention should be the one with the lowest slot number or the one who does hear any energy before starting null data transmission. In the timeline example, user 1 has the lowest SINR since it has high mutual interference with user 2 and is farther from the AP. The winner (assumed to be user 4 in the timeline) sends a *join request message* to the AP announcing itself as the best candidate to be added to the group while reporting its best transmit sector ID (i.e. $S_{4}^{TX}$) for the future directional transmissions. The winner also sets its RX beam vector to be the one which maximized its SINR in equation 4.2. If there is no potential user with SINR above the threshold, the AP terminates the user selection after waiting for a timeout without receiving any messages.

4) **Inferring Sum-rate from Feedback:** The *join request message* introduces the best candidate of joining the group. However, it is not still verified that the interference produced by adding this new user neither degrades the SINR of already established link below the threshold nor reduces the sum-rate of the downlink transmission. To this end, the AP transmits one beacon to all selected users (and the candidate) simultaneously and estimates an approximate MCS rate of the returned’ ACKs using Table 4.1. If the AP unable to received all users’ ACKs or the estimated sum rate is reduced from previous round, the AP removes the candidate from the list of selected users and terminates the user selection. This is called as early termination which happens when the AP terminates user selection before achieving the full rank.
4.2.1 Early termination

The proposed user selection method is subject to early termination which means terminating the incremental user grouping without selecting $N_{RF}$ users. The early termination may take place in one of the following conditions: (i) when all unselected users compute their SINR to be below the threshold for participating in the contention (ii) when collision occurs (iii) when the estimated sum rate at the end of user selection rounds degrades compared to the previous round

When the AP stops the user selection, it directly starts data transmission to the selected users, so as not to waste the channel time.

4.2.2 Fairness

To achieve fairness, a simple randomized algorithm for prime user selection is necessary; since once the prime user is selected, other grouped members will be determined in the case of stationary channel for all the clients. We employ proportional throughput fairness which select the user with lowest historic throughput as the prime user. To this end, the AP needs to keep the record of all the users average throughput and pick the one with lowest throughput as the prime user in the beginning of user selection procedure.

Table 4.1: MCS and SINR Threshold

<table>
<thead>
<tr>
<th>MCS Mode</th>
<th>MCS1</th>
<th>MCS2</th>
<th>MCS3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation</td>
<td>QPSK</td>
<td>QPSK</td>
<td>16QAM</td>
</tr>
<tr>
<td>Code rate</td>
<td>1/2</td>
<td>2/3</td>
<td>2/3</td>
</tr>
<tr>
<td>Data rate</td>
<td>0.952 Gbps</td>
<td>1.904 Gbps</td>
<td>3.807 Gbps</td>
</tr>
<tr>
<td>SINR$_{threshold}$</td>
<td>5.5 dB</td>
<td>13 dB</td>
<td>18 dB</td>
</tr>
</tbody>
</table>
4.2.3 Scalability

The proposed user selection mechanism is scalable to growing user population and number of antenna elements since user grouping rounds is bounded to $N_{RF} \ll N_{ant}, K$ and it does not require CSI feedback per antenna element.
SINR Boost with Antenna Allocation and Polarization Diversity

In general, multi-user transmission can be implemented using shared or split architecture as shown in Figure 5.1. In both architectures, each data stream uses independent phase shifters. In the shared architecture shown in Figure 5.1b, multiple phase shifters share the same power amplifier and antenna. The phase shifters sharing the same power amplifier are driven individually by independent data streams. In the split architecture, we have fixed antenna arrays for each RF chain or for generating each spatial stream. Whereas in shared architecture, there is a flexibility on allocating different portion of the antenna arrays to different spatial streams. This non-uniform antenna partitioning is helpful in further degrading the inter-stream interference. This non-uniform antenna partitioning has to meet the range requirement for the user while mitigating the mutual interference for simultaneous transmission.
5.1 Non-uniform Antenna Partitioning

5.1.1 Optimal antenna share selection

The exhaustive search through all user and antenna share selections induces an overwhelming overhead. Assume AP is equipped with \(N_{RF}\) number of RF chains and \(N_{ant}\) number of antenna elements located in a linear array as shown in Fig. 5.1b. The general optimization problem which maximizes the sum capacity by arbitrary partitioning the phased array for any subset of \(N_{RF}\) users selected from total \(K\) available users can be written as:

\[
\text{Max } C = \sum_{i=1}^{N_{RF}} W \log_2(1 + \text{SINR}_i) \quad (5.1)
\]

Subject to:

\[
\sum_{i=1}^{N_{RF}} k_i = N_{ant} \quad k_i \in \{0, 1, 2, \ldots, N_{ant}\}
\]

\[
\text{SINR}_i > \text{SINR}_{\text{threshold}} \quad \forall i \in \{1, 2, \ldots, N_{RF} | k_i \neq 0\}
\]
where $W$ or channel bandwidth and $SINR_{\text{threshold}}$ have been determined in Table 1. $k_i$ is the array size of the $i^{th}$ RF chain which will be zero for an inative RF chain.

The key challenge in this optimization problem is that $SINR_i = f(k_1, k_2, ... k_N)$ meaning that the $SINR$ of each link is a function of antenna array size dedicated to all clients in the network since the intended signal strength for $i^{th}$ user depends on $k_i$ while its interference is a function of all other clients antenna share $k_u$ ($u \neq i$). This implies that optimizing sum capacity (or sum-rate) requires the full CSI in the AP which is not practical in 60 GHz band as discussed earlier.

Intuitively the number of antennas allocated for a single user should be inversely proportional to its downlink link quality. Thus the suboptimal solution can be achieved by solving these two equations:

$$\sum_{i=1}^{N_{RF}} k_i = N_{\text{ant}}, \quad k_i \propto \frac{1}{SINR_i}$$

This leads us to propose a suboptimal algorithm for dynamic antenna array allocation.

