NGUB: Novel Greedy Algorithms for User and Beam Selection in mmWave Networks

Santosh Kumar Singh, Satyabrata Sahu, Ayushi Thawait, Prasanna Chaporkar, and Gaurav S. Kasbekar
Department of Electrical Engineering
Indian Institute of Technology Bombay, Mumbai 400076, India
(santoshiitb, satyabrata, iucthawait, chaporkar, gskasbekar) @ee.iitb.ac.in

***Abstract*—We study the problem of maximization of the sum of weighted rates by determining user equipment (UE) and a beam for each access point (AP) for concurrent transmissions, in millimeter wave (mmWave) networks. The inherent directional nature of communication in mmWave networks, along with the susceptibility of connections to blockage makes the problem challenging. In prior works, several attempts have been made to design algorithms for UE and beam selection in different mmWave network scenarios. However, only a few works consider beam and UE selection in mmWave networks having multiple APs and UEs. In this paper, we design two novel greedy algorithms, NGUB1 and NGUB2, for UE and beam selection in mmWave networks containing multiple APs and UEs. Through extensive simulations, we show that our proposed algorithms outperform the most relevant algorithms proposed in prior work.**

***Index Terms*—User selection, user scheduling, beam selection, millimeter wave networks**

I. Introduction

The volume of data traffic exchanged using wireless networks is increasing rapidly, due to an increase in demand for voice and data services [1], which the existing sub-6 GHz cellular bands are unable to meet even using advanced techniques such as massive Multiple Input Multiple Output (MIMO) and heterogeneous networking [2], [3]. To meet this demand, millimeter wave (mmWave) bands can be used, since they have a large amount of unutilized spectrum available and also have the potential to provide multi-gigabit data rates [4]. But because of the high carrier frequency, mmWave communications suffer from significant propagation loss. Therefore, beamforming needs to be used, which makes mmWave communications inherently directional. To achieve effective communication, the characteristics of mmWave networks, viz., their directional nature, short transmission range, and dense deployment of access points (APs), which give rise to various challenges including blockage, interference, and frequent handovers, need to be handled by developing novel strategies [4], [5], [6], [7].

To overcome the above mentioned challenges and to provide robust connectivity to user equipment (UEs), several algorithms have been proposed to select beams and UEs for each AP in different mmWave networks [8], [9], [10], [11], [12], [13], [14], [15], [16]. In [8], [9], [10], mmWave networks with a single AP and a single UE are considered and algorithms for beam selection at the AP for the UE are designed such that the connection remains robust to blockage and UE mobility. In [11], mmWave networks with multiple cooperating APs and a single UE are considered and an algorithm is designed to select a beam for each AP to make a robust connection with the mobile UE. In [12], [13], [14], mmWave networks with multiple APs and multiple UEs are considered and algorithms are designed to select a beam and a UE for each AP using the measured received signal strength (RSS) information at each UE corresponding to each beam of every AP in the network. The work in [11], [12], [13], [14] performs beam and UE selection for each AP in two steps. First, they select mutually exclusive subsets of UEs for each AP. Second, they select a UE from each subset obtained in the first step. This two-step selection process may not provide a weighted sum rate maximizing set of UE and beam pairs for each AP.

In this paper, we consider mmWave networks containing multiple APs and multiple UEs. We design two greedy approach-based algorithms, NGUB1 and NGUB2, for beam and UE selection at each AP. Unlike the work in [11], [12], [13], [14], our algorithms perform joint beam and UE selection and thus avoid the above-mentioned inefficiency of the prior works. As in the prior works [12], [13], [14], our proposed algorithms use RSS information for beam and UE selection. However, unlike the above prior works, where RSS information is obtained through measurement, we obtain the information using a statistical channel model proposed in [17], [18], and [19] for mmWave networks. Through extensive simulations, we show that our proposed algorithms, NGUB1 and NGUB2, outperform the most relevant algorithms proposed in prior works [11], [12], [14].

The rest of this paper is organized as follows. Section II provides a review of related work. Section III presents the system model and problem formulation. Section IV describes the most relevant algorithms proposed in prior work that we use for performance comparison. Section V describes our proposed novel algorithms. Section VI presents simulation results. Finally, Section VII provides conclusions and directions for future research.

II. Related Work

One of the major challenges in mmWave networks is to design an algorithm to select a beam and/ or a UE at each AP such that each UE which gets served by some AP obtains a high data rate. Also, the selection of beam and/ or UE at each AP should change with time to maintain the quality of service (QoS) experienced by each UE in the presence of the mobility of UEs and blockage present in the considered environment.

