Forming Coalition Sets from Directional Radios

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***Abstract*—Fifth Generation (5G) mobile networks aim to exploit the vast amount of spectrum in the millimeter wave (mmWave) and Terahertz bands for more capacity. mmWave/Terahertz radios fundamentally differ from existing wireless systems in terms of directivity, propagation loss, and blockage sensitivity. As these mmWave/Terahertz directional antennas/nodes are becoming part of mainstream wireless networks, effective and efficient forming of coalitions from such nodes is of interest for the goal of increasing the sum rate of a wireless network. We design a novel heuristic framework to form sets of coalitions by categorizing directional radio nodes and distributing them into coalitions while assuring that no node is isolated, and show that polynomial-time heuristics can perform well in forming coalition sets out of directional radios.**

I. Introduction

Emerging mobile 5G-and-beyond communication technologies rely on mmWave bands (28-300GHz), which provide higher data rates and bandwidth. Highly directional antennas are necessary for practically accessing these frequencies as the transmissions are vulnerable to path loss and atmospheric absorption. Substantial work [1] has been done to address these issues like designing high gain antennas with appropriate beamforming for mitigating propagation loss. However, due to the line-of-sight and alignment requirements of directional transmission, integrating these antennas into mobile and ad-hoc settings is a challenge. Further, in settings with no or minimal infrastructure support (e.g., battlefield or emergency communication), nodes need to form coalitions to attain successful and efficient transmissions [2].

A key benefit of coalitions is higher spatial and frequency reuse. Without coalitions, all inter-node communication has to go through a base station (BS), which limits the aggregate throughput. On the other hand, many nodes participating in a single coalition can use as few as one channel (assigned to the entire coalition) to communicate among themselves and one node in the coalition can forward the message to the BS using one channel. Coalitions of omni-directional radios have been studied heavily for higher throughput [3], higher spectrum efficiency [4], or stronger security against attackers [5]. However, understanding how directionality changes the establishment of coalitions among radios has not been explored well.

In this paper, we explore the concept of 'directional coalitions' among radios utilizing mmWave bands. We consider a collection of highly directional mmWave radio nodes scattered randomly on a 2-dimensional plane. Each node is initialized with its field-of-view (FoV), which limits what other nodes it could potentially talk to. The scheduling of data transmission among the nodes is assumed to be regulated by the BS in phases of downlink and relay. During these phases, the nodes use an optimized set of steering angles and follow randomly scheduling for transmission. Under this phased random scheduling assumption, we formulate achievable rate of a directional coalition. Considering various aspects such as roles of the nodes within a coalition, proximity of the nodes and coalitions to each other, and size of the coalitions, we devise heuristics that aim to maximize the sum rate of all coalitions. We theoretically study our framework and numerically evaluate its heuristics in terms of solving the problem of forming a set of coalition that maximizes the sum rate while making sure all nodes are included in a coalition. Our work's key novelty lies in role categorization of directional nodes and using these roles to guide development of fast coalition formation heuristics. We make the following contributions:

- A step-by-step formal method to categorize directional antenna nodes based on their FoVs and illustration of the method on networks of nodes of varying sizes.
- Formulations of directional link capacities when transmissions are randomly scheduled.
- Calculation of coalitional sum rate or throughput using the scheduling methods and channel allocation schemes.
- Heuristics for forming coalition sets that place all network nodes to a coalition, and exploring possibilities of merging coalitions to improve the network sum rate.

II. Related Works

The problem of increasing aggregate throughput of a wireless network is an old one. Interesting works have been performed in the field of Dynamic Spectrum Sharing using sub-6 GHz 5G spectrum like [6], where the authors have proposed a unique and novel wireless peering concept for cellular operators in the United States. However, directionality of (5G mmWave/THz) transmissions bring in new challenges in attaining high throughput. Prior work explored sub-channel allocation and scheduling methods for directional antennas in mmWave spectrum. Studies included algorithms to efficiently allocate sub-channels to improve resource utilization and network capacity of a Device-to-Device (D2D) network [7], methods to allocate sub-channels to D2D links in a densely populated environment [8] with superior results compared to conventional D2D approaches [9], and QoS-aware scheduling algorithms for concurrent transmission using game-theoretic methods [2].

For improving network capacity, directional wireless communication has offered new features to utilize. In particular, mmWave beams are amenable to beamsteering, opening new ways to improve the aggregate network throughput, or sum rate [10]. Going beyond channel resource allocation [11], the impact of scheduling in the optimality of beamsteering angles needs to be considered to fully take advantage of what is available in directional wireless. Beamsteering optimization of directional antennas are shown to help significantly in mobile fronthaul [12] and cognitive radios [13].

Most relevant literature to ours are the recent works on increasing wireless network throughout using mmWave bands and the models for coalitional communication among radios using legacy sub-6 GHz bands. When coalitions are considered as part of the throughput optimization of directional wireless communication, the problem gets more complicated with interplay of transmit power, beamsteering angles, scheduling, and channel allocation [7], as well as intra- and inter-coalition interference. Putting constraints on the transmit power has proved to be fruitful in reducing the problem's complexity. Applying a transmit power limit on each individual node and dividing the problem into two stages enabled convex optimization solutions [14] in a scenario where scheduling is assumed optimal. When random scheduling is assumed for a single coalition, it was shown that beamsteering optimization can be done fast and comprehensively [15]. These studies did not consider all-covering coalition formation and can yield unfair solutions. We consider a regulated scheduling method based on the structure of directional topology and develop novel and efficient heuristics for forming a set of coalitions that maximize the throughput while making sure all coverable nodes are placed in a coalition.

III. System Model and Problem Statement

Consider mmWave nodes spread over a fixed two dimensional region, that wish to communicate using a channel with bandwidth B. Our goal is to structure them into disjoint and autonomous coalitions. The coalition formation is assumed to be coordinated by a base station (BS) using a secure and interference-free Common Control Channel (CCC). Each node in a coalition is equipped with a half-duplex beam-steerable directional antenna, and hence is capable of steering its beam within the range of its field-of-view (FoV). Given the location and FoV of each node, our goal is find the optimal coalition set formation such that the sum-rate of all coalitions is maximized.

A. All-Covering Max-Throughput Coalition Set

Assumptions. Let $\mathcal{A} = \{\mathcal{A}_1, \mathcal{A}_2, ..\mathcal{A}_A\}$ represent the set of mmWave nodes with directional antennas, where node $\mathcal{A}_i$ is located at Cartesian location (x_i, y_i) for $i = 1, .., A$. The nodes are partitioned into C disjoint coalitions, denoted as $\text{coa}_1, \text{coa}_2, .., \text{coa}_C$ such that $\text{coa}_q \subseteq \mathcal{A}$ for $q = 1, .., C$ and $\text{coa}_k \cap \text{coa}_l = \emptyset$ for all k, l. Due to limited FoV, some nodes in $\mathcal{A}$ cannot establish a communication link with other nodes. These nodes will be isolated and cannot be part of any coalition, which means the union of coalitions may not be equal to $\mathcal{A}$, i.e., $\bigcup_{n=1}^{C} \text{coa}_n \subseteq \mathcal{A}$. Let set $\Omega = \{\text{coa}_1, \text{coa}_2, ..., \text{coa}_C\}$ be an all-covering coalition set, ensuring all nodes in $\mathcal{A}$, except the isolated nodes, are included in different coalitions. The structure of nodes within a coalition and the feasible links for intra-coalition communication are determined based on the FoVs of the nodes. Let $R(\text{coa}_n)$ denote the achievable communication rate of nodes in coalition coa_n and $R(\Omega)$ be the sum-rate across all coalitions. Then, we have $R(\Omega) = \sum_{n=1}^{C} R(\text{coa}_n)$.

