Ad-hoc Coalition Set Formation among Directional Radios

Sayanta Seth*, Murat Yuksel‡ and Azadeh Vosoughi§
Department of Electrical and Computer Engineering, University of Central Florida, Orlando, FL, USA
Email: *sayanta.seth@ucf.edu, ‡murat.yuksel@ucf.edu, §azadeh@ucf.edu

***Abstract*—The vast amount of spectrum in the millimeter wave (mmWave) and Terahertz bands are exploited by Fifth Generation (5G)-and-beyond mobile networks in order to attain more wireless capacity. The fundamental differentiating factor of mmWave/Terahertz radios from existing wireless systems is in terms of directivity, propagation loss, and blockage sensitivity. With the dramatic increase in adoption of mmWave/Terahertz directional antennas/nodes within the mainstream wireless networks, efficient, effective and decentralized forming of coalitions from such nodes is of interest for the goal of improving the throughput of a wireless network. In this work, we form sets of coalitions in a decentralized manner using a novel heuristic framework by categorizing directional radio nodes and placing them into coalitions. We explore heuristic designs that guarantee placement of all nodes in a coalition as well as focus on maximizing the sum rate of the coalition set at the expense of isolating some nodes. We perform simulations to gain insight into the design of these ad-hoc coalition set formation heuristics.**

I. Introduction

In order to provide higher data rates and bandwidth, emerging mobile 5G-and-beyond communication technologies rely on mmWave bands, which are considered to be part of 28-300 GHz. Highly directional antennas become essential for practically accessing these frequencies since the transmissions are vulnerable to path loss and atmospheric absorption in these high frequencies. Directional transmission enables longer communication ranges by focusing the transmit signal energy to a smaller volume. The authors in [1], [2] have done substantial work to address issues and challenges like designing high gain antennas with precise beamforming for mitigating propagation loss. However, due to the requirements of line-of-sight and alignment aspects of directional transmission, integration of these antennas into mobile and ad-hoc scenarios becomes challenging. Such scenarios exist in battlefields or emergency communication settings where no or minimal infrastructure support are available. Further, as the number of Internet-of-Things (IoT) devices is increasing, device-to-device (D2D) communication where devices need to organize themselves is becoming more important for regular wireless communication scenarios as well. Relieving the base stations from the load of transmission and reception of data packets among cellular or IoT devices and offloading these D2D communication to the devices themselves have become a necessity as these also help in increasing the spatial reuse in spectrum access. To realize such localized and ad-hoc communication, radio nodes need to come together into coalitions for attaining successful and efficient transmissions [3], [4].

Higher spatial and frequency reuse is a key benefit of coalition formation. In the absence of coalition structures, a centralized Access Point (AP) has to be involved for routing all inter-node communications. If there are multiple nodes, on the other hand, participating in a single coalition, they can use as few as one channel (allocated to the whole coalition) to communicate among themselves; and then one node in the entire coalition may forward the message to the AP using a channel. Further, the process of coalition formation among nodes can be of two types: Centralized and Decentralized/Ad-hoc. In the centralized process, the coalition formation algorithms are run by the AP, which further directs/guides the individual nodes into joining different coalition sets, in the decentralized process, the AP altogether refrains itself from participating in coalition formation. The nodes themselves form coalition structures among themselves with information available to them. Decentralized coalition formation method is more applicable to critical scenarios like a battlefield, where radios need to maximize their overall throughput by participating in coalitions created in an ad-hoc manner among themselves. Coalitions of omni-directional radios have been studied heavily for higher throughput [5], higher spectrum efficiency [6], or stronger security against attackers [7]. However, understanding how directionality changes the establishment of coalitions among radios has not been explored well.

In this work, we explore the concept of forming coalitions of directional radios in a decentralized and ad-hoc manner. We assume that the radio nodes are utilizing mmWave frequencies. We consider a collection of highly directional mmWave radio nodes which are scattered randomly on a 2-dimensional (2D) plane. Each radio node is initialized with its field-of-view (FOV), that limits what other radio nodes it could potentially talk to. The scheduling of data transmission among the nodes is assumed to be regulated by the AP in phases of downlink and relay. During each of these phases, the nodes use an optimized set of steering angles and follow random scheduling for data transmission. We calculate achievable rate of a directional coalition under this phased random scheduling assumption, and design heuristics that aim to maximize the sum rate of all coalitions 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. Our framework is studied theoretically and we numerically evaluate its heuristics in terms of solving the problem of forming a set of coalition which maximizes the overall coalitional sum. Our prior work [8] solved this problem with a centralized assuming that all node information (e.g., node positions and FOVs) are available to a central controller such as an AP. This work's key novelty lies in role categorization of directional nodes in a coalition and using these roles to guide development of fast, decentralized coalition formation heuristics. We make the following contributions:

- A formal, step-by-step, decentralized method to categorize directional antenna nodes based on their FOVs and illustration of the method on networks of nodes of varying sizes.
- Calculation of coalitional sum rate or throughput using the scheduling methods and channel allocation schemes.
- Heuristics for forming coalition sets in ad-hoc manner such that all network nodes to a coalition.
- Evaluation of the pros and cons of relaxing the requirement of *all-covering* coalition set to a *partially-covering* coalition set when forming the coalitions among the directional radios.
- Simulation-based evaluation of the ad-hoc coalition set formation heuristics in terms of sum rate of all coalitions.