### 5.1.2 SUSAN with non-uniform antenna partitioning

The optimum number for spatial streams depends on the environment, location of clients and directivity of the channel which are not pre-known to the AP. Therefore, the AP does not whether the incremental user selection is exposed to early termination or not. Therefore, our strategy is to allocate an equal share to each RF chain or each spatial stream initially. The AP starts SUSAN user selection scheme with equal antenna partitioning and selects a subset of users (assume the set of selected users’ indexes is $Group$ and the number of members to be $G$).

If early terminations takes place then there will be at least one inactive RF chain along with those antenna elements dedicated to that specific RF chain. The unused
antennas elements (if any) can improve sum rate of the system with either increasing the number of spatial streams (i.e. add another user to the group) or by increasing the link quality of already selected users.

The key idea is to dedicate more antennas for the new selection candidate which is equivalent to generating more focused beams with higher antenna gain for the new candidate. A new round of selection may now become successful since channel’s orthogonality highly depends on the antenna gain and channel directivity.

In addition, the AP can also share all the remaining antennas among existing selected users based on their estimated SINRs. In the situation of early termination, one of the following cases can happen:

- **Case 1: Number of selected users < $N_{RF} - 1$**

In this case, there are at least 2 inactive RF chains and $2 \times \left( \frac{N_{ant}}{N_{RF}} \right)$ antenna elements in the AP. The pseudo code of the proposed protocol has been described in Algorithm 1.

The array size for the new candidate of joining the group is initialized with $X = 2 \times \left( \frac{N_{ant}}{N_{RF}} \right)$. In each round, AP attempts to add the the first unselected user in the queue to the group using X antenna elements. If this try fails due to any reason, AP doubles the correspondent array size and retry until applying the maximum possible antenna resources (line 2 to 6 in the pseudo code).

The beamforming training in the beginning of each beacon interval was initially executed with a fixed number of antenna elements and based on the codebook described in Equation 5.1.2 where the total number of beam patterns is bounded to the number of antenna elements. Therefore, more antenna elements gives us the opportunity of using more beams pattern with narrower beamwidth. However, it changes the codebook entries in Equation 2.1 and the transmit sector ID selected during the initial SLS is no longer the beam which provides the highest signal strength at the
Algorithm 1 SP-DAA: Case 1

**Input:** $N_{\text{ant}}, N_{\text{RF}}, G$

**Output:** $\{k_i\}$ for $\forall i \in \{1, 2, ..., N_{\text{RF}}\}$

**Description:**

1. **Initialize** $X = 2 \times \frac{N_{\text{ant}}}{N_{\text{RF}}}$ and flag=0;
2. **While** $X < N_{\text{ant}} - G \times \frac{N_{\text{ant}}}{N_{\text{RF}}} \& \ flag = 0$
3. Attempt to add user $l$ using $X$ antennas;
4. **If** *successful* then set flag=1;
5. **If** *unsuccessful* then set $X = 2 \times X$;
6. **End While**
7. **If** $N_{\text{ant}} - G \times \frac{N_{\text{ant}}}{N_{\text{RF}}} - X > 0$
8. Then solving Equation 5.2 for $\{k_i\}$;
9. **Else** $k_i = \frac{N_{\text{ant}}}{N_{\text{RF}}} \forall i \in Group$, $k_l = X$;
10. **End If**

user. We claim that the new best beam ID is twice of the previously selected index, thus there is no need for re-beamforming with extra overhead.

Proof: Let $q^*$ be the index of the selected beam from previous SLS for a particular user. The antenna weights corresponds to beam $q^*$ are:

$$W(p, q^*) = j^{\text{floor}(\frac{px \mod (q^*+(Q/2),Q)}{Q/4})}$$

for $\forall p \in \{0, 1, 2, ..., P-1\}$

The codebook entries for beam $2q^*$ of the double sized array are:

$$W'(p, 2q^*) = j^{\text{floor}(\frac{px \mod (2q^*+(Q'/2),Q')}{Q'/4})}$$

for $\forall p \in \{0, 1, 2, ..., 2P-1\}$ and $Q' = 2Q$
From above equations can be simply driven that:

for \( p \in \{0, 1, 2, ..., P - 1\} : \ W'(p, 2q^*) = W(p, q^*) \)

for \( p \in \{P, P + 1, P + 2, ..., 2P - 1\} \) and \( P = Q : \)

\[
W'(p, 2q^*) = W(p - P, q^*) \times j^{4\pi n (q^* + (Q/2), Q)}
\]

\[
= W(p - P, q^*)
\]

On the other side, the array factor of a linear uniform-spaced antenna array can be written as [13]:

\[
A_q(\theta) = \sum_{p=0}^{P-1} w_{p,q} e^{j2\pi n (d/\lambda) \cos \theta}
\]  (5.3)

where \( w_{p,q} \) is the \( p^{th} \) element of \( q^{th} \) weight vector in the codebook, \( d \) is the antenna spacing and \( \lambda \) is the wave length. If the antenna elements are locate along y-axis, then \( \theta \) is the polar angle with respect to x-axis. From equation 5.3, it is easy to show:

\[
A'_{2q^*}(\theta) = 2 \ast A_{q^*}(\theta)
\]

Therefore, if \( q^* \) is index of the best beam to send data to a particular direction using \( X \) antennas , \( 2q^* \) is the best beam’ index when having \( 2X \) antenna elements.

To see if the new candidate can join the group or not, AP sends simultaneous beacons to all selected users and the candidate using. If the AP hears ACK from all of them the candidate will be grouped with other selected ones.

After the procedure of adding a new user is complete (either successfully or unsuccessfully), AP dedicates all remaining antennas (if any) to the selected users based on their estimated SINR (Equation 5.2).