Optimization. Given that Ω consists of C coalitions, the problem of finding the optimal coalition set Ω that maximizes $R(\Omega)$ can be formulated as the following:

$$\text{Given } C, \qquad \Omega^* = \arg\max R(\Omega) \tag{1}$$
$$s.t. \;\; \text{coa}_q \subseteq \mathcal{A}, \forall q; \qquad \text{coa}_k \cap \text{coa}_l = \emptyset, \forall k, l;$$
$$\bigcup_{n=1}^{C} \text{coa}_n \subseteq \mathcal{A}; \qquad \bigcup_{n=1}^{C} \text{coa}_n \equiv \mathcal{A}'$$

where $\mathcal{A}'$ is the set of nodes in $\mathcal{A}$ that can form a link with at least one other node. Since it assumes a fixed count of coalitions, the problem in (1) is a simpler version of the main problem we aim to solve where C can be any integer in $[1, A]$. To analyze the computational complexity of the main problem, we define C empty sets, denoted as $\text{coa}_1, \text{coa}_2, ..., \text{coa}_C$. Let the binary variable a_i^n indicate whether or not node $\mathcal{A}_i$ is in the set coa_n, i.e., if $a_i^n = 1$ then $\mathcal{A}_i$ is in the set coa_n, and if $a_i^n = 0$ then $\mathcal{A}_i$ is not in the set coa_n. Given C, finding Ω^* requires solving a_i^n for $i = 1, ..., A, n = 1, ..., C$, i.e., solving AC binary variables. Finding Ω^* requires solving the above problem for each C values, where $C = 1, ..., A$. Hence, the computational complexity of finding Ω^* is upper bounded by the solution search space, i.e., $\mathcal{O}(A2^{A^2})$. Exhaustively scanning this search space to find the optimum partitioning of the nodes to coalitions is prohibitive as it is known to be an NP-complete problem [16]. Hence, we resort to designing effective heuristics to form coalition sets.

B. Structure of Nodes within a Coalition

Potential Coalition Partners (PCPs). Recall the set of nodes $\mathcal{A}$ has A elements, i.e., $|\mathcal{A}| = A$. We associate each node $\mathcal{A}_i \in \mathcal{A}$ with a set $\text{PCP}_{\mathcal{A}_i}$ consisting of the nodes in $\mathcal{A}$ that $\mathcal{A}_i$ can potentially establish a directional wireless link with, and hence they are "Potential Coalition Partners (PCPs)" of $\mathcal{A}_i$. A node $\mathcal{A}_j \in \mathcal{A}$ belongs to set $\text{PCP}_{\mathcal{A}_i}$ if and only if $\mathcal{A}_j$ and $\mathcal{A}_i$ are within FoVs of each other. We denote the communication link between $\mathcal{A}_i$ and $\mathcal{A}_j$ by $(\mathcal{A}_i, \mathcal{A}_j)$. We note the following:

- If two nodes are within FoVs of each other, their PCPs must include each other. Therefore, two nodes can form a link iff they fall within each other's PCPs.
- If $|\text{PCP}_{\mathcal{A}_i}| = 0$, $\mathcal{A}_i$ cannot communicate with any other node and hence cannot be part of any coalition.

Isolated Nodes, Primary Antenna, and Secondary Antenna. We call the nodes with empty PCPs *isolated nodes*. Excluding the isolated nodes from the set $\mathcal{A}$, we categorize the remaining nodes in $\mathcal{A}$ as *Primary Antenna (PA)* or *Secondary Antenna (SA)* nodes. Node $\mathcal{A}_i \in \mathcal{A}$ is a PA if $|\text{PCP}_{\mathcal{A}_i}| > 1$, i.e., a

PA node can potentially establish links with more than one other nodes. Node $\mathcal{A}_i \in \mathcal{A}$ is an SA if $|\text{PCP}_{\mathcal{A}_i}| = 1$, i.e., an SA node can potentially establish a link with only one other node. Let $\mathcal{A}^p = \{\mathcal{A}_1^p, \mathcal{A}_2^p, ..., \mathcal{A}_D^p\}$ and $\mathcal{A}^s = \{\mathcal{A}_1^s, \mathcal{A}_2^s, ..., \mathcal{A}_V^s\}$ signify the sets of PAs and SAs, respectively, and $\mathcal{A}_i^p$ and $\mathcal{A}_j^s$ be the ith PA and the jth SA, respectively. Clearly, $\mathcal{A}^p \subseteq \mathcal{A}$, $\mathcal{A}^s \subseteq \mathcal{A}$, and $\mathcal{A}^s \cap \mathcal{A}^p = \emptyset$. Let $\{\mathcal{X}\}^s$ and $\{\mathcal{X}\}^p$ represent the sets of SAs and PAs in set $\mathcal{X}$, respectively. Then, $\{\text{PCP}_{\mathcal{A}_i}\}^s$ and $\{\text{PCP}_{\mathcal{A}_i}\}^p$ represent, respectively, the sets of SAs and PAs that node $\mathcal{A}_i$ can potentially form a link with. Table I shows a summary of our notations.

The classification of nodes into SA or PA categories enables the following interesting observations regarding forming of an all-covering coalition set:

1) *An SA-only coalition can have only two nodes.*
2) *An SA-PA coalition must have least one PA and at least two SAs.* In a coalition including PA(s) and SA(s) nodes, there must be at least two SAs. For the PA node, there will have to be at least two SAs otherwise the PA would not be a PA.
3) *A PA-only coalition has at least three PAs.*

These observations enable design of very fast heuristics for forming coalition sets out of directional radios.