II. Related Works

Researchers have been working on the problem of increasing aggregate throughput of a wireless network for a long time. Mustafa et. al. in [9] have performed interesting works in the field of Dynamic Spectrum Sharing using sub-6 GHz spectrum. The authors have proposed a novel and unique wireless peering concept for cellular operators in the United States. For attaining even higher network throughput, 5G mmWave/THz communication systems are currently becoming the norm but the directionality aspect of these new radio nodes bring in new challenges. Sub-channel allocation and scheduling methods for directional antennas in mmWave spectrum have been explored in previous works. In [10], authors have studied algorithms to efficiently allocate sub-channels to improve resource utilization and network capacity of a D2D network and in [11], compared to conventional D2D approaches [12], superior results are shown to have been achieved by employing novel methods to allocate sub-channels to D2D links in a densely populated environment. The results in [11] show superior results even against QoS-aware scheduling algorithms for concurrent transmission using game-theoretic methods [3].

In order to improve network capacity, directional wireless communication has presented new features to utilize. Specifically, mmWave beams are open to beamsteering, which have enabled new avenues for improving the aggregate network throughput, or sum rate [13]. Going beyond channel resource allocation [14], we need to fully consider the impact of scheduling in the optimality of beamsteering angles in order to completely take advantage of what is available in directional wireless. Considering mobile fronthaul [15] and cognitive radios [16], beamsteering optimization of directional antennas are shown to help significantly.

Most relevant literature to our work are the recent ones that focus on improving wireless network throughput by utilizing mmWave/THz bands and the ones that model coalitional communication among radios using legacy sub-6 GHz bands [7]. The problem of throughput optimization of directional wireless communication gets even more complicated when coalitions are considered along with inter-play of beamsteering angles, transmit power, channel allocation and scheduling [10], as well as inter- and intra-coalition interference. Constraining the transmit power has proven to be fruitful in reducing the problem's complexity. Convex optimization solutions [17] were enabled in a scenario where scheduling is assumed optimal when the authors applied a transmit power limit on each individual node and divided the problem into two stages. For a single coalition setup, when random scheduling is assumed, we showed that beamsteering optimization can be done fast and comprehensively [8]. However, all-covering coalition formation has not been considered in these studies which could result in unfair solutions. In [4], we have considered a regulated scheduling method based on the structure of directional network topology and have developed novel and efficient heuristics for forming a set of coalitions maximizing the throughput while making sure all coverable nodes are placed in a coalition. Our prior work in [4] is similar as it also aimed to construct all-covering coalition sets, but, unlike our decentralized approach, the algorithms used were centralized. Our work fundamentally differs from [4] as we design coalition formation algorithms that are decentralized and constructs coalitions as an emerging result of ad-hoc decisions made by directional radio nodes.

III. System Model and Problem Statement

In this work, we largely follow the system model laid out in [4] as we tackle the same problem set albeit in a decentralized manner. The mmWave radio nodes are considered to be scattered over a 2-dimensional region, and they communicate using a channel of bandwidth W Hz. In order to structure them into disjoint and autonomous coalitions, we devise two decentralized approaches: 1. Create an *all-covering coalition set*; where all eligible nodes put themselves into a coalition and 2. Create a *partial-covering coalition set*; where nodes contributing negatively to the overall throughput bar themselves from becoming part of any coalition structure. Unlike a coordinated coalition formation procedure that necessitates the inclusion of a centralized controller like an AP and a centralized Common Control Channel (CCC) to run the coalition formation algorithms, our decentralized methods relax these requirements to a great extent. Apart from allocating bandwidth and dividing time slots (as described in Sections IV-A and IV-B), AP plays no role in our coalition set formation procedure.

A. Preliminaries and Assumptions

Inherent properties of every node in the system are: 1. They are equipped with a beam-steerable, half-duplex directional antenna. 2. They have fixed Field-of-View (FOV), within which they can freely steer their beams. Our goal is to realize and compare various fast decentralized coalition formation methods that take care of covering full or partial set of nodes, and, particularly for the latter case, classifying positively contributing (in terms of sum rate) nodes into coalition structures enabling them to maximize the overall coalitional sum rate while effectively utilizing bandwidth W Hz.

Let $\mathcal{N} = \{\mathcal{N}_1, \mathcal{N}_2, ..\mathcal{N}_A\}$ be the set of directional mmWave radio nodes. Node $\mathcal{N}_i$ is the node that is located at location (x_i, y_i) on a Cartesian plane, for $i = 1...A$. We partition these nodes into C disjoint coalitions, denoted as $\text{coa}_1, \text{coa}_2, .., \text{coa}_C$ such that $\text{coa}_p \subseteq \mathcal{N}$ for $p = 1, .., C$ and $\text{coa}_i \cap \text{coa}_j = \emptyset$ for all i, j. Since all nodes have limited FOVs, some nodes in $\mathcal{N}$ may not establish any communication link with the other nodes. These now become *isolated nodes* and hence, cannot participate in any coalition. FOVs of the nodes determine their structures within a coalition and the feasible links for intra-coalition communication. 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 $R(\Omega) = \sum_{n=1}^{C} R(\text{coa}_n)$.

B. Partially-Covering Coalition Set

With the set of assumptions mentioned before, the problem of decentralized coalition set formation can be written as an optimization problem, similar to [4]. The problem of finding the set of coalitions Ω which maximizes R can be written as follows:

$$\begin{aligned} \text{Given } C, \quad & \Omega^* = \arg\max R(\Omega) && (1) \\ & \text{s.t. } \ \text{coa}_q \subseteq \mathcal{N}, \forall q; \\ & \text{coa}_i \cap \text{coa}_j = \emptyset, \forall i, j. \end{aligned}$$

Here, set Ω^* is the coalition set that maximizes the coalitional sum rate R. Also, any coalition consisting of nodes become a subset of set of nodes $\mathcal{N}$ and no two coalitions are overlapping. Since we assume 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 $[1, N]$. Here, we are not enforcing any constraint such that all nodes present in set Ω^* must be present in set $\mathcal{N}$, and hence we call this 'partially-covering coalition set'.