- **Case 2: Number of selected users= \( N_{RF}-1 \)**

In this case, only one RF chain and its corresponding antenna elements are inactive. If
there was a chance of increasing multiplexing gain, the full rank was already achieved during user selection. Therefore, AP shares all $\frac{N_{ant}}{N_{RF}}$ inactive antennas among selected users in order to increase beamforming gain (line 7-10 of the Algorithm 1).

### 5.1.3 Distributed antenna selection

In previous section, we discussed about how number of antenna associated with each spatial streams are selected. However, we did not talk about how we actually select a sub set of antennas from the transmit array in the AP. The search space for choosing a subset containing $X$ antennas from $N_{ant}$ elements yields to $\binom{N_{ant}}{X}$ different combinations. However there two main factors that constraints our selection:

1. We want the antennas associated to one spatial stream to be as separate as possible. Equation 5.3 implies that, larger inter element antenna spacing ($d$) yields to the higher array factor and higher antenna array directivity.

2. We prefer uniformly spaced linear antenna arrays due to the simplicity of the codebook design.

Based on the above constraints, we want to have uniform and large inter-element space for the subset of antennas corresponds to every spatial stream. Figure 5.2 explains our antenna selection strategy with an example. In this example $N_{ant} = 16$ and $N_{RF} = 4$. Assume in the user selection two users (1 and 2) were grouped; the third user was added after early termination with all the remaining antennas. In Figure 5.2, the red and orange color shows the antenna elements dedicated to user 1 and user 2 while the purple ones are dedicated to user 3. This strategy results in having approximately the same antenna aperture size for all selected users.
5.2 Polarization Diversity

We target polarization diversity as mechanism to dramatically reduce inter-stream interference enabling vastly improved aggregate rate.

5.2.1 Polarization concepts

The polarization of an electromagnetic wave is defined based on the orientation of the electric field vector $\vec{E}$. The electric wave is perpendicular to the propagation direction and can be decomposed to two orthogonal elements, $E_X$ and $E_Y$, which are received by the horizontal and vertical elements of the antenna respectively. When $\vec{E}$ socialites on a straight line, which means that one of the component is zero, the wave is referred to linearly polarized wave. There are two types of linear polarization, horizontal and vertical, where $E_Y$ and $E_X$ is equal to zero respectively. When $E_X$ and $E_Y$ have equal magnitudes and 90 degree phase difference, the electric field rotates around a circumference and the wave polarization is called as circular. If the electric filed rotates counterclockwise which means that $E_X$ is 90 degree ahead of $E_Y$, the wave is called Right Hand Circular Polarized (RHCP), otherwise, it is Left Hand Circular Polarized (LHCP).

The polarization of an antenna is the polarization of the electromagnetic waves radiated by that antenna in the far field. If polarization of the propagating wave and the receiver antenna are not matched, the received signal will attenuate at the
antenna significantly. In general, where the electric field vector of a propagating wave and an antenna has $\phi$ phase difference, the power loss due to polarization mismatch is described by the \textit{Polarization Loss Factor} (PLF):

$$PLF(\phi) = \cos^2(\phi)$$  \hspace{1cm} (5.4)

Equation 5.4 implies that a vertical polarized antenna and a horizontal polarized antenna cannot communicate with each other. In addition, a linear polarized antenna and a circular polarized one can communicate with each other by 3 dB attenuation.

\subsection*{5.2.2 Dual-polarized antenna array architecture}

Exploiting polarization diversity necessitates the AP and all clients to be equipped with dual-polarized antenna array architecture. We introduce an architecture where clients have separate RF chains for vertically and horizontally polarized antenna arrays while the AP has a dual-polarized architecture meaning that each antenna element can switch between horizontal and vertical mode as shown in Figure 5.3. Having this architecture, the AP is capable of transmitting data streams with both orthogonal polarizations simultaneously. Furthermore, each client receiving a stream within two orthogonally polarized antenna arrays can decide the best polarization with signal strength and interference consideration.

\subsection*{5.2.3 SUSAN with polarization diversity}

While SUSAN’s basic mechanism does not consider polarization diversity explicitly, we demonstrate its compatibility with dual-polarized phased arrays. The received signal strength obtained in beamforming training procedure depends on the polarization of the incoming wave and received antennas. When the AP is equipped with
dual-polarized antenna arrays, all training frames need to be transmitted with horizontal and vertical antennas. As described in Figure 5.3, clients are equipped with a separate RF chains are able to find the received signal strength from both horizontal/vertical antenna array simultaneously. Storing this information, clients are able to find the best polarization based on the received signal strength of the intended signal (obtained during beamforming training) and the amount of estimated interference (during probing time). The selected polarization information for each user will be included in the acknowledgment packet.
In this chapter, we describe our simulator and our testbed for over the air measurements.

6.1 Polarimetric 3D Ray Tracing

We first describe the 60 GHz WLAN propagation and reflection model. Then the polarization model for 60 GHz has been explained. Lastly, we illustrate the simulation setup including our image-based 3-D Ray Tracing technique.

6.1.0.1 Propagation and Reflection Model

The path loss between a transmitter and a receiver is modeled in [18] as:

\[ PL(d) = 10n \log\left(\frac{4\pi d}{\lambda}\right) \]  

(6.1)

where, \( n \) is the path loss exponent set to 2 in our model and \( d \) is the distance along the propagation path between center of the transmitter antenna array to the center of receiver array, and \( \lambda \) is the wavelength of the carrier signal.
We assume that reflective materials is modeled as a single-layer homogenous dielectric plate with a smooth surface. Furthermore, we assume the angle of reflection to be equal to the angle of incidence. The reflection coefficients for a particular material with aforementioned characteristics is a function of the angle of incident and polarization. In [19], the reflection coefficient $R$ is expressed as:

$$ R = \frac{1 - \exp(-j2\delta)}{1 - R'^2\exp(-j2\delta)}R' \tag{6.2} $$

where $\delta = \frac{2\pi d}{\lambda} \sqrt{n^2 - \sin^2\theta}$, $\lambda$ is the wavelength of signal, $d$ is the thickness of the plate, $\theta$ is the angle of incident, and $n$ is the complex refractive index of the plate. A table of complex refractive indices of different material has been measured and provided in [19].