Symbol	Description
$\mathcal{A}$	Set of all nodes in the network
$\mathcal{A}_n$	nth node
$\mathcal{A}^p$	Set of all PA nodes
$\mathcal{A}_u^p$	uth PA
$\mathcal{A}^s$	Set of all SA nodes
$\mathcal{A}_v^s$	vth SA
$\mathcal{A}(\mathcal{A}_n)$	Set of nodes in FoV of $\mathcal{A}_n$
$\text{PCP}_{\mathcal{A}_n}$	Set of nodes that $\mathcal{A}_n$ can form a link with
$(\mathcal{A}_m, \mathcal{A}_n)$	Link between $\mathcal{A}_m$ and $\mathcal{A}_n$
$\{\mathcal{X}\}^s$	Set of SAs in the node set $\mathcal{X}$
$\{\mathcal{X}\}^p$	Set of PAs in the node set $\mathcal{X}$

Table I: List of symbols and their descriptions

All-Covering Coalition Set Examples. Consider the all-covering coalition set $\Omega = \{\text{coa}_1, \text{coa}_2, ..., \text{coa}_C\}$. Figs. 1 and 2 provide two examples of an all-covering coalition sets. Without showing the SA nodes in these sets, they can be respectively written as $\Omega_1 = \{\{\mathcal{A}_1^p, \mathcal{A}_2^p, \mathcal{A}_3^p\}, \{\mathcal{A}_4^p, \mathcal{A}_5^p, \mathcal{A}_6^p\}, \{\mathcal{A}_7^p\}, \{\mathcal{A}_8^p, \mathcal{A}_9^p, \mathcal{A}_{10}^p\}$ and $\Omega_2 = \{\{\mathcal{A}_1^p, \mathcal{A}_2^p, \mathcal{A}_3^p\}, \{\mathcal{A}_4^p, \mathcal{A}_5^p, \mathcal{A}_8^p, \mathcal{A}_9^p\}, \{\mathcal{A}_6^p, \mathcal{A}_7^p, \mathcal{A}_{10}^p\}$. We see that, on the same set of nodes, the coalition set formed can be different. The PA nodes along with their SA nodes are marked by blue lines and coalitions are marked by green lines. There is a PA-only coalition in Fig. 1 comprised of $\mathcal{A}_8^p$, $\mathcal{A}_9^p$ and $\mathcal{A}_{10}^p$. It is possible that these PAs can join other coalitions and form a different coalition set, as shown in Fig. 1. It is clear from this example that categorizing the nodes into PAs and SAs significantly reduces the number of possible coalition sets. Fig. 3 shows the dynamics inside a coalition in more details by zooming into the bottom-left coalition in Figs. 1 and 2, which is comprised of $\mathcal{A}_1^p$, $\mathcal{A}_2^p$ and $\mathcal{A}_3^p$ and their SA nodes. In Fig. 3, the FoV of each node is shown with dashed lines and the feasible links among them with solid lines along with the full list of nodes within each node's FoV.

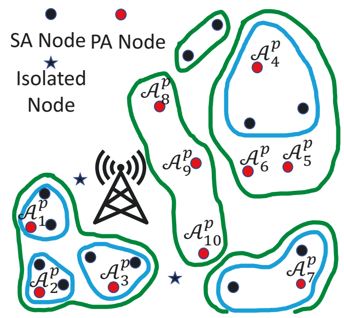


Figure 1: Coalition example 1

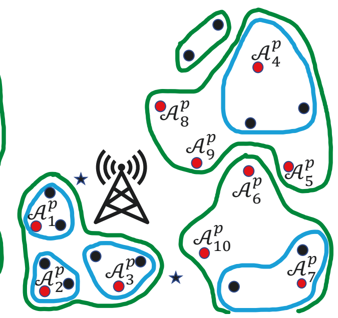


Figure 2: Coalition example 2

C. Scheduling and Bandwidth Allocation

The BS is responsible for finding the best coalition set Ω via solving the coalition formation optimization problem, a simpler version of which is formulated in (1). Then, BS informs the nodes to which coalition they belong through the CCC. Once the coalitions are formed, each coalition operates autonomously based on a time-slotted communication mechanism, where time is divided into sub-frames of duration T_f sec, and the nodes in a coalition schedule intra-coalition communication themselves without relying on the BS. We assume intra-coalition communication consists of two consecutive phases: the Downlink Phase and the PA-PA Phase, with duration T_d and $T_p = T_f - T_d$ sec, respectively (see Fig. 4). We define the transmission scheduling of nodes within a coalition in each phase as follows:

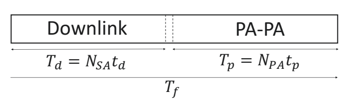
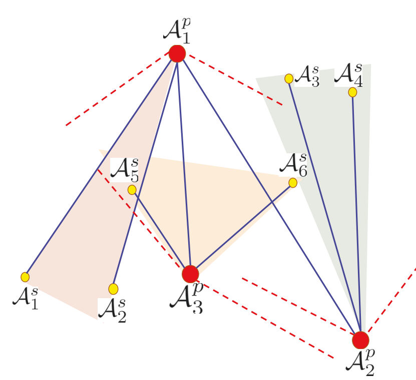


Figure 4: Two phases corresponding to a time frame

Downlink Phase. During this phase, all PA nodes in coa_n are in transmitting mode and all SA nodes in coa_n are in receiving mode. Each PA node acts independently and divides T_d sub-frame equally among the SA nodes in its PCP and transmits data to them during their corresponding allocated time fraction in a deterministic manner. This



The FOVs are as follows:

- $\mathcal{A}(\mathcal{A}_1^p) = \{\mathcal{A}_1^s, \mathcal{A}_2^s, \mathcal{A}_2^p, \mathcal{A}_5^s, \mathcal{A}_3^p\}$
- $\mathcal{A}(\mathcal{A}_2^p) = \{\mathcal{A}_1^p, \mathcal{A}_3^s, \mathcal{A}_4^s, \mathcal{A}_6^s\}$
- $\mathcal{A}(\mathcal{A}_3^p) = \{\mathcal{A}_5^s, \mathcal{A}_6^s, \mathcal{A}_1^p \mathcal{A}_2^p, \mathcal{A}_3^s, \mathcal{A}_4^s\}$
- $\mathcal{A}(\mathcal{A}_1^s) = \{\mathcal{A}_1^p, \mathcal{A}_3^s\}$
- $\mathcal{A}(\mathcal{A}_2^s) = \{\mathcal{A}_1^p, \mathcal{A}_3^s\}$
- $\mathcal{A}(\mathcal{A}_3^s) = \{\mathcal{A}_2^p\}$
- $\mathcal{A}(\mathcal{A}_4^s) = \{\mathcal{A}_2^p, \mathcal{A}_6^s\}$
- $\mathcal{A}(\mathcal{A}_5^s) = \{\mathcal{A}_3^p, \mathcal{A}_2^p\}$
- $\mathcal{A}(\mathcal{A}_6^s) = \{\mathcal{A}_3^p, \mathcal{A}_1^p, \mathcal{A}_1^s, \mathcal{A}_2^s, \mathcal{A}_5^s\}$

Figure 3: PAs and SAs of a coa in Fig. 1

scheduling does not depend on how other PA nodes utilize their Downlink phase.