Several attempts [8], [9], [10], [11], [12], [13], [14] have been made to design algorithms for beam and/ or UE selection for each AP in different mmWave networks. Note that mmWave networks considered in prior work are different in terms of the number of APs, the number of UEs, blockage

The work of SKS, PC, and GSK is supported in part by the project with code RD/0121-MEITY01-001.

present in the network environment, and the mobility of UEs. In [8], Beamspy is proposed to select an alternative beam for a UE whenever the current beam quality degrades without costly beam searching. It exploits channel sparsity and spatial correlation information available at the AP to predict the outage of the current beam and to suggest a new beam. In [9], Beamforecast is proposed, which predicts the beam at the AP for a mobile UE in real time without costly beam scanning. It exploits spatial correlation in channel profiles for prediction. In [10], Listeer is proposed which steers the beam at the AP towards a mobile UE. It acquires direction estimates for beams at APs using indicator Light Emitting Diodes (LEDs) on APs and off-the-shelf light sensors at UEs. The work in [8]-[10] considers mmWave networks having only one AP and only one UE and designs algorithms for an adaptive beam selection for the UE such that the QoS of the UE becomes robust to the mobility of the UE and/ or blockage. However, in [11], beam selection at multiple cooperating APs for a mobile UE using pose information– location and orientation of the UE– is proposed. It maps pose information of the mobile UE with measured link quality and selects a beam based on pose information.

In [12], [13], [14], the considered mmWave networks have multiple APs and multiple UEs. In [12], BounceNet is proposed, which selects a beam and UE for each AP by mapping the problem to a conflict graph and the selection of beam and UE corresponds to the selection of a weighted maximum independent set. In [13], mmMuxing is proposed for joint user and beam selection using channel measurements in each schedule. It can determine the user and beam for each AP that lead to the minimum interference in each schedule. In [14], MDSR is proposed for a joint user and beam selection and is an extension of the work in [13]. The authors in [14] also quantify the impact of interference on network performance through measurement and conclude that the prediction-based interference minimizing approach [8], [9], [11] in existing work is inefficient.

In this paper, we consider mmWave networks containing multiple APs and multiple UEs. Our proposed algorithms are robust to UE mobility and the presence of blockage in the network; also, via extensive simulations, we show that they outperform the algorithms proposed in prior work [11], [12], [14].

III. System Model and Problem Formulation

A. System Model

We consider a mmWave network with N_A APs and N_U UEs. Each AP has N_B beams, and it can communicate with one UE at any instant of time using one of its beams. Also, at any instant of time, a UE can communicate with at most one AP. Each AP in the network is linked to a central controller via a high-capacity wired Ethernet backhaul link. Time is divided into slots of equal duration; additionally, a slot $t \in \{0, 1, 2, \cdots\}$ is considered to be the duration of time from time instant tT to time instant $(t+1)T$. Each slot is further divided into K schedules of equal duration. We assume that a UE can move only at the beginning of each slot and remains static during the slot. Also, the movement of a UE is independent of the movement of other UEs. We assume that the APs remain static. Since APs are static and UEs move only

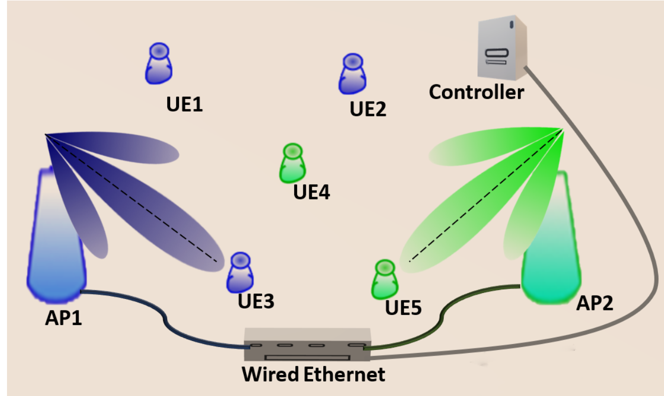

Figure 1: This is an illustration of our system model for an example scenario in which there are two APs and five UEs.

at the beginning of each slot, the RSS at each UE from each AP and for each of its beams is computed only at the start of each slot. The same RSS computed at the beginning of a slot is used for each of the K schedules of the slot for UE and beam selection. Note that our goal is to determine a UE and a beam for each AP for concurrent transmission in each schedule. In this work, we have used the statistical channel model proposed for mmWave networks in [17] to obtain RSS information. Fig. 1 illustrates our system model, for an example scenario in which there are two APs and five UEs. At the time instant depicted in Fig. 1, UE_3 and UE_5 are concurrent users.