The plane of incident is the plane containing the reflection surface normal, the incident ray and reflected ray. When the electric field of the incident wave is perpendicular and parallel to the plane of incident, $R'$ is substituted with $R'_s$ and $R'_p$, respectively [19].

$$ R'_s = \frac{\cos\theta - \sqrt{n^2 - \sin^2\theta}}{\cos\theta + \sqrt{n^2 - \sin^2\theta}} \tag{6.3} $$

$$ R'_p = \frac{n^2 \cos\theta - \sqrt{n^2 - \sin^2\theta}}{n^2 \cos\theta + \sqrt{n^2 - \sin^2\theta}} \tag{6.4} $$

where $R'_s$ and $R'_p$ are Fresnel’s reflection coefficients In calculation of reflection coefficient at each reflection point, we decompose electric field into two components, perpendicular and parallel to the plane of incident and then calculate both $R'_s$ and $R'_p$. The reflection coefficient can be found by their combination.
6.1.1 Polarization Model for 60 GHz

To evaluate the potential of polarization diversity as an interference mitigation technique, a polarization model for 60 GHz WLAN systems has been introduced in the next two sections.

• Polarization characteristics of antennas

The electric field vector $\vec{E}$ in the far field is a function of azimuth angle $\varphi$ and elevation angle $\theta$ in the spherical coordinate system. In this new coordinates, $\vec{E}$ can be decomposed to $E_\varphi$ and $E_\theta$ which belong to the plane of constant $\theta$ and constant $\varphi$ respectively.

The polarization of an antenna can be modeled by Jones calculus. Jones vector was originally introduced in optics to describe polarized lights where the Jones vector represents the amplitude and phase of the electric field [20]. Here Jones vector is assumed to be a $2 \times 1$ vector which contains $E_\theta$ and $E_\varphi$ components. For instance, the corresponding Jones vector for a linear polarization antenna in $\theta$ direction and the LHCP antenna is $\begin{pmatrix} 1 \\ 0 \end{pmatrix}$ and $\frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ i \end{pmatrix}$ respectively.

Assume the Jones vector of the transmit to be and receive antenna to be $J_{TX}$ and $J_{RX}$. In addition, consider $H$ as the matrix of channel polarization model for a particular ray. Thus, the PLF due to antenna mismatch can be calculated easily by finding the angle between $J_{TX} \times H$ and $J_{RX}$ and using equation 5.4.

• Polarization characteristics of channel

In order to model polarization characteristics of 60 GHz channels, we need to define a matrix $H$ for each single ray. This matrix include gain coefficients between $E_\theta$ and $E_\varphi$ and the signal attenuation due to reflection.

The polarization of an electromagnetic waves remains constant by propagation; however, the reflecting from an obstacle may vary the polarization. Therefore, for
LOS path, the H matrix is the identity matrix (e.g. \( H_{LOS} = I_{2 \times 2} \)). We explained how reflection coefficients of reflected ray are different for E components which are parallel or perpendicular to the plane of incident. Thus, polarization of a reflected path depends on both the angle of incident and polarization of incoming wave since.

To find the polarization matrix \( H \) for the first-order reflected path, we need to change the coordinates of E vector from the one the coordinate system associated with TX to the one which is associated with the plane of incident. Next, we need to decompose \( \vec{E} \) into two components, parallel and perpendicular to the plane of incident and find the reflection coefficient using Equation 6.2-6.4. Finally, the coordinates system must change by a rotation to the coordinates system associated with RX. Fig. 6.1a shows an example of the first order reflected ray. The corresponding H matrix for this path can be found as:

\[
H = \begin{bmatrix}
\cos(\psi_{rx}) & \sin(\psi_{rx}) \\
-sin(\psi_{rx}) & \cos(\psi_{rx})
\end{bmatrix} \times \begin{bmatrix}
R_s(\alpha_{inc}) & 0 \\
0 & R_p(\alpha_{inc})
\end{bmatrix} \times \begin{bmatrix}
\cos(\psi_{tx}) & \sin(\psi_{tx}) \\
-sin(\psi_{tx}) & \cos(\psi_{tx})
\end{bmatrix}
\] (6.5)

In our simulation we considered up to two reflections from the source toward destination. The polarization channel matrix for second order reflections is similar to what was described for the first order reflection paths unless one additional coordinates system rotation and reflection matrices must be added.

Modeling polarization of antennas and 60 GHz channels enables us to find the RSS and the interference strength at each client with a specific polarized antennas so that the evaluation of polarization diversity gains becomes possible.
Figure 6.1: (a) An example of the first order reflection ray. (b) Illustration of image-based ray tracing technique.

6.1.2 Simulation Setup

Environment. We consider a typical 60 GHz conference room model [21]. In our simulation model, the interior structure and obstacles (e.g. conference table) are modeled by flat cuboids while each surface of walls, ceiling, and other surfaces is modeled as a single-layer dielectric and the reflection coefficients are computed as described in previous section. We assume one fixed AP located at the center of ceiling which is equipped with $N_{RF}$ number of RF chains and $N_{ant}$ antenna elements in a linear configuration ($N_{ant} \gg N_{RF}$). We only consider reflection and ignore diffraction and diffuse scattering from surfaces for simplicity. In addition, the maximum number of reflections for each ray is consider to be two.