PA-PA Phase. During this phase, the SA nodes in coa_n do not transmit or receive, and the PA nodes talk among themselves. Each PA node can be in transmitting or receiving mode with equal probability. Consider $\mathcal{A}_i^p \in \text{coa}_n$ and the set of PA nodes represented by $\{\text{PCP}_{\mathcal{A}_i^p}\}^p$, some of which may be in coa_n. If $\mathcal{A}_i^p$ is in transmitting mode, it randomly chooses a PA node in its PCP that is also in coa_n and transmits data to the chosen PA node. If $\mathcal{A}_i^p$ is in receiving mode, it randomly chooses a PA node in its PCP that is also in coa_n and receives data from the chosen PA node. Suppose $\mathcal{A}_i^p, \mathcal{A}_j^p \in \text{coa}_n$. To establish the link ($\mathcal{A}_i^p$,$\mathcal{A}_j^p$), the following three conditions must be met: (i) $\mathcal{A}_i^p$ and $\mathcal{A}_j^p$ are in transmitting and receiving modes, respectively, (ii) $\mathcal{A}_i^p \in \{\text{PCP}_{\mathcal{A}_j^p}\}^p$ and $\mathcal{A}_j^p \in \{\text{PCP}_{\mathcal{A}_i^p}\}^p$, and (iii) $\mathcal{A}_i^p$ chooses to transmit to $\mathcal{A}_j^p$ and $\mathcal{A}_j^p$ chooses to receive from $\mathcal{A}_i^p$ simultaneously.

We let $R(\text{coa}_n)$ be the overall communication rate of nodes in coalition coa_n. Since in this scheduling scheme only PAs transmit, the corresponding communication rate of an SA-only coalition is zero. Hence, we allocate bandwidth B to PA-only and SA-PA coalitions. Consider the all-covering coalition set $\Omega = \{\text{coa}_1, \text{coa}_2, ..., \text{coa}_C\}$. Suppose $\Omega' \subseteq \Omega$ where Ω' excludes SA-only coalitions and consists of C' PA-only and SA-PA coalitions, and C' is less than or equal to the total number of PA nodes, i.e., $C' \leq D$. Given a total bandwidth B, we devise the following scheme to split B to sub-channels:

Bandwidth Allocation Scheme. B is divided into C' sub-channels with bandwidth $w_1 = \frac{B}{C'}$. During the Downlink Phase, all PA nodes in a coalition transmit simultaneously over the same channel and cause co-channel interference.

During the PA-PA Phase, all transmitting PA nodes in a coalition transmit simultaneously over the same channel and cause co-channel interference. Suppose, $\mathcal{A}_i^p, \mathcal{A}_j^p \in \text{coa}_n$. When the link ($\mathcal{A}_i^p$,$\mathcal{A}_j^p$) is established, $\mathcal{A}_j^p$ is susceptible to interference from other transmitting PA nodes in coa_n that $\mathcal{A}_j^p$ is in their FoVs. Also, $\mathcal{A}_i^p$ imposes interference on other receiving PA nodes in coa_n that are in its FoV. Consider Fig. 3 and suppose the network is in Downlink phase. In coa_n four PA nodes are transmitting simultaneously. For example, $\mathcal{A}_1^p$ imposes interference on SA nodes associated with $\mathcal{A}_2^p, \mathcal{A}_3^p, \mathcal{A}_4^p$ that fall within the FoV of $\mathcal{A}_1^p$. Similarly, $\mathcal{A}_2^p$ imposes interference on SA nodes associated with $\mathcal{A}_1^p, \mathcal{A}_3^p, \mathcal{A}_4^p$ that fall within the FoV of $\mathcal{A}_2^p$. This interference will affect the signal-to-interference-plus-noise ratio (SINR) calculation of the links in which the receiving SA node is subject to interference from other transmitting PA nodes in the coalition.

D. Directional Antenna Model

Consider node $\mathcal{A}_i$ and let Γ_i represent the initial inclination angle of node $\mathcal{A}_i$ with reference to the x-axis, and θ_i denote the steering angle corresponding to the central line of the beam of node $\mathcal{A}_i$ with reference to the positive x-axis. We let node $\mathcal{A}_i$ to freely choose its beam steering angle θ_i. Let β_i denote the FoV of node $\mathcal{A}_i$, which defines the maximum angular sweeping range of the main beam of $\mathcal{A}_i$. A representation of the deployment of directional nodes along with the parameters of node $\mathcal{A}_i$ is shown in Fig. 5. The deviation angle $\psi_{i\to j}$ indicates the digression of the center of the beam of node $\mathcal{A}_i$ away from the straight line connecting two nodes: $\mathcal{A}_i$ and $\mathcal{A}_j$.

A reference directional antenna model with side lobe for IEEE 802.15.3c. is considered. However, in this paper, we focus on the main lobe (without side lobe), applicable for line-of-sight (LoS) transmission that uses high frequency signals like 60 GHz or above, and safely ignore the side lobe gain [17]. Let us assume $G_i(\theta_i)$ is the directional antenna gain of node $\mathcal{A}_i$. Then,

$$G_i(\theta_i) = e^{-(\ln 2)(\frac{\theta_i}{\alpha_i})^2}, \qquad \beta_i^{\min} \leq \theta_i \leq \beta_i^{\max} \tag{2}$$

where $\beta_i^{\min} = \Gamma_j - \beta_j/2$ and $\beta_i^{\max} = \Gamma_j + \beta_j/2$ are the minimum and maximum beam steering angles allowed within the FoV of $\mathcal{A}_i$, assuming $\Gamma_j > 2\beta_j$.

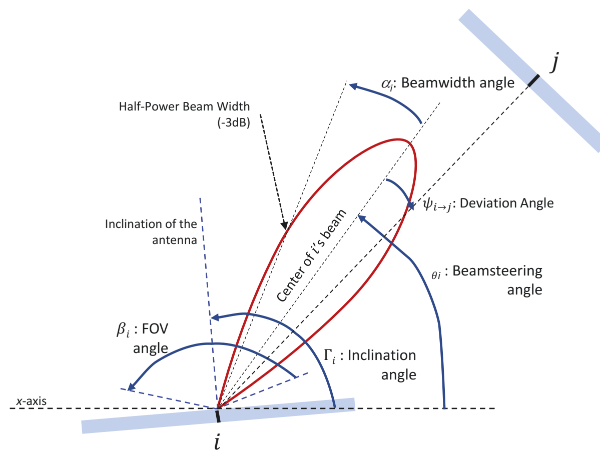


Figure 5: Antenna array of $\mathcal{A}_i$

E. SINR Formulation with Directional Antenna

Consider the link $(\mathcal{A}_i, \mathcal{A}_j)$ between two nodes $\mathcal{A}_i \in \mathcal{A}$ and $\mathcal{A}_j \in \mathcal{A}$. Suppose d_{ij} signifies the distance separating the two nodes $\mathcal{A}_i$ and $\mathcal{A}_j$. Also, assume that $\mathcal{A}_i$ is steered towards $\mathcal{A}_j$ with a beam steering angle θ_i. Given the coordinates of $\mathcal{A}_i$ and $\mathcal{A}_j$,the deviation angle $\psi_{i\to j}$ is found (see Fig. 5). Let P_t and $P_r(\mathcal{A}_i, \mathcal{A}_j)$ be the transmit power of $\mathcal{A}_i$ and the received power at $\mathcal{A}_j$. Using THz communication channel model in [18], $P_r(\mathcal{A}_i, \mathcal{A}_j)$ can be expressed in terms of P_t as follows:

$$P_r(\mathcal{A}_i, \mathcal{A}_j) = \frac{P_t}{d_{i,j}^{\alpha}} G_i(\theta_i - \psi_{i\to j}) G_j(\theta_j - \pi - \psi_{i\to j}) \tag{3}$$

where α is the path-loss exponent, and G_i and G_j are the directional antenna gains of nodes $\mathcal{A}_i$ and $\mathcal{A}_j$, respectively.