B. Problem Formulation

Let $\mathcal{B} := \{1, 2, \cdots, N_B\}$, $\mathcal{U} := \{1, 2, \cdots, N_U\}$, and $\mathcal{A} := \{1, 2, \cdots, N_A\}$ denote the set of beams at each AP, set of UEs, and set of APs, respectively. Let $b_a \in \mathcal{B}$ (respectively, $u_a \in \mathcal{U}$) denote the beam (respectively, UE) chosen at (respectively, for) AP $a \in \mathcal{A}$ in a schedule. Let $S_{b,u,a}$ denote the RSS obtained at UE u when beam b is used at AP a. Let $\mathcal{S} := \{S_{b,u,a} | b \in \mathcal{B}, u \in \mathcal{U}, a \in \mathcal{A}\}$ denote the RSS information of a slot. Note that this information remains the same for each schedule of the slot. Let w_u denote the weight of a UE in a schedule. The weight of the UE can be assigned in various ways. The weight of the UE can be based on how urgently data needs to be transmitted to the UE, equal to the quantity of data that is waiting in a queue for transmission to the UE, or selected so as to ensure fairness across different UEs. Note that the weight of a UE can be changed in each schedule of a slot to ensure fairness across UEs. Let $\mathcal{W} := \{w_u | u \in \mathcal{U}\}$ denote the set of the weights of UEs in a schedule. Let $\mathcal{P}_a = \{(b_a, u_a)\}$ be a set that contains the beam and UE pair that is assigned to an AP a in a schedule. Note that $\mathcal{P}_a$ can be the null set in two ways. First, $N_A > N_U$ and all UEs $u \in \mathcal{U}$ are scheduled to be served by APs other than a. Second, $S_{b,u,a} < S_t, \forall b \in \mathcal{B}, u \in \mathcal{U}$, where S_t denotes a RSS threshold. A UE obtaining an RSS below S_t can not communicate. Let $\breve{\mathcal{A}} := \{a \in \mathcal{A} | \mathcal{P}_a \neq \emptyset\}$ denote the set of APs selected for transmission in a schedule. Our objective is to select $\mathcal{P}_a, \forall a \in \mathcal{A}$ for a schedule such that the sum of weighted rates

$$R_{\mathcal{S},\mathcal{W}} = \sum_{a\in\breve{\mathcal{A}}} w_{u_a} B \log_2\left(1 + \frac{S_{b_a,u_a,a}}{N_0 + \sum_{a'\in\breve{\mathcal{A}},a'\neq a} S_{b_{a'},u_a,a'}}\right) \tag{1}$$

of concurrent transmissions given $\mathcal{S}$ and $\mathcal{W}$ of the schedule gets maximized. In the above equation, N_0, B, and w_{u_a} represent noise power, bandwidth, and weight of UE u_a, respectively. Also, note that the cardinality of $\breve{\mathcal{A}}$ can be less than N_A.

Let $M = \max(N_A, N_U)$ and $m = \min(N_A, N_U)$. Then the exhaustive search based method to find a solution to the above problem requires $\binom{M}{m} m!(N_B)^m$ evaluations of the expression in (1). Since the number of computations grows exponentially with the increase in m, it is essential to design algorithms for the determination of P_a, $a \in \breve{\mathcal{A}}$, which require less computation but achieve near-optimal solutions.

IV. Algorithms Considered for Performance Comparison

In this section, we describe the most relevant algorithms in prior works, for user and beam selection, with which we have compared the performance of our proposed algorithms.

Before we describe the algorithms in prior works, let us state a few notations used in the description of the algorithms. Recall that $S_{b,u,a}$, u_a, b_a, $\breve{\mathcal{A}}$ denote the RSS at UE u when beam b is used at AP a, user selected to be served by AP a in a schedule, beam selected for AP a, and set of APs selected for a schedule for concurrent transmission, respectively. Let $\mathcal{A}_a$ denote a set of UEs that can be served by AP a. Note that in any schedule, only one UE from the set $\mathcal{A}_a$ can be served by AP a.

A. MDSR [14]

It consists of three steps– user association, user scheduling, and beam selection.

1) User Association: In this step, the algorithm iteratively selects $\mathcal{A}_a, \forall a \in \mathcal{A}$ using a matrix Q, whose (a,u)th element represents the weight at UE u from AP a and is defined in [14] as

$$Q(a,u) = \alpha\frac{\text{SINR}(a,u)}{\sum_{u'\in\mathcal{U}} \text{SINR}(a,u')} + \beta\frac{\text{SINR}(a,u)}{\sum_{a'\in\mathcal{A}} \text{SINR}(a',u)},$$

where, $\alpha = \frac{1}{N_U}$ and $\beta = \frac{1}{N_A}$ and

$$\text{SINR}(a,u) = \frac{\frac{1}{N_B}\sum_{b\in\mathcal{B}} S_{b,u,a}}{N_0 + \sum_{\hat{a}\neq a}\frac{1}{N_B}\sum_{b\in\mathcal{B}} S_{b,u,\hat{a}}}.$$

In each iteration, a UE is selected for some AP $a \in \mathcal{A}$ using the matrix Q obtained from the previous iteration. Note that the matrix Q is updated in each iteration after the selection of the UE by deleting the column corresponding to the selected UE. Let $\mathcal{A}_a^i$ denote the set of UEs associated with AP a till the end of the ith iteration. Let $\hat{\mathcal{A}}^i := \{a' \in \mathcal{A} \mid |\mathcal{A}_{a'}^{i-1}| \leq \lceil N_U \div N_A \rceil\}$ denote the set of APs with which UEs can be associated in the ith iteration. In the ith iteration, a UE $u \in \mathcal{U}\setminus\bigcup_{a\in\mathcal{A}}\mathcal{A}_a^{i-1}$ is associated with an AP $a \in \hat{\mathcal{A}}^i$ such that $< a, u >= \text{argmax}_{a'\in\hat{\mathcal{A}}^i, u'\in\mathcal{U}\setminus\bigcup_{a\in\mathcal{A}}\mathcal{A}_a^{i-1}} Q(a', u')$.