Clients. We consider multiple clients which are located randomly in the environment and are equipped with one RF chain and a linear antenna array with $k_u$ antenna elements. We assume that there is a Line of Sight (LOS) link from AP to every single client.
Table 6.1: Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier frequency</td>
<td>60 GHz</td>
</tr>
<tr>
<td>MAC and PHY</td>
<td>IEEE 802.11ad</td>
</tr>
<tr>
<td>Dimensions of environment</td>
<td>3m (\times) 4m (\times) 3m</td>
</tr>
<tr>
<td>Transmission power</td>
<td>10 dB</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>1.7 GHz</td>
</tr>
<tr>
<td>Noise figure</td>
<td>7 dB</td>
</tr>
<tr>
<td>Max number of reflections</td>
<td>2</td>
</tr>
<tr>
<td>SINR threshold</td>
<td>5.5 dB</td>
</tr>
<tr>
<td>Number of RF chain per user</td>
<td>1</td>
</tr>
</tbody>
</table>

**Ray Tracing method.** We use 3-D imaged-based ray tracing technique for wave propagation modeling in 60 GHz [22]. In this technique, an arbitrary path can be defined by the sequence of reflection surfaces which the ray hits when propagating from transmitter to the receiver.

Once the sequence of reflecting surfaces for a particular ray is known, one can find reflection points easily. The general procedure suggests to find the image of the receiver antenna from the last reflecting surface and then find the image of the image with respect to the following reflecting surface and repeat this process until no reflecting surface is left. Fig. 6.1b illustrates the method by a 2D example. In this figure, we wish to find a path from TX to RX that reflects from surface 1 and surface 2 respectively in its propagation. First, we find the image of RX from surface 2 and call it R’. Then, the image of R’ with respect to surface 1 is found and noted as R”. By having the coordinates of TX, RX, R’, and R”, the intersection points of A and B can be easily computed.

**Simulation parameters.** The set of important constant simulation parameters is represented in Table 1. Table 2 contains Modulation and Coding Scheme (MCS) and minimum achievable data rate based on link SINR with Bit Error Rate (BER) to be \(10^{-5}\).
6.2 Testbed Implementation and Data Collection

We perform over the air measurements using our novel software-radio to evaluate the potential of the spatial reuse. In this section, we describe the spatial reuse implementation and data collection followed by evaluation of spatial reuse with the help of experiment results.

6.2.1 Testbed Implementation

Our testbed consists of commercial mm-wave transceivers from the VubIQ 60 GHZ development system [23], two WARP v1 boards, and connecting circuits for signal adjustment outlined in Fig. 6.2a. The mm-wave transceivers are capable of communicating in 57-64 unlicensed band with up to 1.8 GHZ modulation bandwidth.

One computer is connected to the WARP boards via ethernet connections and is communicating with them using MATLAB, WARP-lab [24] and VubIQ control panels. In this paper, we apply the transmit module as the AP and the receive module as the client. A random set of binary data is generated via WARPLab and encoded using BPSK. Our WARP board supports single carrier transmission with both BPSK and QAM with up to 20 MHZ transmission bandwidth and 40 MSps sampling rate. WARP analog daughter card converts encoded data to single-ended I/Q signals and send it to the transmit module. Since the output signals of the WARP board does not match the VubIQ module’s input specification (and vice versa), we need to adjust baseband signals using ADL5565 differential amplifier, which convert the single-ended I/Q output of the WARP to differential I/Q signals and removes the DC offset. The output of differential amplifier passed to the transmitter’s VubIQ module and is converted to 60 GHz band and is transmitted by horn antennas.

Horn antennas provides directional transmission and emulated phased array antennas in our system. To achieve different beamwidth, we apply 7°, 20° and 80° horn
antennas. In the receiver’s VubIQ module, the signal is received by horn antenna and is down-converted to analog I/Q baseband. To clean up the this signal, we pass the differential I/Q signal to a low pass filter (LT6600-15) and then to the WARP board where the signal is demodulated in the WARPlab. In our testbed, transceivers are configured to have a common clock. In order to collect RSS for different locations and antenna orientations, we use mechanical motors and DC micro-step driver with a motion control setup [25] connected to the transceivers to steer the beams with sub-degree accuracy. Next we explain how we collect data with explained setup.

### 6.2.2 Data Collection

Using our 60 GHz testbed, we measure signal strengths for a high density client distribution over a conference room depicted in Fig. 8b. The room is composed of several reflectors including glass windows, a white board, AC cover and a large TV screen. As we mentioned in previous chapters, the AP needs to be equipped with multiple RF chains in order to transmit streams to multiple clients simultaneously. Since our hardware is not capable of multiple concurrent transmission, we find the
map of signal strength over the environment with different beamwidth level.

We place the AP at one end of the conference table and locate the clients in 20 different positions as shown in Fig. 8b. To emulate the effect of different array size in the AP, we conduct the measurements with 7°, 20° and 80° horn antennas since narrower beams imply larger array size; however, in the client side we only use 20° horn antenna which is close to the reality according to size and power constraints in the mobile client mentioned in 3.3.4. For each client position, we consider three different orientations which one of them provide the LOS path to the AP and other two force NLOS paths by 60° rotation from the LOS orientation. Per each selected horn antenna in the AP and per each client position and orientation, AP performs a 360° sweep in steps of 5° and we take RMS baseband measurements.

We normalize the RMS baseband measurements based on the maximum value observed during the entire experiments and map them to Table. 4.1 in order to find the corresponding data rate.
In this chapter, we first describe our preliminary results which helps study spatial reuse factor and mutual interference for a downlink multi-user transmission in 60 GHz indoor environment. Then, we evaluate SUSAN’s performance through testbed experiments and simulation analysis.

7.1 Preliminary Analysis

7.1.1 Evaluating Spatial Reuse and Interference

To analyze channel orthogonality in 60 GHz indoor environment, we study the spatial reuse static links in 60 GHz WLANs. If we have a set of users (S) in the environment, the spatial reuse factor can be defined as [26]:

\[ \beta_S = \frac{R_S}{\sum_{i \in S} R_i / |S|} \]  

(7.1)

where \( R_S \) is the sum rate of simultaneous transmission to all users in the set, \( R_i \) is the achievable isolated downlink rate for \( i^{th} \) user and \(|S|\) is cardinal of S or number of users in the S. The data rate is a translation of the received signal strength using
Figure 7.1: Measured distribution of $\beta$ over 190 different locations pairs with 3 different Tx horn antennas.