F. Coalition Set Formation: Formal Problem

Consider $\Omega' = \{\text{coa}_1, \text{coa}_2, ..., \text{coa}_{C'}\}$, which is obtained from an all-covering coalition set Ω after removing SA-only coalitions, i.e., Ω' consists of C' PA-only and SA-PA coalitions, and C' is less than or equal to the total number of PA nodes, i.e., $C' \leq D$, where the equality can hold only when no PA-only coalition exists and all coalitions in Ω' are

SA-PA coalitions. The sum-rate across all coalitions in Ω' is $R(\Omega') = \sum_{n=1}^{C'} R(\text{coa}_n)$.

We define the binary optimization variable a_ℓ^n to indicate whether or not $\mathcal{A}_\ell^p$ is in coa_n, i.e., if $\mathcal{A}_\ell^p \in \text{coa}_n$ then $a_\ell^n = 1$, and if $\mathcal{A}_\ell^p \notin \text{coa}_n$ then $a_\ell^n = 0$.

Sum Rate Calculations. Let $R_\ell^d(\text{coa}_n)$ denote the contribution of $\mathcal{A}_\ell^p$ during Downlink phase to $R(\text{coa}_n)$ if $\mathcal{A}_\ell^p \in \text{coa}_n$. In particular, $R_\ell^d(\text{coa}_n)$ is the total amount of data (measured in bits/sec) transmitted by $\mathcal{A}_\ell^p$ and received by its associated SA nodes during Downlink phase. In Section IV-A we characterize $R_\ell^d(\text{coa}_n)$ in terms of the binary optimization variables a_ℓ^n's.

Let $R_\ell^p(\text{coa}_n)$ denote the contribution of $\mathcal{A}_\ell^p$ during PA-PA phase to $R(\text{coa}_n)$ if $\mathcal{A}_\ell^p \in \text{coa}_n$. $R_\ell^p(\text{coa}_n)$ is the total amount of data (measured in bits/sec) received by $\mathcal{A}_\ell^p$ and transmitted by some other PA nodes in coa_n during PA-PA phase. In Sec. IV-B we characterize $R_\ell^d(\text{coa}_n)$ in terms of the binary optimization variables a_ℓ^n's.

Using the binary optimization variables a_ℓ^n's, we can write $R(\text{coa}_n)$ in terms of $R_\ell^d(\text{coa}_n)$ and $R_\ell^p(\text{coa}_n)$ as the following

$$R(\text{coa}_n) = \sum_{\mathcal{A}_\ell^p \in \mathcal{A}^p} a_\ell^n (R_\ell^d(\text{coa}_n) + R_\ell^p(\text{coa}_n)). \quad (4)$$

Therefore, $R(\Omega')$ becomes

$$R(\Omega') = \sum_{n=1}^{C'} \sum_{\mathcal{A}_\ell^p \in \mathcal{A}^p} a_\ell^n (R_\ell^d(\text{coa}_n) + R_\ell^p(\text{coa}_n)). \quad (5)$$

Optimization. The problem of finding the best coalition formation in (1) becomes equivalent to putting PA nodes into C' disjoint sets, denoted as $coa_1, coa_2, ..., coa_{C'}$, i.e., finding the binary optimization variables a_ℓ^n for $\ell = 1, ..., D, n = 1, ..., C'$, such that $R(\Omega')$ is maximized.

$$\text{Given } C',\ \Omega^* = \arg\max \sum_{n=1}^{C'} R(\Omega') \quad (6)$$

$$\text{s.t.} \quad \sum_{n=1}^{C'} a_\ell^n = 1, \text{for } \ell = 1, ..., D$$

$$\sum_{\ell=1}^{D} a_\ell^n \geq 3, \text{if coa}_n \text{ is a PA-only coalition}$$

$$\sum_{\ell=1}^{D} a_\ell^n \geq 1, \text{if coa}_n \text{ is an SA-PA coalition}$$

It is clear that all three constraints in (1) are satisfied, i.e., $\text{coa}_q \subseteq \mathcal{A}$ for $q = 1, ..., C'$, $\text{coa}_k \cap \text{coa}_l = \emptyset$ for all k, l, and $\bigcup_{n=1}^{C'} \text{coa}_n \subseteq \mathcal{A}$. The first constraint in (6) ensures that Ω^* is a viable coalition set with no overlapping coalitions. The second and third constraints in (6) assure that the solution Ω^* includes legitimate coalitions only.

IV. Achievable Channel Rate

Recall $R_i^d(\text{coa}_n)$ denote the contribution of $\mathcal{A}_i^p$ during Downlink phase to $R(\text{coa}_n)$ if $\mathcal{A}_i^p \in \text{coa}_n$. In this phase, we assume that SA nodes steer their beams directly towards their respective PA node for data reception. Also, recall $R_i^p(\text{coa}_n)$ denote the contribution of $\mathcal{A}_i^p$ during PA-PA phase to $R(\text{coa}_n)$ if $\mathcal{A}_i^p \in \text{coa}_n$. In this phase, we assume that PA nodes steer their beams directly towards each other for data communication. Further, recall the binary optimization variables a_i^n's, which indicate whether or not $\mathcal{A}_i^p$ is in coa_n. In the following, we use Bayesian rule and conditional probability to formulate $R_i^d(\text{coa}_n)$ and $R_i^p(\text{coa}_n)$ in terms of a_i^n's for the bandwidth allocation scheme in Section III-C.

A. Rate Formulation in Downlink Phase

Consider a PA node in coa_n, denoted as $\mathcal{A}_i^p$. Recall $\{\text{PCP}_{\mathcal{A}_i^p}\}^s$ is the set of SA nodes that are in coa_n and $\mathcal{A}_i^p$ can form a directional link with. Suppose $\mathcal{A}_j^s \in \{\text{PCP}_{\mathcal{A}_i^p}\}^s$, and consider the link $(\mathcal{A}_i^p, \mathcal{A}_j^s)$ in coa_n, where $\mathcal{A}_i^p, \mathcal{A}_j^s$ are transmitter and receiver, respectively. The capacity of this link, measured in bits/sec, is

$$R_{ij}^d(\text{coa}_n) = \frac{w_1}{|\{\text{PCP}_{\mathcal{A}_i^p}\}^s|} \log_2\left(1 + \frac{P_r(\mathcal{A}_i^p, \mathcal{A}_j^s)}{N_0 w_1 + I_{\mathcal{A}_j^s}(\text{coa}_n)}\right), \quad n = 1, ..., C' \quad (7)$$

where $I_{\mathcal{A}_j^s}(\text{coa}_n)$ is the interference imposed on $\mathcal{A}_j^s$. This interference is imposed by other PA nodes in coa_n that $\mathcal{A}_j^s$ is in their FoVs. In other words

$$I_{\mathcal{A}_j^s}(\text{coa}_n) = \sum_{\mathcal{A}_k^p : \mathcal{A}_k^p \neq \mathcal{A}_i^p, \mathcal{A}_k^p \in \text{coa}_n, \mathcal{A}_j^s \in \mathcal{A}(\mathcal{A}_k^p)} P_r(\mathcal{A}_k^p, \mathcal{A}_j^s). \quad (8)$$