2) User Scheduling: In this step, the algorithm selects UEs $\{u_1, u_2, \cdots, u_{N_A}\}$, where $u_a \in \mathcal{A}_a$, for concurrent transmissions using the weighted sum rate $R_{\mathcal{S},\mathcal{W}}$, which is a function of $\breve{\mathcal{A}}$ and is defined in (1). Recall that the computation of $R_{\mathcal{S},\mathcal{W}}$ given $u_a, \forall a \in \breve{\mathcal{A}}$ also requires $b_a, \forall a \in \breve{\mathcal{A}}$ and $w_{u_a}, \forall a \in \breve{\mathcal{A}}$. Note that in ***MDSR***, the weights, $w_u, \forall u \in \mathcal{U}$ are assumed equal, $\breve{\mathcal{A}}$ is equal to $\mathcal{A}$, and $b_a, \forall a \in \breve{\mathcal{A}}$ is selected using the procedure described in Section IV-A3. Initially, a UE is selected for each AP $a \in \mathcal{A}$ at random from the set of associated UEs $\mathcal{A}_a$ for concurrent transmission. After that, in each iteration, an AP is selected in a round-robin fashion and the weighted sum rate maximizing UE of the selected AP is chosen for concurrent transmission. Note that, in a given iteration, the UEs for concurrent transmission at APs other than the selected AP remain unchanged. This process is repeated till no further improvement in the weighted sum rate is observed.

3) Beam Selection: In this step, the beam at each AP is selected based on the signal-to-leakage ratio (SLR) [14]. The SLR for beam $b_a \in \mathcal{B}$ at AP a used to serve user u_a is defined as

$$\text{SLR}(b_a, u_a, a) = \frac{S_{b_a,u_a,a}}{\sum_{a'\neq a} S_{b_a,u_{a'},a}}.$$

Recall that $S_{b_a,u_a,a}$ (respectively, $S_{b_a,u_{a'},a}$) is the RSS at user u_a (respectively, $u_{a'}$) associated with AP a (respectively, AP a') during concurrent transmission when beam b_a is used at AP a. The beam with the highest SLR is selected for transmission in this method.

B. BounceNet [12]

It consists of three steps– user association, direct path scheduling, and indirect path scheduling.

1) User Association: In this step, the algorithm performs the association of UEs to APs in an iterative manner. Before we explain the procedure for the association, let us define some notation. Let b_a^u denote the best beam at AP a for UE u based on RSS. Let $\mathcal{A}_a^i$ denote the set of UEs associated with AP a till iteration i. Let $I_{u,a}^{\hat{u},\hat{a}} = \max(S_{b_a^u,\hat{u},a}, S_{b_{\hat{a}}^{\hat{u}},u,\hat{a}})$ denote the maximum of two interferences– (i) interference at UE u due to the best beam at $\hat{a}$ for UE $\hat{u}$ and (ii) interference at UE $\hat{u}$ due to the best beam at a for UE u. Let $I_{u,a} = \max(I_{u,a}^{\hat{u},\hat{a}} | \forall(\hat{u},\hat{a})$ s.t. $\hat{u} \in \mathcal{A}_{\hat{a}}^i$ and $\hat{a} \neq a)$ denote the maximum pairwise interference that can happen during concurrent transmission when UE u chooses to associate with AP a in the ith iteration. In any iteration i, a UE u– not already associated to any AP, i.e., $u \in (\mathcal{U}\setminus\bigcup_{a\in\mathcal{A}}\mathcal{A}_a^i)$– is selected randomly and associated with the AP a such that,

$$a = \underset{a'\in\mathcal{A}}{\text{argmin}}\, I_{u,a'}.$$

2) Direct Path Scheduling: The direct path from an AP to a UE is defined as the highest RSS beam direction at the AP for the UE. The direct path scheduling algorithm uses a conflict graph. A node of the conflict graph represents a possible direct path. An edge is present between two nodes if they are mutually interfering. In the first schedule of a slot, each node is assigned the same weight and it is equal to some scalar times the number of schedules per slot (SPS). A weighted maximum independent set is then selected for that schedule. After each schedule, the weight of each node is updated and it depends on the degree (number of interfering neighbors) of each node. For more details, see Algorithm 2 of [12].

3) Indirect Path Scheduling: The indirect path from an AP to a UE is defined as the second-highest RSS beam direction at the AP for the UE. It is used to serve those UEs which are not selected in the direct path scheduling and associated with APs that are not utilized in the direct path scheduling. The algorithm for indirect path scheduling remains the same as that for direct path scheduling except for the assignment and update of the weight of each node, which is done differently. For more details about the indirect path scheduling, see Section 6.3 of [12].

C. PIA [11]

It consists of three steps– user association, user scheduling, and beam selection.