C. All-Covering Coalition Set

We use the same set of assumptions as before. However, the problem of finding the best set of coalitions Ω that maximizes R becomes as follows:

$$\begin{aligned} \text{Given } C, \quad & \Omega^* = \arg\max R(\Omega) && (2) \\ & \text{s.t. } \ \text{coa}_q \subseteq \mathcal{N}, \forall q; \\ & \text{coa}_i \cap \text{coa}_j = \emptyset, \forall i, j; \\ & \bigcup_{n=1}^{C} \text{coa}_n \equiv \mathcal{N}' && (3) \end{aligned}$$

where $\mathcal{N}'$ is the set of nodes that can establish a link with at least one other node. This version of the problem is called 'all-covering coalition set' problem because other than the isolated nodes, we enforce the additional constraint (3) which enforces that all nodes that can form a link with another node are included in a coalition.

The computational complexity of finding Ω^* is upper bounded by the solution search space, i.e., $\mathcal{O}(A2^{A^2})$ for $|\mathcal{N}| = A$ nodes. Exhaustively scanning this search space to find the optimum partitioning of the nodes to coalitions is prohibitive. Further, the problem of finding Ω^* is known to be NP-complete [18], [4]. Henceforth, we design novel and effective coalition set formation heuristics that are able to form all-covering coalition sets as well as partial-covering coalition sets that maximize R.

D. Structure of Nodes within a Coalition

Potential Coalition Partners (PCPs). According to [4], each node $\mathcal{N}_i \in \mathcal{N}$ is associated with a set $\text{PCP}_{\mathcal{N}_i}$ that consists of other nodes in $\mathcal{N}$ that $\mathcal{N}_i$ can potentially establish a directional wireless link with, and hence they are "Potential Coalition Partners (PCPs)" of $\mathcal{N}_i$. It must be noted that if two nodes are within FOVs of each other then their PCP lists must include each other, which implies that two nodes can form a link iff they fall within each others' FOVs. Also, if the PCP list of node $\mathcal{N}_i$ is empty, it cannot communicate with any other node, signifying that it cannot be part of any coalition. The nodes with empty PCP lists are called *isolated nodes* and they are excluded from the system.

Concepts of Primary Antenna and Secondary Antenna. The concepts of Primary and Secondary antennas are described in detail in [4], [8]. Excluding the isolated nodes from the set $\mathcal{N}$, the remaining nodes in $\mathcal{N}$ are categorized as *Primary Antenna (PA)* or *Secondary Antenna (SA)* nodes. Node $\mathcal{N}_i \in \mathcal{N}$ is a PA if $|\text{PCP}_{\mathcal{N}_i}| > 1$, i.e., a PA node can potentially establish links with more than one other nodes. Node $\mathcal{N}_i \in \mathcal{N}$ is an SA if $|\text{PCP}_{\mathcal{N}_i}| = 1$, i.e., an SA node can potentially establish a link with only one other node. From this classification of nodes into SA and PA categorization, the authors in [4] have made the following interesting observations:

1) An SA-only coalition has only two nodes.
2) An SA-PA coalition must have at least one PA and at least two SAs.
3) A PA-only coalition has to have at least three PAs.

Let $\{\mathcal{X}\}^s$ and $\{\mathcal{X}\}^p$ represent the sets of SAs and PAs in set $\mathcal{X}$, respectively. Then, $\{\text{PCP}_{\mathcal{N}_i}\}^s$ and $\{\text{PCP}_{\mathcal{N}_i}\}^p$ represent, respectively, the sets of SAs and PAs that node $\mathcal{N}_i$ can potentially form a link with. We use Table I that shows a summary of our notations.

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

Table I: Symbol list along with their descriptions

All-Covering and Partial-Covering Coalition Set Examples. Let us consider two different coalition sets: 1. All covering and 2. Partially covering. Figs. 1 and 2 provide examples of each respectively. In these figures, we do not show the SA nodes. So these coalitions can be respectively written as $\Omega_1 = \{\mathcal{N}_1^p, \mathcal{N}_2^p, \mathcal{N}_3^p\}, \{\mathcal{N}_4^p, \mathcal{N}_5^p, \mathcal{N}_6^p$
and $\Omega_2 = \{\mathcal{N}_1^p, \mathcal{N}_2^p, \mathcal{N}_3^p\}, \{\mathcal{N}_4^p,$
On the same set of nodes, we see th
different coalition sets. We use yello
PA nodes along with their SA nodes
are marked by green boundaries. In F
are participating in coalition sets. W
which is comprised of $\mathcal{N}_8^p$, $\mathcal{N}_9^p$ anc
coalition set scenario, it is possible
other coalitions and form a differen
However, in Fig. 2 we see a similar s
out of any coalition. This is becaus
coalition set, $\mathcal{N}_{10}^p$ acts altruistically.
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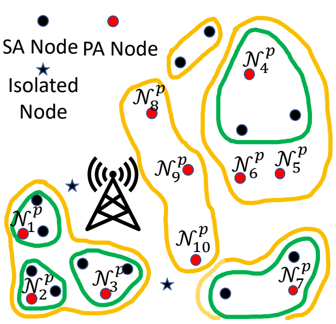


Figure 1: Coalition example 1 **Figure 2: Coalition example 2**

E. Directional Antenna Model

We follow the directional antenna model in [4], [8]. If we consider node $\mathcal{N}_i$ then its defining parameters are as mentioned in table II.