Note that the set $\{\text{PCP}_{\mathcal{A}_i^p}\}^s$ in (7) does not depend on the optimization variables a_i^n's, since the nodes in this set are always in the same coalition as $\mathcal{A}_i^p$. However, $I_{\mathcal{A}_j^s}(\text{coa}_n)$ in (8) depends on a_i^ns. To characterize $I_{\mathcal{A}_j^s}(\text{coa}_n)$ in terms of a_i^ns, we introduce another binary variable $b(\mathcal{A}_m, \mathcal{A}_k)$ to indicate whether or not node $\mathcal{A}_m$ is within FoV of node $\mathcal{A}_k$, i.e., if $b(\mathcal{A}_m, \mathcal{A}_k) = 1$ then $\mathcal{A}_m \in \mathcal{A}(\mathcal{A}_k)$, and if $b(\mathcal{A}_m, \mathcal{A}_k) = 0$ then $\mathcal{A}_m \notin \mathcal{A}(\mathcal{A}_k)$. Now, we can rewrite $I_{\mathcal{A}_j^s}(\text{coa}_n)$ in (8) as the following

$$I_{\mathcal{A}_j^s}(\text{coa}_n) = \sum_{\mathcal{A}_k^p \in \mathcal{A}^p \setminus \{\mathcal{A}_i^p\}} a_k^n b(\mathcal{A}_j^s, \mathcal{A}_k^p) P_r(\mathcal{A}_k^p, \mathcal{A}_j^s) \quad (9)$$

We note that $R_{ij}^d(\text{coa}_n)$ in (7) depends on a_i^ns through the interference $I_{\mathcal{A}_j^s}(\text{coa}_n)$ in (9). Recall $R_i^d(\text{coa}_n)$ is the total amount of data transmitted by $\mathcal{A}_i^p$ and received by its associated SA nodes. In other words

$$R_i^d(\text{coa}_n) = \sum_{\mathcal{A}_j^s \in \{\text{PCP}_{\mathcal{A}_i^p}\}^s} R_{ij}^d(\text{coa}_n). \quad (10)$$

Recall that the set $\{\text{PCP}_{\mathcal{A}_i^p}\}^s$ in (10) does not depend on a_i^ns. Hence, $R_i^d(\text{coa}_n)$ in (10) depends on a_i^ns only through $R_{ij}^d(\text{coa}_n)$.

B. Rate Calculation in PA-PA Phase

Consider a PA node in coa_n, denoted as $\mathcal{A}_i^p$. Recall $\{\text{PCP}_{\mathcal{A}_i^p}\}^p$ is the set of PA nodes that $\mathcal{A}_i^p$ can potentially form a directional link with. These PA nodes may or may not be part of coa_n. Node $\mathcal{A}_i^p$ can be in transmitting or receiving mode, with equal probability. Also, if in transmitting (receiving) mode, $\mathcal{A}_i^p$ chooses randomly another PA node from the set $\{\text{PCP}_{\mathcal{A}_i^p}\}^p$ that is also in coa_n to transmit to (receive from). Suppose $\mathcal{A}_j^p \in \{\text{PCP}_{\mathcal{A}_i^p}\}^p$ and also $\mathcal{A}_j^p \in coa_n$. To form the link $(\mathcal{A}_i^p, \mathcal{A}_j^p)$, node $\mathcal{A}_i^p$ needs to be in transmitting mode, and chooses to transmit to $\mathcal{A}_j^p$. Also, node $\mathcal{A}_j^p$ needs to be in receiving mode, and chooses to receive from $\mathcal{A}_i^p$. Let $R_i^p(\text{coa}_n)$ be the total amount of data (measured in bits/sec) received by $\mathcal{A}_i^p$ and transmitted by some other PA nodes in coa_n. Let set $\mathcal{Y}_{\mathcal{A}_i^p}^{(\text{coa}_n)} = \{\mathcal{A}_k^p | \mathcal{A}_k^p \neq \mathcal{A}_i^p, \mathcal{A}_k^p \in \text{coa}_n \text{ and } \mathcal{A}_k^p \in \{\text{PCP}_{\mathcal{A}_i^p}\}^p\}$. We can express $R_i^p(\text{coa}_n)$ as below

$$R_i^p(\text{coa}_n) = \frac{w_1}{4 \times |\mathcal{Y}_{\mathcal{A}_j^p}^{(\text{coa}_n)}| \times |\mathcal{Y}_{\mathcal{A}_i^p}^{(\text{coa}_n)}|} \times \sum_{\mathcal{A}_j^p \in \{\text{PCP}_{\mathcal{A}_i^p}\}^p} a_j^n \log_2\left(1 + \frac{P_r(\mathcal{A}_j^p, \mathcal{A}_i^p)}{N_0 w_1 + I_{\mathcal{A}_i^p}(\text{coa}_n)}\right) \quad (11)$$

where $I_{\mathcal{A}_i^p}(\text{coa}_n)$ is the interference imposed on $\mathcal{A}_i^p$. The sum in (11) is over all PA nodes in PCP of $\mathcal{A}_i^p$ that are also in coa_n. The fraction outside the sum in (11) stems from the facts that (1) $\mathcal{A}_i^p$ and $\mathcal{A}_j^p$ should be in transmitting and receiving modes, respectively, (2) $\mathcal{A}_j^p$ chooses randomly $\mathcal{A}_i^p$ from the nodes in $\{\text{PCP}_{\mathcal{A}_j^p}\}^p$ that are also in coa_n. Also, $\mathcal{A}_i^p$ chooses randomly $\mathcal{A}_j^p$ from the nodes in $\{\text{PCP}_{\mathcal{A}_i^p}\}^p$ that are also in coa_n. Hence, this fraction is equal to $\frac{1}{2} \times \frac{1}{2} \times \frac{1}{|\mathcal{Y}_{\mathcal{A}_i^p}^{(\text{coa}_n)}|} \times \frac{1}{|\mathcal{Y}_{\mathcal{A}_j^p}^{(\text{coa}_n)}|}$.