Table 4.1. Spatial reuse factor is an indicator of interference in the environment since smaller $\beta_s$ shows stronger mutual interference and $\beta_s = |S|$ shows perfect spatial reuse with no mutual interference.

**Distribution of spatial reuse factor.** The amount of mutual interference for two users is highly correlated to their relative positions. To acquire the realistic knowledge of interference variation in the environment, we find the distribution of spatial reuse factor across 190 different location pairs using over-the-air measurements. Each time, two users are placed in two of marked positions in Figure 6.2(b) (i.e. total number of position pairs is $\binom{20}{2} = 190$). For a pair of positions and for a specific antenna beamwidth at the AP, we measure rms. values of the LOS links and then translate them to the $\beta_s$ using Table 4.1. Fig. 7.1 shows the Complementary CDF (CCDF or 1-CDF) of $\beta_s$ across all pairs. Wider beams suffer from more interference while the perfect spatial reuse factor, which is 2 here, was never achieved even with $7^\circ$ horn antenna. This implies that the amount of inter-user interference, in any two location pairs for the receivers, is never zero due to the reflection.
Figure 7.2: Measured $\beta$ using 20° horn antenna at the AP across 8 different location pairs for the clients.

**Impact of side lobes on mutual interference.** The beam pattern of horn antennas are designed to have no side lobes [27]; thus, reflection is the only source of interference in Fig. 7.1. However, beam patterns which are practically generated by phased antenna arrays often have side lobes. To evaluate the impact of side lobes on spatial reuse, we emulate a back lobe in the beam pattern of horn antennas by finding the signal strength received from transmitter rotated by 180° from the LOS direction. We measure interference of unintended data stream in each client with and without side lobe effects for 8 different randomly selected client location pairs. Fig. 7.2 shows the impact of side lobes on $\beta$ factor with 20° horn antennas in the AP. This figure confirms the high variation of spatial reuse based on the choice of locations; for instance, the spatial reuse can be as large as 1.9 or as low as 0.4. We also observe that side lobes can degrade spatial reuse by up to 38% which results in 1.7556 Gbps aggregate data rate reduction. Therefore, the amount of interference caused by reflection and side lobe leakages is not negligible and in some cases it makes the coexistence of several spatial streams impossible. Therefore, we need a user selection scheme to choose users which highest channel orthogonality in 60 GHz WLANs and
maximum number of spatial streams which are able to co-exist is channel dependent parameter.

7.1.2 Upper bound on number of spatial streams

An interesting question to look into is how many spatial streams ($N_{ss}$) are able to provide the highest sum rate in 60 GHz WLANs? From sum rate perspective, adding another simultaneous transmission adds an offset to the sum rate of the system while decreasing other users’ SINR (and data rate consequently) due to the additional induced interference. Therefore it is not clear whether the resulting system would have a higher sum rate or not. In general, we define $N_{ss}^*$ as the number of spatial streams that provide the highest sum rate in a particular environment. The inherent multipath richness of the propagation channel, Tx and Rx antenna aperture size and directivity (i.e. number of antenna elements in the antenna array) [28] are key factors on the amount of mutual interference and maximum number of spatial streams consequently. In Fig. 7.1, we showed that in a given environment, higher spatial reuse can be achieved using narrower beams or larger antenna arrays consequently. In legacy downlink MU-MIMO, the multiplexing gain is practically limited by the rank of the channel [29], i.e. there is an upper bound for the spatial multiplexing which only depends on the environment, regardless of what kind of equipment is used. Here we want to find out whether ($N_{ss}^*$) in 60 GHz multi-user downlink transmission is bounded due to the 60 GHz channel characteristics or due to the limited number of antennas that can be practically installed in the AP. To this goal, we consider two scenarios where the AP is equipped with 8 RF chains and 256 antenna elements (which is a practical number based on antenna size in 60 GHz) in one scenario and 2048 antenna elements in the second one. Figure 7.3 shows the total PHY rate obtained for different number of spatial streams. In part (a), the sum PHY rate first increases as a
result of more simultaneous transmission; however, increasing number spatial streams from 4 to 6 reduces the downlink aggregate PHY rate due to additional interference. Therefore, with 256 antenna elements in the AP, $N_{ss}^* = 4$ maximizes the sum rate in this particular scenario. However, Figure 7.3(b) implied that $N_{ss}^* \geq 8$; hence, we conclude that $N_{ss}^*$ is upperbounded due to the size constraint (i.e. maximum number of antenna elements) rather than environmental characteristic of 60 GHz.

7.1.3 Antenna array partitioning: uniform vs non-uniform

In SUSAN algorithm, one of the key strategies is to share any unused antennas non-uniformly among selected users based on their SINR values. To find the impact of this dynamic allocation on the spatial reuse factor ($\beta$) using over the air measurements, we need to emulate different array sizes with 7°, 20° and 80° horn antennas. Assume the number of antenna elements required to generate a 7° beam is 3X while this number for a 20° and 80° beam is 2X and X respectively. Assume the AP is equipped with 6X antenna elements and 3 RF chains and three users are placed in 8 different randomly chosen location sets (from the 20 marked positions in Figure. 6.2(b)). Per each choice of locations, the Tx side employs only 20° horn antenna to transmit to

Figure 7.3: The downlink aggregate PHY rate with increasing number of users when AP is equipped with total (a) 256 and (b) 2048 antenna elements.
all three receivers which emulating equally partitioning of antennas into 3 subarrays of 2X elements. Then, 7° is chosen for the farthest user from the Transmitter (with lower signal strength), 80° for the closest and 20° for the last user which emulates unequal partitioning of antenna elements into 3 subarrays with 3X, X and 2X antennas respectively. We translate the measured rms. values for both scenarios to $\beta$ and plot the result in Figure 7.4. We observe that by utilizing different horn antennas, the spatial reuse factor improves by 14% to 82% which provides 532 Mbps to 3.1 Gbps aggregate data enhancement in different location sets. To conclude, non-uniform SNR based antenna partitioning, which is one of SUSAN’s design strategies, improves spatial reuse compared to equal antenna partitioning in the same topology.