1) User Association: In this step, the algorithm associates a UE u to an AP a based on the maximum average RSS, i.e.,

$$a = \underset{a' \in \{1,2,\cdots,N_A\}}{\text{argmax}} \frac{1}{N_B} \sum_{b \in \mathcal{B}} S_{b,u,a'}.$$

However, the computation of the RSS array needs to be done in each schedule by estimating pose information. Also, the computation of the RSS from an AP a to a UE u considers only those paths at the UE which fall within the field of view (FoV) of the UE [11]. Note that the RSS computation for the other algorithms consider all the paths received at the UE.

2) User Scheduling: For scheduling at each AP $a \in \mathcal{A}$, a UE $u \in \mathcal{A}_a$ is selected based on the outcome of a fair $|\mathcal{A}_a|$-faced coin.

3) Beam Selection: Beam selection is performed in the same way as in Section IV-A3.

V. Proposed Algorithms

Recall that our objective is to design an algorithm that selects set $\mathcal{P}_a, \forall a \in \mathcal{A}$ for concurrent transmission in each schedule. In this section, we provide a description of two novel algorithms, NGUBI and NGUB2, that we designed.

A. NGUB1

Let $\bar{\mathcal{A}}^i$ denote the set of APs that already got a (u_a, b_a) pair till the beginning of the $(i+1)$th iteration. Let $\bar{\mathcal{U}}^i$ denote the set of UEs that are already associated with some AP in $\bar{\mathcal{A}}^i$ till the beginning of the $(i+1)$th iteration. Note that $\bar{\mathcal{A}}^0 = \emptyset$ and $\bar{\mathcal{U}}^0 = \emptyset$. Let b_a^u denote the best beam at AP a for UE u based on RSS. The algorithm runs in two steps– the first, *Initial Selection*, and the second, *Improvement over the Initial Selection*.

1) Initial Selection: In the ith iteration, the algorithm selects an AP a and a UE u_a such that

$$< u_a, a > = \underset{(u,a)|a \in \mathcal{A}\setminus\bar{\mathcal{A}}^{i-1}, u \in \mathcal{U}\setminus\bar{\mathcal{U}}^{i-1}}{\text{argmax}} w_u B \times \log_2\left(1 + \frac{S_{b_a^u,u,a}}{N_0 + \sum_{a' \in \bar{\mathcal{A}}^{i-1}} S_{b_{a'}^{u'},u,a'}}\right). \quad (2)$$

In (2), u' is the UE assigned to the AP $a' \in \bar{\mathcal{A}}^{i-1}$. Note that the above process of initial selection is complete after $\min(N_A, N_U)$ iterations. Also, the computation required in each iteration decreases with the iteration number.

2) Improvement over Initial Selection: In this step, in each iteration, an AP is selected in a round-robin fashion. A new UE from the set of free UEs is assigned to the selected AP if the new UE maximizes, across all the free UEs, the weighted sum rate and the new weighted sum rate is larger than the current weighted sum rate, otherwise, the UE does not change at the selected AP. Note that the UEs at the other APs remain the same as in the current selection. Let u_a^c (respectively, u_a^n) denote the current UE (respectively, new UE) for AP a. Let $\mathcal{U}_a^c := \mathcal{U}\setminus\{u|u = u_{a'}^c$ for some $a' \in \mathcal{A}$ and $a' \neq a\}$ denote the set of free UEs that can replace u_a^c at AP a. Let $r_{u,u_a^c}^n$ denote the new weighted sum rate when u_a^c is replaced by UE u. Then,

$$u_a^n = \underset{u \in \mathcal{U}_a^c \bigcup \{u_a^c\}}{\text{argmax}} r_{u,u_a^c}^n.$$

This step can be terminated in two ways– (i) after a fixed number of iterations and (ii) after the increment in the weighted sum rate becomes less than a threshold value after one complete round over APs. In our simulations, we use the first stopping criterion.

B. NGUB2

In this algorithm, a *Modified Initial Selection* step– similar to *Initial Selection* of the *NGUB1* algorithm with some modification– is followed some fixed number of times, let us say J times, where J can depend on N_A and/ or N_U. Each time the step is followed, it gives a set of pairs $\{(b_a, u_a), a \in \mathcal{A}\}$. Let $\breve{\mathcal{A}}^j$ (respectively, R_j) denote the set of the beam and UE pairs (respectively, the weighted sum rate of UEs corresponding to $\breve{\mathcal{A}}^j$) when the *Modified Initial Selection* step is run for the jth time. The algorithm stores $\breve{\mathcal{A}}^j$ along with R_j in memory and after the completion of J runs of the *Modified Initial Selection* step, the algorithm chooses $\breve{\mathcal{A}}^j$ for scheduling if $j = \text{argmax}_{i \in \{1,2,\cdots,J\}} R_i$.

In the ith iteration of a run of the *Modified Initial Selection* step, the algorithm selects an AP $a \in \bar{\mathcal{A}}^{i-1}$ uniformly at random and a UE u_a such that

$$u_a = \underset{u|u \in \mathcal{U}\setminus\bar{\mathcal{U}}^{i-1}}{\text{argmax}} w_u B \times \log_2\left(1 + \frac{S_{b_a^u,u,a}}{N_0 + \sum_{a' \in \bar{\mathcal{A}}^{i-1}} S_{b_{a'}^{u'},u,a'}}\right).$$

Note that the above process of selection is complete after $\min(N_A, N_U)$ iterations. Also, the computation required in each iteration decreases with the iteration number.