The interference $I_{\mathcal{A}_j^p}(\text{coa}_n)$ is imposed by other transmitting PA nodes in coa_n that $\mathcal{A}_j^p$ is in their FoVs:

$$I_{\mathcal{A}_j^p}(\text{coa}_n) = \frac{1}{2} \sum_{\mathcal{A}_k^p : \mathcal{A}_k^p \neq \mathcal{A}_i^p, \mathcal{A}_k^p \in \text{coa}_n, \mathcal{A}_j^p \in \mathcal{A}(\mathcal{A}_k^p)} P_r(\mathcal{A}_k^p, \mathcal{A}_j^p) \quad (12)$$

where $\frac{1}{2}$ in (12) comes from the fact that $\mathcal{A}_k^p$ is transmitting and thus interfering with $\mathcal{A}_j^p$ only with probability $\frac{1}{2}$. The set cardinalities $|\mathcal{Y}_{\mathcal{A}_i^p}^{(\text{coa}_n)}|, |\mathcal{Y}_{\mathcal{A}_j^p}^{(\text{coa}_n)}|$ in (11) as well as $I_{\mathcal{A}_j^s}(\text{coa}_n)$ in (12) depend on the optimization variables a_i^n's. Using the same binary variables we used in Section IV-A we can rewrite $I_{\mathcal{A}_j^p}(\text{coa}_n)$ in (12) as

$$I_{\mathcal{A}_j^p}(\text{coa}_n) = \sum_{\mathcal{A}_k^p \in \mathcal{A}^p \setminus \{\mathcal{A}_i^p\}} a_k^n a_j^n b(\mathcal{A}_j^p, \mathcal{A}_k^p) P_r(\mathcal{A}_k^p, \mathcal{A}_j^p). \quad (13)$$

Also, we can characterize the set cardinalities as below

$$|\mathcal{Y}_{\mathcal{A}_i^p}^{(\text{coa}_n)}| = \sum_{\mathcal{A}_k^p \in \{\text{PCP}_{\mathcal{A}_i^p}\}^p} a_k^n, \; |\mathcal{Y}_{\mathcal{A}_j^p}^{(\text{coa}_n)}| = \sum_{\mathcal{A}_k^p \in \{\text{PCP}_{\mathcal{A}_j^p}\}^p} a_k^n \quad (14)$$

We note that $R_i^p(\text{coa}_n)$ in (11) depends on the optimization variables a_i^n's through the interference $I_{\mathcal{A}_j^p}(\text{coa}_n)$ in (13) and the set cardinalities $|\mathcal{Y}_{\mathcal{A}_i^p}^{(\text{coa}_n)}|, |\mathcal{Y}_{\mathcal{A}_j^p}^{(\text{coa}_n)}|$ in (14).

V. Coalition Set Formation Heuristics

The main problem we aim to solve is the generic version of (6), where C' is not fixed; i.e., we need to look at the ways in which coalitions can be formed such that the overall sum rate $R^d + R^p$ is maximized. In Sec. IV, we detailed how R can be calculated for a coalition as well as for the entire network. These achievable R values give us a way to compare the efficacy of coalition sets, which we use steer our heuristic search towards a better coalition set. Further, the insights obtained from the classification of directional radio antennas in Section III-B allows us to reduce the search space significantly as can eliminate infeasible coalitions based on whether or not a node is an SA or PA. Next, we first present a technique (Heuristic 1) that yields an *all-covering* initial coalition set, composed of smallest possible coalitions. We, then, design two heuristics (Heuristics 2 and 3) that attempt to merge the small coalitions in the initial coalition set with hopes to improve the sum rate.

A. Heuristic 1: Minimalist Coalitions (MC)

We first start with composing the list of PCPs for A nodes, the complexity of which is $\mathcal{O}(A^2)$. Then, we initialize the coalition set $\Omega \leftarrow \emptyset$, and inspect PCP of all nodes. If $|\text{PCP}_{\mathcal{A}_i}| = 0$, $\mathcal{A}_i$ cannot be part of a coalition and is excluded from $\mathcal{A}$. If $|\text{PCP}_{\mathcal{A}_i}| = 1$, then $\mathcal{A}_i$ is an SA and it will have to be in coalition with the node in its PCP. We first check if there exists a specific coalition that already contains the PCP member of $\mathcal{A}_i$. If so, then, $\mathcal{A}_i$ gets merged into that coalition and removed from $\mathcal{A}$. Otherwise, we form a coalition $coa_i = \{\mathcal{A}_i\} \cup \{\text{PCP}_{\mathcal{A}_i}\}$, and add this coalition to the set of coalitions, i.e., $\Omega \leftarrow \Omega \cup coa_i$. Once the above steps are applied to all nodes in $\mathcal{A}$, there will be no SA left alone, as all of them will be placed to a coalition. However, there will be isolated PA nodes as the above initialization does not add nodes with $|\text{PCP}| > 1$ to a coalition. We create a set Δ to store the outstanding PAs in increasing order of their PCP sizes. We also move all 2-node coalitions to set $\Omega_{\text{SA-SA}}$. All the other coalitions stay in Ω. This process is detailed in Algo. 1 as the InitialCoalitionSet($\mathcal{A}$) function which returns the coalitions with one PA and one or more PAs, the coalitions with only two SAs, and the set of PAs left alone, i.e., Ω, $\Omega_{\text{SA-SA}}$, and Δ.

To satisfy the all-covering property, we, next, focus on placing the outstanding PAs, Δ, that got left alone after the InitialCoalitionSet($\mathcal{A}$) procedure. Our approach here exploits the fact that none of the PAs in Δ has an SA in its PCP. This is the due to the fact that InitialCoalitionSet($\mathcal{A}$), once it is done, places all SAs to a coalition. Hence, the PCPs of all PAs in Δ must only be composed of one PA or more PAs. Given this, the essence of our approach is to place the outstanding PAs in the same coalition as the PA with minimum PCP size. So, for a PA $\mathcal{A}_i^p$, we place $\mathcal{A}_i^p$ in the same coalition as the PA in $\text{PCP}_{\mathcal{A}_i}$ that has the smallest PCP size. The ConsumeOutstandingPAs(Ω, Δ) procedure in Algo. 2 details the steps for merging outstanding PAs to the coalition set Ω.

Execution of InitialCoalitionSet($\mathcal{A}$) and ConsumeOutstandingPAs(Ω, Δ) guarantees a feasible solution, Ω, to the all-covering coalition set formation problem. However, it may be possible to further improve the sum rate of the coalition set by merging some of the coalitions in Ω. The next two sections will detail heuristics for this purpose. the MC heuristic has a complexity of $\mathcal{O}(A^2)$.

Algorithm 1: Generate and Sort Initial Coalitions

```
function InitialCoalitionSet(𝒜)
    Generate PCP_{𝒜_1..𝒜_A}
    Ω ← ∅ \*Coalition Set *\
    coaCount ← 0
    for 𝒜_i = 1 : A do
        if |PCP_{𝒜_i}| = 0 then
            Exclude 𝒜_i from 𝒜;
        else if |PCP_{𝒜_i}| = 1 then
            foundPA ← FALSE;
            for j = 1 : coaCount do
                if coa_j contains PCP_{𝒜_i} then
                    foundPA ← TRUE;
                    coa_j ← coa_j ∪ {𝒜_i};
                    Exclude 𝒜_i from 𝒜;
                    break;
            if not foundPA then
                coaCount ++;
                coa_coaCount = {𝒜_i} ∪ {PCP_{𝒜_i}};
                Ω ← Ω ∪ coa_coaCount;
                Exclude 𝒜_i and PCP_{𝒜_i} from 𝒜;
    Δ ← 𝒜 \*Outstanding PA set*\
    Sort Δ in ascending order of |PCP_{𝒜_k}|, ∀𝒜_k ∈ Δ;
    Ω_{SA−SA} ← ∅
    Move all coa_i ∈ Ω with two nodes (i.e., |coa_i| = 2) to Ω_{SA−SA}
    Sort Ω in ascending order of coa_j, ∀j ∈ Ω;
    return Ω, Ω_{SA−SA}, Δ
end function
```