### 7.1.4 Channel orthogonality with dual-polarized arrays

We introduced polarization diversity as an interference mitigation technique to boost channel orthogonality in a multi-user network. Here we want to study the effectiveness of this technique in different user population scenarios. In the absence of reflection, side lobes and any kind of scattering, exploiting two orthogonal polarization for downlink transmission doubles the spatial reuse and the reason is isolation.

![Figure 7.4: Effectiveness of dynamic antenna allocation on interference mitigation.](image-url)
between two orthogonally polarized transmissions. Therefore, in such scenarios we have $\beta^V_P = \min(2 \times \beta^V_P, |S|)$ where $\beta^V_P$ are the spatial reuse factor over user set $S$ using both vertical and horizontal polarizations and $|S|$ is cardinal of $S$.

Figure 7.5 shows the average of $\beta_S$ for different cardinal numbers with vertically polarized and dual polarized antennas. The dual-polarized scenario diverges from the ideal case (where $\beta_S$ equals to $|S|$) as $|S|$ grows due to excessive reflection and signal leakages. Polarization diversity provides higher channel orthogonality in all cases; in particular, it achieves near optimal spatial reuse for the case of $|S| = 2$. Figure 7.5 also shows that exploiting dual-polarized antennas does not double the spatial reuse; hence, orthogonally polarized transmissions are not isolated in the environment.

### 7.2 Protocol Evaluation

In this section we analyze the performance of SUSAN in terms of capacity, fairness, and overhead. For performance comparison, we have implemented three other user selection schemes as a baseline comparison: (1) Random User Selection (RUS) which selects $N_{RF}$ users randomly with equal probability (2) SNR-based User Selection
(SNRUS) which selects $N_{RF}$ users with highest individual signal strengths found during BFT. (3) Maximum Angular Separation based User Selection (ASUS) which selects $N_{RF}$ users with maximum angular separation based on the the information obtained during mandatory beam training. In ASUS, the angle of transmission for a user is estimated by the central angle of the best transmit sector selected during beam training.

7.2.1 Capacity gain from proposed user selection.

To evaluate the performance of SUSAN’s user selection algorithm, we compare its achievable PHY rate (no MAC overhead) and the number of selected users with baseline schemes in Figure 7.6a and Figure 7.6b, respectively.

**Setup.** For this experiment, we fix the number of clients to 8 to represent a WLAN scenario. All clients communicate with a single AP which is equipped with different number of RF chains as in x-axis. To have a fair comparison, all protocols were implemented with uniform single-polarized antenna array partitioning. We consider a fixed 32-element linear antenna array per RF chain in the AP and a fixed 16-element array at each client.

**Results.** First, we observe in Figure 7.6 that even if the AP has the capability to aggregate more spatial streams and more clients, it is not always beneficial. As shown in Figure 7.6a, the aggregate PHY rate of the baseline schemes first increases and then degrades as the number of RF chains at the AP increases. The reason is adding another spatial streams boosts the sum rate with enabling the AP to transmit more data packets in the same time interval. However, the new data stream may cause excessive interference for already existing clients and degrade the data rate of the already established links.

Second, the results from Figure 7.6b confirms that our proposed user selection
method incrementally adds users to achieve the maximum achievable sum rate and terminates the procedure when adding more user degrade the aggregate PHY rate; even if that means not using the full capability of the AP for user aggregation. Fig. 7.6a shows that proposed user selection method outperforms other schemes under all $N_{RF}$ topologies. With lower number of RF chain, e.g. 2 or 4, the performance difference between baseline methods and SUSAN algorithm is not significant. However, when number of RF chains pass the channel’ SDoF (which is four in this scenario), SUSAN keeps boosting the sum rate while the sum rate of all the baselines’ schemes degrade. When SDoF is less than $N_{RF}$, there is a great potential of employing unused antennas to boost aggregate rate as proposed in SUSAN algorithm.

### 7.2.2 Performance loss in compared to exhaustive search

In this section we want to compare the performance of SUSAN with exhaustive search. For scenarios with fixed (non-mobile) clients, including backhaul, it may be feasible to exhaustively test all client grouping, polarization combinations and antenna array partitioning. In particular, aggregating up to $N_{RF}$ clients out of $K$ existing clients
yields $\sum_{m=1}^{N_{RF}} \binom{K}{m} \times 2^m \times \binom{N_{ant}}{m-1}$ possible user, polarization and antenna share combinations. With a larger number of clients having changing channels, the search space and testing overhead would yield overwhelming control overhead. In this thesis, we introduced SUSAN which is an scalable incremental user aggregation mechanism with limited overhead time. In this section, we want to show the percentage of capacity loss in SUSAN as a result of not doing an exhaustive search.

**Setup.** For this experiment we fix the number of RF chains to 8 and total number of antenna elements available at the AP to 256 (i.e. $N_{RF} = 8$ and $N_{ant} = 256$). The x-axis shows the number of existing clients in the environment and the y-axis depicts the achieved sum rate normalized to the maximum possible sum rate from the exhaustive search. In each user population scenario, we find the normalized sum rate with Angular Separation based User Selection (ASUS) as a baseline scheme, SUSAN with uniform antenna partitioning and SUSAN with all of its key features.

**Results.** First, we observe in Figure 7.7 that SUSAN achieves close to the maximum achievable sum rate with exhaustive search (value of 1) under any user population, therefore the performance loss of SUSAN is insignificant in compared to the benefits yielding from limited overhead and scalability. The maximum angular sepa-
ration policy attains 50% of the maximum possible sum rate at the best case scenario with 2 existing users and its aggregate rate degrades with dense user population.