A representation of the deployment of directional nodes along with the parameters of node $\mathcal{N}_i$ is shown in Fig. 3. We have considered reference directional antenna model with side

Param.	Description
Γ_i	Initial inclination angle, with reference to x-axis
θ_i	Steering angle corresponding to central line of beam, with reference to positive x-axis
β_i	FOV: maximum angular sweeping range of main beam
$\psi_{i\to j}$	Deviation angle: indicates the digression of the center of the beam away from the straight line connecting nodes $\mathcal{N}_i$ and $\mathcal{N}_j$

Table II: Antenna parameters of node $\mathcal{N}_i$

lobe for IEEE 802.15.3c. In this piece of work, however, 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 [19]. Let us assume $G_i(\theta_i)$ is the directional antenna gain of node $\mathcal{N}_i$. Then,

$$G_i(\theta_i) = e^{-(\ln 2)(\frac{\theta_i}{\alpha_i})^2}, \qquad \beta_i^{\text{min}} \leq \theta_i \leq \beta_i^{\text{max}} \tag{4}$$

where $\beta_i^{\text{min}} = \Gamma_i - \beta_i/2$ and $\beta_i^{\text{max}} = \Gamma_i + \beta_i/2$ are the minimum

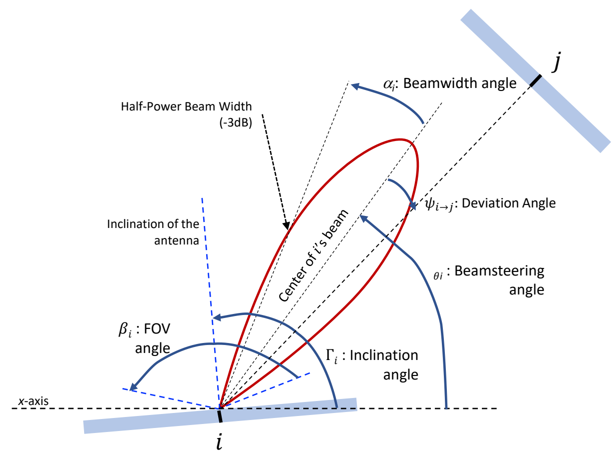


Figure 3: Antenna array of $\mathcal{N}_i$ [8]

F. SINR Formulation with Directional Antenna

Let us consider the link $(\mathcal{N}_i, \mathcal{N}_j)$ between two nodes $\mathcal{N}_i \in \mathcal{N}$ and $\mathcal{N}_j \in \mathcal{N}$. Let d_{ij} signify the distance that separates the two nodes $\mathcal{N}_i$ and $\mathcal{N}_j$. It is also assumed that $\mathcal{N}_i$ is steered towards $\mathcal{N}_j$ with a beam steering angle θ_i. With the Cartesian coordinates of $\mathcal{N}_i$ and $\mathcal{N}_j$ given, the deviation angle $\psi_{i\to j}$ is found (see Fig. 3). Let W_t and $W_r(\mathcal{N}_i, \mathcal{N}_j)$ be the transmit power of $\mathcal{N}_i$ and the received power at $\mathcal{N}_j$. Using THz communication channel model in [20], $W_r(\mathcal{N}_i, \mathcal{N}_j)$ can be expressed in terms of W_t as follows:

$$W_r(\mathcal{N}_i, \mathcal{N}_j) = \frac{W_t}{d_{i,j}^{\alpha}} G_i(\theta_i - \psi_{i\to j}) G_j(\theta_j - \pi - \psi_{i\to j}) \tag{5}$$

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

IV. Achievable Rate

We assume that the AP does not perform any data transmission but helps the nodes coordinate their coalition formation process as well as intra- and inter-coalition data transmission schedules. The overall coordination process is divided into two subsequent stages: coalition formation and bandwidth allocation. Once the coalitions are formed, the coalition leaders (in this case the coalition leaders are one of the PAs within each coalition) contact the AP to request bandwidth for their coalitions. Every coalition leader (instead of all nodes) in the system is assumed to have access to a CCC that they can use to communicate with the AP. In the second stage, the AP allocates bandwidth to each coalition. Once these two stages are over, the AP notifies the coalition leaders that data transmission can start. We envision this coordination process to be repeated regularly. Hence, the time spent during these stages should be minimized to reduce the overhead on the data transmission. This motivates us to design fast coalition heuristics for the coalition formation stage, which is the focus of this paper.

In order to calculate achievable data rate of each coalition, $R(\Omega)$ in (1) and (2), we need to define (i) the intra- and inter-coalition scheduling of data transmissions among nodes and coalitions, and (ii) allocation of bandwidth to coalitions.

A. Scheduling

Each coalition operates autonomously based on a time-slotted communication mechanism and the nodes within a coalition schedule intra-coalition communication by themselves without relying on the AP. Time T (which is the duration of the data transmission period after the coalitions are formed) is divided into sub-frames of duration T_f sec. Following the approach in [8], [4], we assume T_f consists of two consecutive phases: Downlink Phase and PA-PA Phase, with durations T_d and $T_p = T_f - T_d$ sec, respectively. During the Downlink Phase, PAs talk to their SAs. This phase can further be divided into PA to SA and SA to PA transmissions. However, this would not significantly change the overall throughput of a coalition and, hence, the coalition formation algorithm. Thus, we consider only the downlink communication, from PAs to their SAs. After the Downlink phase, a PA-PA phase with non-zero T_p makes sure that nodes within a coalition can reach each other.

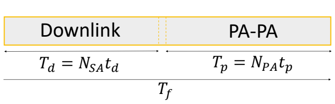


Figure 4: Two phases corresponding to a time frame

Downlink Phase. While in this phase, all the PAs in coa_n remain in transmitting mode and all the SAs in coa_n remain in receiving mode. The downlink time sub-frame T_d is divided by each PA (acting independently) among the SAs within its PCP list. Each PA node transmits data to its corresponding SAs during this allocated time frame in a deterministic manner. With respect to a PA's transmission schedule, how other PAs utilize their downlink phase has no impact.