C. Difference between Proposed Algorithms and the Algorithms Described in Section IV

The algorithms proposed in [11], [12], [14] and described in Section IV perform the task of UE and beam selection in mmWave networks in two steps. In the first step, they select mutually exclusive subsets of UEs for each AP. In the second step, they select a UE from each subset obtained in the first step. Also, in the second step, they select a beam at each AP for the selected UE. Note that this two-step process may not provide an optimal set of UE and beam pairs for each AP. In contrast, our proposed algorithms, NGUB1 and NGUB2, jointly select UE and beam for each AP. Also, note that our proposed algorithms do not restrict themselves to a subset of

UEs during UE selection. Intuitively, due to the above reasons, our proposed algorithms outperform those proposed in [11], [12], [14], as demonstrated by the simulation results in Section VI.

VI. Simulation Results

In this section, we compare the performance of the most relevant algorithms proposed in prior works with that of our proposed novel greedy algorithms– NGUB1 and NGUB2– for UE and beam selection in mmWave networks via simulations. To show the robustness of our algorithms, we consider different mmWave network scenarios by varying the network parameters N_A, N_U, operating frequency, serving area, and the number of SPS. We consider $N_A = 2, 4, 6$, $N_U = 10, 15, 20$, frequency=73 GHz, 28 GHz, 60 GHz, area= (12 m $\times$ 10 m), (18 m $\times$ 15 m), (24 m $\times$ 20 m), and number of SPS=1, 5, 10. Throughout the simulations, we consider a non line of sight (NLOS) environment. For all simulations, we consider the number of slots equal to 20000. We use the three-dimensional statistical channel model in [17] for RSS generation and choose the parameters in the model as provided in [17], [18], [19]. Note that the channel model in [17] is based on extensive field measurements conducted in different mmWave network scenarios and the RSS generated by the model is approximately the same as the original measurement in the statistical sense. We use per-user average throughput as a performance metric. In particular, we have plotted the mean and the standard deviation of the per-user throughput obtained from 100 runs of the simulation for each algorithm and for each mmWave network scenario. Note that a run of the simulation of an algorithm in a given network scenario gives one per-user throughput value.

The results in Figs. 2-6 clearly show that our proposed algorithms– *NGUB1* and *NGUB2*– for UE and beam selection outperform the most relevant algorithms– *BounceNet*, *MDSR* and *PIA* (see Section IV)– for UE and beam selection in prior work in all mmWave network scenarios.

VII. Conclusions and Future Work

In this paper, we proposed two novel greedy algorithms– NGUB1 and NGUB2– for user and beam selection in mmWave networks that contain multiple APs and multiple UEs. We compared the performance of the most relevant UE and beam selection algorithms available in prior work with that of our proposed algorithms. Through simulations, we have shown that our algorithms outperform the most relevant algorithms for UE and beam selection in prior work.

The most relevant algorithms for UE and beam selection in prior work as well as those in this work are designed for the scenario where an AP can communicate with only one user at any time. However, it may be possible for an AP to communicate with multiple UEs simultaneously. Extension of the algorithms designed in this paper to the case where each AP can simultaneously communicate with multiple UEs is a direction for future research.

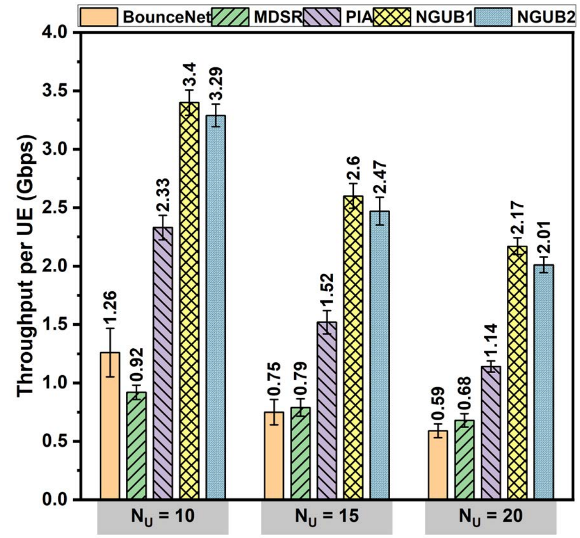

Figure 2: The plot shows a performance comparison in terms of the per-user average throughput metric under the different algorithms for a mmWave network. The parameters are $N_A =$ 4, $N_U = 10, 15, 20$, operating frequency= 73 GHz, area= (12 m $\times$ 10 m), number of SPS=1.