Algorithm 2: Merge Outstanding PAs to Coalition Set

```
function ConsumeOutstandingPAs(Ω, Δ)
    while Δ ≠ ∅ do
        for k = 1 : |Δ| do
            c ← PCP_k;
            c ← c\{j}, ∀j ∈ Δ;
            if c ≠ ∅ then
                u ← u ∈ c : |PCP_u| = min{|PCP_{j∈c}|};
            else
                u ← u ∈ PCP_k : |PCP_u| = min{|PCP_{j∈Δ}|};
            if coa_u = ∅ then
                Ω ← Ω ∪ {k, u};
            else
                coa_u ← coa_u ∪ {k}, coa_u ∈ Ω;
            Δ ← Δ\{k};
    return Ω
end function
```

B. Heuristic 2: Smaller Coalitions (SC)

The possibility of merging two coalitions is possible only if they have PAs that are in the PCP of each other. Since $\Omega_{\text{SA-SA}}$ does not include coalitions with a PA, it is excluded from this merging process. We start from the coalition set Ω found by Heuristic 1, i.e., first call the functions InitialCoalitionSet($\mathcal{A}$) and ConsumeOutstandingPAs(Ω, Δ). Then, we pick two coalitions from Ω with a probability inversely proportional to the sizes of the coalitions The intuition is that by merging smaller coalitions earlier in the process, a larger portion of the search space is left untried, which increased the likelihood of finding a better solution eventually. If merging the two coalitions results in a larger R, we merge them. If not, we retract. If no improvement on R is observed after stopCount=3 merger trials, the process stops. Assuming that the probability of finding mergeable coalitions is high, The complexity of this heuristic is $\mathcal{O}(\text{stopCount} \times A^3)$.

C. Heuristic 3: Smaller & Closer Coalitions (SCC)

This heuristic is a finer tuned version of SC using the intuition that merging coalitions closer to each other should yield a better outcome. Basically, we run SC three times and gather the smaller coalition pairs that are mergeable and those that yield a higher R. Then, for each of these coalition pairs, we calculate the relative distance separating them. For this, we apply the process of finding the center of gravity of each coalition and then, find the Euclidean distance separating them. We check if SCC yields a higher R over SC and if it does, we report that, otherwise, no improvement is made. Since this heuristic simply runs Heuristic 2 a constant number of times, its worst-case complexity follows the same behavior as Heuristic 2.

Parameter	Value
B	1 GHz
N_0	-110dBm [13]
α	2
HPBW	$15°$
Γ_i	$[0°, 360°]$

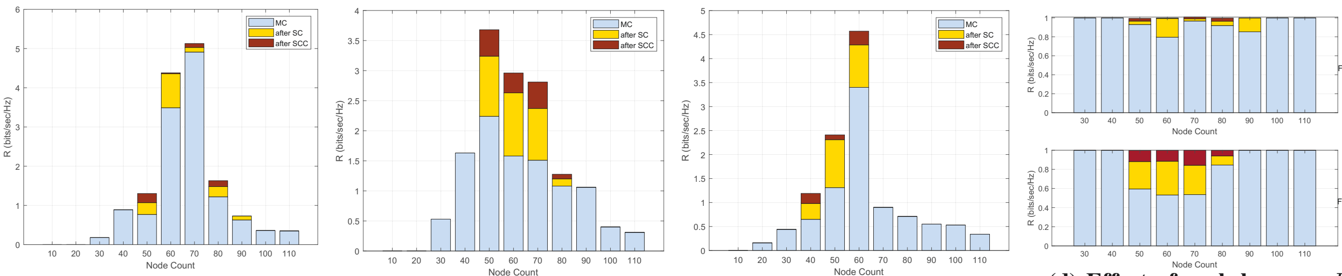
Table II: Sim. Parameters

VI. Simulation Results and Discussion

We present and discuss various coalition formation and sum-rate related results. The simulation parameters are shown in Table II. We have repeated each simulation three to ten times, with randomly scattered nodes, within a fixed geographical area, from which we generated coalition sets. All nodes are assumed to have the same FoV, β_i, and a randomly generated inclination angle, Γ_i. The isolated nodes are excluded from the simulation. We evaluate our heuristics for dense (10×10 m^2) networks.

We capped transmit power of the overall coalition set to a maximum of 1 mW. This means that the 1 mW is split into the total number of coalitions formed and nodes within each coalition equally share the coalitional power. Fig. 6 shows how the sum rate behaves w.r.t. network density and FoV using the proposed power allocation scheme for the dense network case. MC attains a peak in R (e.g., at 80 nodes for FoVs $50°$) as more nodes are added, indicating that the number of nodes in the network plays a critical role. The transmit power is not simply added up, rather interference plays a major role. Also limiting the area of node deployment helps us in observing the peak in R.

Since their complexity is higher, a critical question to answer is whether or not there is a need for the SC and SCC heuristics that try to merge small coalitions for improving the sum rate. Figs. 6a, 6b and 6c show R w.r.t node density and FoV. We see significant improvement for medium node density, and beyond a certain limit, the SC and SCC heuristics make little sense due to increased interference. This is more



(a) FoV = 50° **(b) FoV = 70°** **(c) FoV = 90°** **(d) Effect of each heur on R**

Figure 6: Impact of heuristics SC and SCC on R for a dense network

clear in the Fig. 6d that shows the percentage of R attained by each heuristic for the cases with FoVs 50° and 70°. Also, we have not shown results beyond FoV = 90° because, in the smaller area, SC and SCC with such wide FoVs rarely provide any improvement due to added interference.

VII. Conclusion and Future Work

mmWave antennas are becoming necessary for ultra-high speed 5G-and-beyond communication. Proper resource allocation and throughput management including rate maximization are the keys to designing a successful 5G infrastructure. In this paper, we have characterized the mmWave directional nodes into SAs and PAs, and, using this categorization of nodes, we have presented an extensive all covering coalition set representation. We have meticulously written down the sum rate expressions for each link in a coalition. Then, we have extended the sum rate calculations for a coalition and ultimately, for the all covering coalition set. We have used a coalition-based channel allocation scheme and presented corresponding rate expressions. Next, using the SA and PA categorization, we designed novel heuristics, which showed improvement over our original coalition set for dense networks.

Several aspects need to be explored in forming coalitions of directional radios. We assumed a two-phased random scheduling of data transmissions during the Uplink and PA-PA phases. Exploring different methods of transmission scheduling and bandwidth allocation to coalitions and along with coalition formation algorithm design may yield fruitful results. As we focused on the sum rate of the coalition set, it is of interest of study the fairness among coalitions in terms of achievable data rate. Finally, understanding the impact of node mobility and adversarial presence to the coalition set sum rate is an interesting direction to take.

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