PA-PA Phase. During this phase, the PA nodes communicate among themselves, while the SA nodes do not transmit or receive. We assume that each PA node randomly decides when to transmit or receive, which means it may be in transmitting or receiving mode with equal probability. Let us consider $\mathcal{N}_i^p \in \text{coa}_n$ and the set of PA nodes represented by $\{\text{PCP}_{\mathcal{N}_i^p}\}^p$, out of which some may be in coa_n. If $\mathcal{N}_i^p$ is in transmitting mode, it will randomly choose a PA node within its PCP list that is also in coa_n and will transmit data to the chosen PA node. Whereas, if $\mathcal{N}_i^p$ is in receiving mode, it will choose a PA node in its PCP randomly which is also in coa_n and will receive data from the chosen PA node. Suppose $\mathcal{N}_i^p, \mathcal{N}_j^p \in \text{coa}_n$. To establish the link $(\mathcal{N}_i^p, \mathcal{N}_j^p)$, the following three conditions must be met: (i) $\mathcal{N}_i^p$ and $\mathcal{N}_j^p$ must be in transmitting and receiving modes, respectively, (ii) $\mathcal{N}_i^p \in \{\text{PCP}_{\mathcal{N}_j^p}\}^p$ and $\mathcal{N}_j^p \in \{\text{PCP}_{\mathcal{N}_i^p}\}^p$, and (iii) $\mathcal{N}_i^p$ must choose to transmit to $\mathcal{N}_j^p$ and $\mathcal{N}_j^p$ must choose to receive from $\mathcal{N}_i^p$ simultaneously. We consider these requirements when calculating the achievable rate later in Section IV-C.

B. Bandwidth Allocation

With a total given bandwidth of W Hz, the AP is expected to allocate it to coalitions. Since the scheduling mechanism in the previous section assumes transmissions always involve a PA, the AP does not have to consider coalitions consisting of SA nodes only. Therefore, bandwidth W is allocated only to PA-only and SA-PA coalitions. Suppose $\Omega' \subseteq \Omega$ where Ω' excludes SA-only coalitions, and C' is less than or equal to the total number of PA nodes, i.e., $C' \leq D$. The total bandwidth W is segregated into C' sub-channels with bandwidth $w = \frac{W}{C'}$.

During the Downlink Phase, all PA nodes in a coalition transmit simultaneously over the same channel, causing co-channel interference. During the PA-PA Phase, all transmitting PA nodes in a coalition transmit simultaneously over the same channel, causing co-channel interference. Suppose, $\mathcal{N}_i^p, \mathcal{N}_j^p \in \text{coa}_n$. When the link $(\mathcal{N}_i^p, \mathcal{N}_j^p)$ is established, $\mathcal{N}_j^p$ is susceptible to interference from other transmitting PA nodes in coa_n that $\mathcal{N}_j^p$ is in their FOVs. Also, $\mathcal{N}_i^p$ imposes interference on other receiving PA nodes in coa_n that are in its FOV. This interference will affect the signal-to-interference-plus-noise ratio (SINR) calculation of the links in which the receiving PA node is subject to interference from other transmitting PA nodes in the coalition. We consider these co-channel interferences in the rate calculations in the next section.

C. Rate Formulation in Downlink and PA-PA Phases

During downlink phase, the SA nodes are assumed to steer their main lobe beams directly towards their respective PA nodes for data reception. Similarly, during the PA-PA phase, PA nodes are assumed to steer their beams directly towards each other for data transmission/reception. Given the scheduling and the bandwidth allocation mechanisms in the previous sections, the capacity of a PA-SA link $(\mathcal{N}_i^p, \mathcal{N}_j^s)$

in coalition coa_n during the Downlink Phase, measured in bits/sec, is given by [4]:

$$R_{ij}^{d}(\text{coa}_n) = \frac{w}{|\{\text{PCP}_{\mathcal{N}_i^p}\}^s|} \log_2\left(1 + \frac{P_r(\mathcal{N}_i^p, \mathcal{N}_j^s)}{N_0 w + I_{\mathcal{N}_j^s}(\text{coa}_n)}\right), \quad n = 1, ..., C' \tag{6}$$

where $\mathcal{N}_i^p$ is the PA node, $\mathcal{N}_j^s$ is the SA node, $\{\text{PCP}_{\mathcal{N}_i^p}\}^s$ is the set of SA nodes in the same coalition that $\mathcal{N}_i^p$ can talk to, and $I_{\mathcal{N}_j^s}(\text{coa}_n)$ is the amount of interference imposed on $\mathcal{N}_j^s$ by the other PA nodes in coa_n that contain $\mathcal{N}_j^s$ in their FOVs. The total rate of coa_n during the Downlink Phase is calculated by summing (6) over all possible $(\mathcal{N}_i^p, \mathcal{N}_j^s)$ links.

Similarly, the capacity of a PA-PA link $(\mathcal{N}_i^p, \mathcal{N}_j^p)$ in coa_n during the PA-PA phase, measured in bits/sec, is given by [4]:

$$R_{ij}^{p}(\text{coa}_n) = \frac{w}{4 \times |\mathcal{Y}_{\mathcal{N}_j^p}^{(\text{coa}_n)}| \times |\mathcal{Y}_{\mathcal{N}_i^p}^{(\text{coa}_n)}|} \times \sum_{\mathcal{N}_j^p \in \{\text{PCP}_{\mathcal{N}_i^p}\}^p} \log_2\left(1 + \frac{P_r(\mathcal{N}_i^p, \mathcal{N}_j^p)}{N_0 w + I_{\mathcal{N}_j^p}(\text{coa}_n)}\right) \tag{7}$$