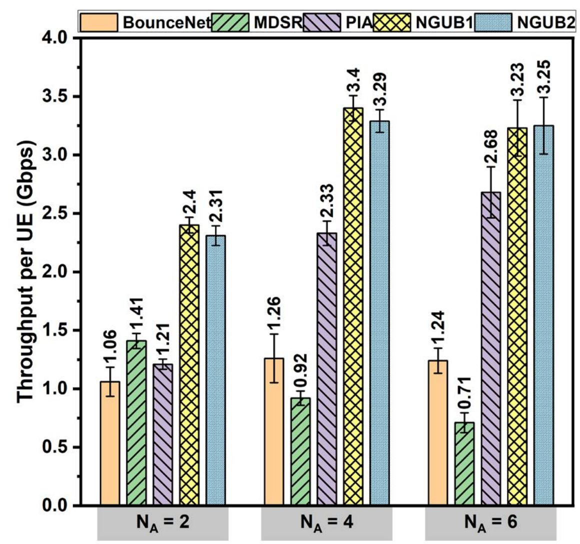

Figure 3: The plot shows a performance comparison in terms of the per-user average throughput metric under the different algorithms for a mmWave network. The parameters are $N_A =$ $2, 4, 6$, $N_U = 10$, operating frequency= 73 GHz, area= (12 m $\times$ 10 m), number of SPS=1.

References

[1] Cisco, "Cisco Annual Internet Report (2018–2023) White Paper." [Online]. Available: https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html

[2] J. G. Andrews, S. Buzzi, W. Choi, S. V. Hanly, A. Lozano, A. C. Soong, and J. C. Zhang, "What will 5G be?" *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 6, pp. 1065–1082, 2014.

[3] M. Agiwal, A. Roy, and N. Saxena, "Next generation 5G wireless networks: A comprehensive survey," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 3, pp. 1617–1655, 2016.

[4] Y. Niu, Y. Li, D. Jin, L. Su, and A. V. Vasilakos, "A survey of millimeter wave communications (mmWave) for 5G: opportunities and challenges," *Wireless Networks*, vol. 21, no. 8, pp. 2657–2676, 2015.

[5] K. Sakaguchi, T. Haustein, S. Barbarossa, E. C. Strinati, A. Clemente, G. Destino, A. Pärssinen, I. Kim, H. Chung, J. Kim *et al.*, "Where, when,

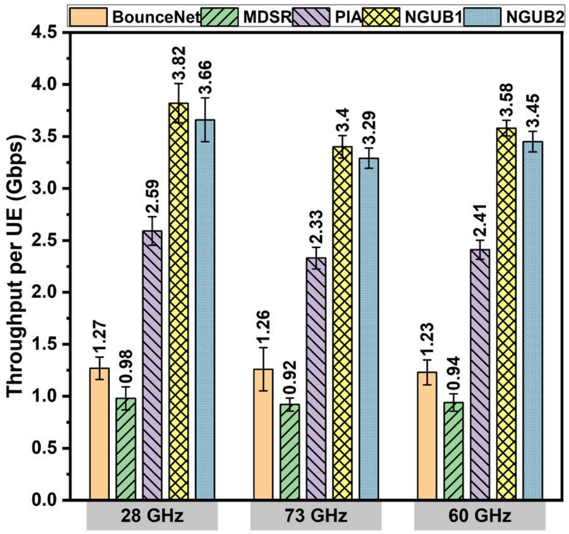

Figure 4: The plot shows a performance comparison in terms of the per-user average throughput metric under the different algorithms for a mmWave network. The parameters are $N_A = 4$, $N_U = 10$, operating frequency= 73 GHz, 28 GHz, 60 GHz, area= (12 m $\times$ 10 m), number of SPS=1.

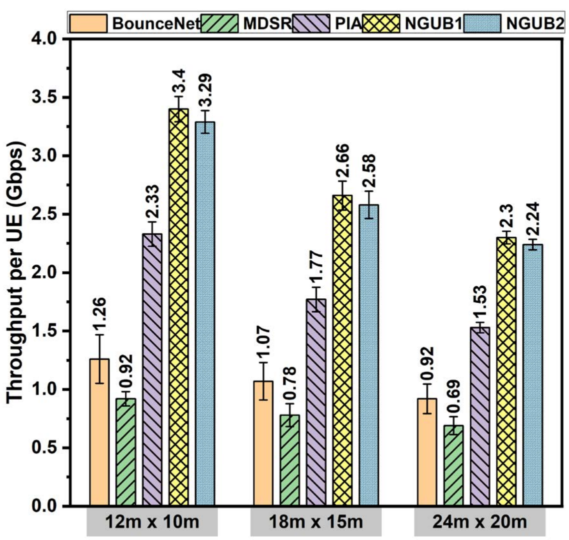

Figure 5: The plot shows a performance comparison in terms of the per-user average throughput metric under the different algorithms for a mmWave network. The parameters are $N_A = 4$, $N_U = 10$, operating frequency= 73 GHz, area= (12 m $\times$ 10 m), (18 m $\times$ 15 m), (24 m $\times$ 20 m), number of SPS=1.