Second, we observe that in sparse user population, a significant capacity gain is provided by non-uniform antenna partitioning while SUSAN’s user selection component plays the main role in capacity improvement in dense user population. The reason behind this is that high user population provides more user grouping combinations and chance of grouping more users with less mutual interference increases. As number of spatial streams become closer to the available number of RF chains in the AP, there will be less unused antenna elements to be exploited and partitioned non-uniformly in SUSAN protocol.

7.2.3 Scalability of SUSAN

In this section, we find the overhead induced by SUSAN and compare it with 802.11ad standard in the same topology. The overhead time in SUSAN accounts for both beam training and incremental user selection. However, for the baseline scheme, we apply point to point link establishment and employ the information obtained during BFT in 802.11ad standard for angular separation based user selection, i.e. without inducing any extra overhead.

**Setup.** We find the overhead needed for SUSAN algorithm using 802.11ad timing values in different user population scenarios. To isolate PHY effects, the results are obtained from the emulated MAC layer. The baseline scheme is repeating the beam training for every single user and use the obtained information during this procedure to group users based on angular separation and without inducing extra overhead. We fix the number of RF to be 8 at the AP in this experiment.

**Results.** We observe in Figure 7.8 that the amount of beam taring overhead increases linearly with number of clients for 802.11ad beamforming training. However,
SUSAN adds users incrementally when adding another spatial streams improves the sum rate. The maximum rounds of user selection is equal to the maximum potential of AP for user aggregation (i.e. number of RF chains) which is independent from number of clients in the environment. Therefor, we observe that, the amount of overhead for SUSAN first increases with growing user population and then saturates implying that having four spatial streams maximized the sum data rate in the system in this particular scenario. This observation confirms that SUSAN is scalable to dense user population.

### 7.2.4 Throughput fairness

In this section, we evaluate the fairness control component of SUSAN for different number of users. To this end, we apply Jain’s fairness index as:

$$J(x_1, x_2, ..., x_n) = \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n \cdot \sum_{i=1}^{n} x_i^2} \quad (7.2)$$
where there are \( n \) users and \( x_i \) is the throughput for the \( i^{th} \) connection. The result ranges from \( \frac{1}{n} \) (worst case) to 1 (best case), and it is maximum when all users receive the same allocation.

**Setup.** SUSAN exploits proportional throughput fairness to select the prime user. We find Jain’s index based on the average PHY throughput per each user population in 10 different topologies.

**Results.** The results in Figure 7.9 indicate that SUSAN’s fairness control mechanism effectively maintains Jain’s index, an indicator of fairness, close to 1 while without fairness control, the jain’s index generally degrades by growing user population. Here no fairness control means choosing the prime user randomly from the available users with equal probability. The proportional throughput fairness component of SUSAN is capable of maintaining Jain’s index close to one by growing user population.
8.1 Spatial Reuse in 60 GHz

Spatial reuse at 60 GHz was studied in [30,31]. These works demonstrate the role of large antenna array size in spatial reuse improvement while confirming the considerable amount of interference in numerous scenarios. However, they did address user selection and interference mitigation algorithms nor scaling the 60 GHz WLANs. The authors of [32] presented a Spatial Degrees of Freedom (SDoF) analysis of measured 60 GHz MIMO channels and showed that the SDoF metric depends on propagation conditions and the Tx and Rx antenna aperture sizes. However, they did not introduce an algorithm to exploit this potential to boost network performance such as SUSAN.

8.2 User Grouping and Selection

At lower bands such as 2.4/5 GHz, multi-user aggregation is typically achieved by zero-forcing inter-user interference via sender-side digital precoding using channel state information at the source. Such techniques were deployed in early research trials
[4,5,14] as well as current standards [15]. Unfortunately, such techniques do not scale to 60 GHz and large element arrays as (i) 60 GHz transmission is highly directional and lacks the rich scattering propagation environment assumed for most prior work; (ii) even efficient mechanisms for CSIT collection (e.g., implicit CSI collection [6–8]) do not scale to two order of magnitude larger antenna arrays; (iii) prior techniques employ a large number of radio frequency (RF) chains (up to one per antenna) which are not feasible in our scenario. Thus, a different tact is needed as the large antenna massive MIMO regime of [33] is not realized here. To the best of our knowledge, this thesis is the first scalable multi-user scheme at 60 GHz.

8.3 Multiplexing or Beamforming

Few prior works compare the capacity improvement capability of spatial multiplexing and beamforming techniques for 60 GHz spatial transmissions using the large antenna arrays [34, 35]. Both works highlight the tradeoff between these schemes but do not provide algorithms for exploiting those tradeoffs such as SUSAN. As reported in [36,37], the use of multiple polarizations improves the channel capacity significantly with spatial multiplexing. Thus, there is larger potential in spatial multiplexing to outperform beamforming when using dual-polarized antenna arrays. However, they did not provide any protocol to exploit dual-polarized antennas for capacity improvement.
In this thesis, we introduce SUSAN, a novel user and antenna share selection that provides scalability for downlink multi-user transmissions in dense 60 GHz WLANs. We introduce a scalable beam training procedure to establish direction links between the AP and existing clients where the number of training frames is independent from user population. Then we propose SUSAN protocol with incremental policies that add clients to a transmission sequentially until the AP’s resources are exhausted or client link budgets, including interference, are exceeded. The number of rounds for our proposed incremental user selection scheme is upper-bounded to the number of RF chains in the AP which is independent from user population.

We also introduce non-uniform antenna partitioning among the users and polarization diversity as mechanism to dramatically reduce inter-stream interference enabling vastly improved aggregate rate.

Our evaluation shows that SUSAN can achieve performance near to that of exhaustive search, yet with substantially less overhead.
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