where $\mathcal{N}_i^p$ and $\mathcal{N}_j^p$ are the PA nodes, set $\mathcal{Y}_{\mathcal{N}_i^p}^{(\text{coa}_n)} = \{\mathcal{N}_k^p | \mathcal{N}_k^p \neq \mathcal{N}_i^p, \mathcal{N}_k^p \in \text{coa}_n \text{ and } \mathcal{N}_k^p \in \{\text{PCP}_{\mathcal{N}_i^p}\}^p\}$, $\{\text{PCP}_{\mathcal{N}_i^p}\}^p$ is the set of PA nodes in the same coalition that $\mathcal{N}_i^p$ can talk to, and $I_{\mathcal{N}_j^p}(\text{coa}_n)$ is the interference imposed on $\mathcal{N}_j^p$ by other PA nodes in coa_n that contain $\mathcal{N}_j^p$ in their FOVs. The total rate of coa_n during the PA-PA phase is calculated by summing (7) over all possible $(\mathcal{N}_i^p, \mathcal{N}_j^p)$ links.

V. Decentralized Coalition Set Formation

Our goal is to solve the generic version of (1) and (2), where C' is not fixed. In other words, we ultimately need to look at ways to form coalitions such that the overall throughput $R = R^d + R^p$ is maximized. In Section IV, we discussed 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 to steer our heuristic search towards a better coalition set. However, a key challenge is to make this optimization process in a decentralized manner.

A. Initializing Coalitions

The first step in the ad-hoc coalition formation process is to have the nodes find out about their neighbors and form their PCP lists. We assume that the nodes communicate with their neighbors via an Industrial, Scientific and Medical (ISM) bands, such as Bluetooth or Wi-Fi. This allows them to discover each other quickly. Then, they can scan for each other using mmWave beam scanning methods [21], [22] to make sure they are within PCP of each other. We expect this bootstrapping process to be quick and do not consider the details of it in our design.

Initially, the coalition set Ω is empty, i.e., $\Omega \leftarrow \emptyset$. However, the full detail of Ω information does not exist in one particular place. Hence, the nodes will have to act themselves to form the coalition set. Once the nodes complete their PCP lists, the nodes with PCP list size of 1 act and communicate with their PCP members. For example if node $\mathcal{N}_i$ and node $\mathcal{N}_j$ contain each other in their PCP lists, they communicate and let each other know about their PCP information. Then, they come to a joint consensus that they are both SA nodes and they create an SA-SA coalition and join set $\Omega_{\text{SA-SA}}$. However, according to our no SA-SA coalition policy, set $\Omega_{\text{SA-SA}}$ is discarded in the end.

For an SA that has a PA in its PCP list, it first asks its PA if there exists a coalition that is already formed by its PA. If yes, it joins the coalition; else, creates a new coalition with its PA. Once all SAs finish this process (which happens in parallel due to decentralized operation), no SA will be left alone. At the end of this process, all SAs and their PAs will be part of a coalition. Further, each coalition will have one PA only. We assume that the PA in a coalition will know which nodes are in its coalition and that the SAs in a coalition will know that they are part of a coalition. However, there will be isolated PA nodes because during this stage, nodes with $|\text{PCP}| > 1$ do not get added to a coalition. Let's denote the set of such outstanding PA nodes with Δ. In the next section, we will focus on designing heuristics that place these outstanding PAs in a coalition.

B. Coalition Set Formation Heuristics

We design three decentralized approaches while forming coalition sets. In the first approach, we focus on creating an all-covering coalition set. In other words, we create coalition set in an *unguided method* without necessarily guaranteeing maximization of the coalitional sum rate. This method acts as a baseline upon which we improve and enforce sum rate maximization bringing us to the second and third approaches, where we come up with our *semi-guided* and *guided* approaches respectively. The semi-guided approach also enables formation of all-covering coalition set while maximizing sum rate, and the guided approach may create a partially-covering coalition set while guaranteeing sum rate maximization.

Algorithm 1: Unguided Method (UM) - Merge Outstanding PAs to Coalition Set (Heuristic 1)

```
1: function UM(Ω, Δ)
2: for k = 1 : |Δ| do
       c = random member (RM) from PCP_k;
       if c in Ω then
           Joinable coa = coalition containing c;
           Joinable coa ← k;
       else
           Create empty coa ec = {};
           ec ← {k, c};
           Ω ← ec;
       Δ ← Δ\{k};
3:     return Ω
4: end function
```

1) Heuristic 1: Unguided Method (UM): Now, our focus is on merging the outstanding PAs given by set Δ which are left out after the bootstrapping phase. We follow an unguided,

Algorithm 2: Semi-guided Method (SM) - Merge Outstanding PAs to Coalition Set (Heuristic 2)

function SM(Ω, Δ)
  for $k = 1 : |\Delta|$ **do**
    Initialize empty list distance vector $dv = []$;
    for p in PCP_k **do**
      dist = Cartesian distance (k, p);
      $dv \leftarrow dist$;
    min_dist = min(dv);
    c = $\text{PCP}_{\text{min\_dist}}$;
    if c in Ω **then**
      Joinable coa = coalition containing c;
      Joinable coa $\leftarrow k$;
    else
      Create empty coa $ec = \{\}$;
      $ec \leftarrow \{k, c\}$;
      $\Omega \leftarrow ec$;
    $\Delta \leftarrow \Delta \backslash \{k\}$;
  return Ω
end function