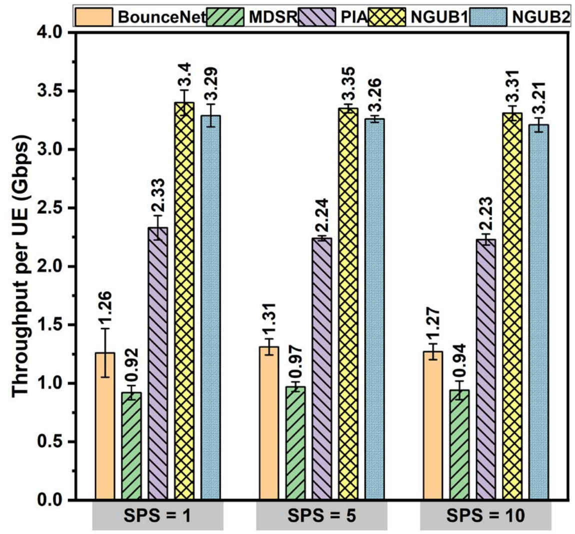

Figure 6: The plot shows a performance comparison in terms of the per-user average throughput metric under the different algorithms for a mmWave network. The parameters are $N_A = 4$, $N_U = 10$, operating frequency= 73 GHz, area= (12 m $\times$ 10 m), number of SPS=1, 5, 10.

and how mmWave is used in 5G and beyond," *IEICE Transactions on Electronics*, vol. 100, no. 10, pp. 790–808, 2017.

[6] D. Liu, L. Wang, Y. Chen, M. Elkashlan, K.-K. Wong, R. Schober, and L. Hanzo, "User association in 5G networks: A survey and an outlook," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 2, pp. 1018–1044, 2016.

[7] M. L. Attiah, A. A. M. Isa, Z. Zakaria, M. Abdulhameed, M. K. Mohsen, and I. Ali, "A survey of mmWave user association mechanisms and spectrum sharing approaches: an overview, open issues and challenges, future research trends," *Wireless Networks*, vol. 26, no. 4, pp. 2487–2514, 2020.

[8] S. Sur, X. Zhang, P. Ramanathan, and R. Chandra, "{BeamSpy}: Enabling robust 60 {GHz} links under blockage," in *13th USENIX symposium on networked systems design and implementation (NSDI 16)*, 2016, pp. 193–206.

[9] A. Zhou, X. Zhang, and H. Ma, "Beam-forecast: Facilitating mobile 60 ghz networks via model-driven beam steering," in *IEEE INFOCOM 2017-IEEE Conference on Computer Communications*. IEEE, 2017, pp. 1–9.

[10] M. K. Haider, Y. Ghasempour, D. Koutsonikolas, and E. W. Knightly, "Listeer: Mmwave beam acquisition and steering by tracking indicator leds on wireless aps," in *Proceedings of the 24th Annual International Conference on Mobile Computing and Networking*, 2018, pp. 273–288.

[11] T. Wei and X. Zhang, "Pose information assisted 60 ghz networks: Towards seamless coverage and mobility support," in *Proceedings of the 23rd Annual International Conference on Mobile Computing and Networking*, 2017, pp. 42–55.

[12] S. Jog, J. Wang, J. Guan, T. Moon, H. Hassanieh, and R. R. Choudhury, "{Many-to-Many} beam alignment in millimeter wave networks," in *16th USENIX Symposium on Networked Systems Design and Implementation (NSDI 19)*, 2019, pp. 783–800.

[13] Y. Yang, A. Zhou, D. Xu, S. Yang, L. Wu, H. Ma, T. Wei, and J. Liu, "mmmuxing: Pushing the limit of spatial reuse in directional millimeter-wave wireless networks," in *2020 17th Annual IEEE International Conference on Sensing, Communication, and Networking (SECON)*. IEEE, 2020, pp. 1–9.

[14] Y. Yang, A. Zhou, D. Xu, K. Liang, H. Ma, T. Wei, and J. Liu, "MDSR: Multi-dimensional spatial reuse enhancement for directional millimeter-wave wireless networks," *IEEE Transactions on Mobile Computing*, vol. 21, no. 12, pp. 4439–4455, 2022.

[15] Y. Zhang and R. W. Heath, "Reinforcement learning-based joint user scheduling and link configuration in millimeter-wave networks," *IEEE Transactions on Wireless Communications*, pp. 1–17, 2022.

[16] Z. Sha, Y. Ming, C. Sun, and Z. Wang, "Versatile resource management for millimeter-wave cellular network: Near interference-free scheduling methodology," *IEEE Transactions on Vehicular Technology*, pp. 1–16, 2023.

[17] M. K. Samimi and T. S. Rappaport, "3-d millimeter-wave statistical channel model for 5g wireless system design," *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 7, pp. 2207–2225, 2016.

[18] S. Ju, Y. Xing, O. Kanhere, and T. S. Rappaport, "3-d statistical indoor channel model for millimeter-wave and sub-terahertz bands," in *GLOBECOM 2020-2020 IEEE Global Communications Conference*. IEEE, 2020, pp. 1–7.

[19] ——, "Millimeter wave and sub-terahertz spatial statistical channel model for an indoor office building," *IEEE Journal on Selected Areas in Communications*, vol. 39, no. 6, pp. 1561–1575, 2021.