Algorithm 3: Guided Method (GM) - Merge Outstanding PAs to Coalition Set (Heuristic 3)

function GM(Ω, Δ)
  for $k = 1 : |\Delta|$ **do**
    Initialize empty rate improvement vector: $riv = []$;
    Initialize empty rate vector: $rv = []$;
    Initialize empty vector: in_coa = [];
    Initialize empty vector: not_in_coa = [];
    for p in PCP_k **do**
      if p $\in \Omega$ **then**
        in_coa $\leftarrow p$;
      else
        not_in_coa $\leftarrow p$;
    for i in in_coa **do**
      potential = Ω_i;
      $R^{\text{w/o}} = R^{\text{potential}}$;
      potential $\leftarrow k$;
      $R^{\text{w}} = R_k^{\text{potential}}$;
      $R^{\text{diff}} = R^{\text{w}} - R^{\text{w/o}}$;
      $riv_i \leftarrow R^{\text{diff}}$;
    for n in not_in_coa **do**
      Create empty coa $ec = \{\}$;
      $ec \leftarrow \{k, n\}$;
      Calculate R^{ec};
      $rv_n \leftarrow R^{ec}$
    if not_in_coa $\neq \emptyset$ **then**
      if max$[rv] >$ max$[riv]$ **then**
        $\Omega \leftarrow ec^{\max[rv]}$;
      else
        $\Omega \leftarrow \Omega_k^{\max[riv]}$;
        $\Delta \leftarrow \Delta \backslash \{k\}$;
    else
      if max$[riv] > 0$ **then**
        $\Omega \leftarrow \Omega_k^{\max[riv]}$;
      else
        $\Delta \leftarrow \Delta \backslash \{k\}$;
  return Ω
end function

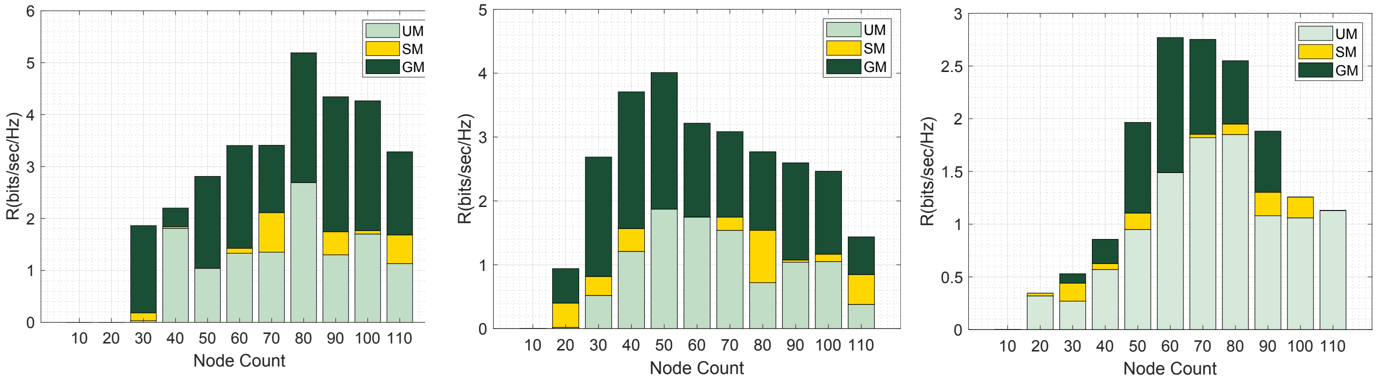
randomized method to merge these outstanding PA nodes to existing coalitions. The essence of our approach here is basically to iterate over set Δ and randomly merge each outstanding PA node with their PCP members. If the randomly chosen PCP member 'RM' of outstanding PA Δ_k already belongs to a coalition formed during the bootstrapping phase, then Δ_k gets itself merged into that coalition, else it creates a new coalition along with its chosen PCP member. This process will continue until set Δ gets exhausted. This approach, although is able to generate coalition set Ω extremely fast, it does not always guarantee the maximum coalitional sum rate R. If a very quick, robust coalition formation method is sought after with lower priority towards maximizing R, this heuristic might be a good choice. Algo. 1 details how this heuristic is simulated.

2) Heuristic 2: Semi-guided Method (SM): Our next fast heuristic method to merge the outstanding PA nodes in set Δ is a semi-guided approach where nodes assume that joining a closeby coalition is beneficial as it would allow establishment of high SNR links. The differentiating factor from heuristic 1 is that this time, instead of randomly choosing the PCP members for every outstanding PA node in set Δ, the PA nodes merge themselves with their closest PCP members. In Algo. 2, we detail the semi-guided method in a simulation. Like heuristic 1, after bootstrapping, each member of Δ iterates over their PCP members and append the Cartesian distances between themselves and their PCP members to the *distance vector* list. Then, they choose the PCP members that are closest to them. Now, if the outstanding PAs find that their chosen members already belong to a coalition, then they add themselves to that coalition. Otherwise, they form a new coalition with their PCP member and join set Ω.

3) Heuristic 3: Guided Method (GM): In this heuristic, the outstanding PAs go through a more rigorous merging process to create the final coalition set Ω. The details are presented in Algo. 3. Every outstanding PA node initializes four empty vectors: 1. rate improvement vector riv, 2. rate vector rv, 3. in_coa, and 4. not_in_coa. As before, after the bootstrapping, each outstanding PA node k starts iterating over its PCP members. It checks which of those PCP members are already part of a coalition and places them in the list in_coa, which is local to the PA node k. Those that are not part of a coalition, are placed into the list not_in_coa. For those nodes that are in in_coa, k communicates with the PA of the coalition that it wishes to join (because that coalition contains its PCP member) and asks about its current sum rate R. It stores this value in variable $R^{\text{w/o}}$. On a trial basis, it temporarily merges itself with that coalition and computes the new coalitional R including itself and stores this value in variable R^{w}. Then, it computes $R^{\text{w/o}} - R^{\text{w}}$ and stores the difference in vector riv. For those nodes that are in list not_in_coa, k adds itself in a temporary coalition and

Parameter	Value
W	1 GHz
N_0	-110dBm [16]
α	2
HPBW	15°
Γ_i	$[0^\circ, 360^\circ]$

Table III: Sim. Parameters



(a) FOV = 50° **(b) FOV = 70°** **(c) FOV = 90°**

Figure 5: R attained by Unguided, Semi-Guided and Guided heuristics

calculates R and stores the value in vector rv. These processes are repeated for all members in the vectors rv and riv. The vector riv now contains differences and the values can be negative (since the R^{w} can be less than $R^{\text{w/o}}$) whereas the minimum possible value within vector rv can be 0 (since R of a coalition in the absolute worst case is 0). It might happen that for k, all of its PCP members are part of Ω. In that case, vector not_in_coa is empty. Then k looks at its riv and chooses the corresponding PCP member that, when joined, would yield a better coalitional R. In other words, k joining that coalition would prove beneficial for the entire coalition set Ω. It must be noted here that the values within riv could be negative signifying k will steer away from joining those coalitions that yield a worse R.

An interesting case is when the outstanding PA k is detrimental to all coalitions it can join to. If all values within riv are negative, that signifies k is unable to improve the R for any coalition it wishes to join and altruistically removes itself from the entire process. On the other hand, if vector not_in_coa is not empty, then k compares maximum value of rv with that of riv and if the former is greater, then k proceeds with adding itself with its PCP member, and creating a new coalition. Otherwise, it joins with its PCP member that is already part of a coalition. This process continues until set Δ gets exhausted.

In this heuristic, each outstanding PA node is sensitive to the state of Ω in terms of overall R and selflessly acts in favor of the greater good by removing itself from the system if it sees that it causes more harm by joining the system. Hence, this heuristic may create a partially-covering coalition set that maximizes overall R but results in some PA nodes to be alone.

VI. Simulation Results and Discussion

In this section, we have presented and discussed various coalition formation and sum rate related results. The simulation parameters are as in Table III. Each simulation run is repeated three to ten times, with randomly scattered directional radio nodes, enclosed within a fixed geographical area, from which coalitional sets are generated. 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. The heuristics are evaluated for dense (20×20 m^2) networks. The transmit power of the overall coalition set is capped 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. 5 shows how the sum rate R in bits/sec/Hz varies w.r.t. network density (in terms of node count) and FOV using the proposed power allocation scheme. Heuristic UM (denoted by light green bars) attains a peak in R (e.g., at 80 nodes for FOVs 50°). For nodes fewer than 80, R is lower and for very few node count like 10 or 20, there are not enough nodes to form coalition set. The overall plot has a ‘hump’-like structure because after node count of 80, the node density becomes too high and individual nodes within a coalition end up receiving more interference from others and that results in lower R. Similar trend is noticeable across the board in Figs. 5b and 5c. It must be noted here that the maximum R achievable for the latter two cases are lower than that of Fig. 5a. This is because of higher FOV values (signifying a wider ‘eye’ for every node which means every node can see more nodes outside of its PCP list and is susceptible to more interference), which in turn invites more interference for each node in the system. Overall, in general, we can say that limiting the area of node deployment helps us in observing these peaks in R.

Heuristic SM (in golden bars) on top of heuristic UM for FOV values 50°, 70° and 90° in Figs. 5a, 5b and 5c show the improvement that we can expect when we switch to semi-guided method. As described in section V-B2, the outstanding PA nodes are more careful in choosing their PCP members while merging to Ω. The overall trends for all three FOV values are preserved. In the same figure, using deep green bars representing R attained by GM on top of SM, we show the attainable R for the three FOV values and same node densities. From these deep green bar plots we can see that the overall attainable R in general is much higher than those attainable by the prior heuristics. This is because the heuristic GM, in terms of overall coalitional R is much more strict in terms of outstanding PA nodes merging themselves to set Ω, as discussed in section V-B3. The gains are clearly visible in terms of peaks in each of the FOV values when compared to other heuristics. For FOV value 90° in Fig. 5c, we see very minor improvement for node count 100 and 110 using GM. This is because for such FOV value and high node density, GM provides negligible improvement. In general, for higher FOV values like 70° and 90° we observe that R tapers off faster than lower FOV values like 50°. This is because as we increase the node count, higher FOV values result in higher interference within coalitions.

VII. Conclusion and Future Work

For ultra-high speed 5G-and-beyond communication mmWave antenna equipped radios are becoming a necessity. The keys to designing a successful 5G-and-beyond infrastructure are proper resource allocation and throughput management systems. In this piece of work, mmWave directional nodes are characterized into SAs and PAs and we have used this characterization to present an extensive all-covering as well as partially-covering coalition set formation. Using the SA and PA categorization of nodes, decentralized, fast, robust and novel heuristics are designed and are shown to have proven beneficial for maximizing the sum rate of coalition set. We studied the trade-off between guaranteeing placement of all nodes in a coalition (i.e., all-covering coalition set) and maximizing the sum rate of the coalition set. For networks with too few or too many nodes, the trade-off did not show to be strong; while for networks with mediocre number of nodes, the relaxation of the requirement of covering all nodes showed significant benefits in terms of sum rate.

In the future, we aim at extending our decentralized heuristics approach by exploring additional methods of transmission scheduling and bandwidth allocation schemes. Here, we focused on the sum rate of the coalition set, however, it will be interesting to study the fairness among coalitions in terms of achievable data rate. Another key aspect is the inter-coalition transmission rate. In our work, we did not consider data transmissions among coalitions. Incorporating the inter-coalition data rate to the sum rate will assure full end-to-end connectivity among all nodes regardless of which coalition they belong to. More research is needed in this direction. Finally, introducing adversarial presence to the coalition set and understanding node mobility will be interesting directions to take.

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