SynergyWave: Bandwidth Splitting and Power Control in Integrated Access and Backhaul Networks

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***Abstract*—Integrated Access and Backhaul (IAB) networking paradigm and the use of mm-wave technology have emerged as key enablers for the deployment of B5G/6G systems. In this paper we introduce the SynergyWave framework that empowers the IAB nodes and the users to independently optimize their transmission power levels, while simultaneously the IAB nodes perform optimal bandwidth splitting across the access and backhaul links. The key objective of SynergyWave framework is the enhancement of the energy efficiency of each participating entity in a decentralized and autonomous manner. Exploiting the channel modeling framework established by the 3rd Generation Partnership Project (3GPP) for mm-wave networks, we initially model the achievable data rate for both the access and backhaul links in the IAB network. Subsequently, a two-stage energy efficiency optimization problem is formulated and treated based on a Stackelberg game theoretic approach. In particular, it models and optimizes resource allocation in mm-wave IAB networks, determining optimal bandwidth splitting and uplink transmission power levels for IAB nodes and their users. The SynergyWave framework is assessed via modeling and simulation, and the obtained numerical results demonstrate that substantial energy efficiency improvements can be achieved for both users and IAB nodes.**

***Index Terms*—Bandwidth Splitting, Power Control, mm-wave communications, Integrated Access and Backhaul, Game Theory.**

I. Introduction

The emergence of 6G mm-wave communications promises unprecedented data rates, minimal latency, and extensive device connectivity [1]. Within the 5G/B5G era, Integrated Access and Backhaul (IAB) technology is vital for optimizing network performance by integrating access and backhaul functions [2]. Although significant research efforts have enhanced resource management in mm-wave IAB networks [3], the simultaneous bandwidth splitting and power control challenge remains unaddressed. This paper introduces the SynergyWave framework, rooted in Game Theory, enabling IAB nodes and users to independently optimize bandwidth allocation and transmission power levels. SynergyWave enhances energy efficiency for both IAB nodes and users, offering promising solutions for efficient resource management in the era of 6G mm-wave communications.

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A. Related Work

Several recent research works have been focused on the problem of resource management in IAB-enabled 6G networks. The problem of meeting ultra-reliability and low latency requirements in IAB networks is addressed in [4] based on a cross-layer design involving routing and resource allocation. In particular a reinforcement learning framework with an entropy-based algorithm and federated learning is presented to enhance performance, reduce latency, and improve convergence speed compared to baseline algorithms. The authors in [5] present an analytical framework for IAB networks, demonstrating that offloading users from macro base stations to small cell base stations (SBS) may not yield similar rate improvements as in traditional heterogeneous networks with fiber-backhauled small cells, due to wireless backhaul link limitations between macro and small cell base stations. The challenge of efficient backhauling for densely deployed SBS by utilizing mmWaves and renewable energy sources is discussed in [6]. Specifically, the authors introduce a mathematical optimization problem and a heuristic algorithm to optimize the user association, dynamic sleeping, backhauling, and transmission power.

The problem of optimizing energy efficiency in mm-wave IAB networks has attracted significant academic and industrial interest, aiming to achieve an optimal balance between the high data rates delivered and the energy consumption of both users and IAB nodes [7]. An energy-efficient beamforming design for a full-duplex IAB network is studied in [8], where simultaneous transmission and reception occur on the same frequency band. The authors formulate an optimization problem to maximize network energy efficiency, addressing the self-interference cancellation at full-duplex access points, and propose an iterative algorithm that outperforms existing energy efficiency optimization approaches applied in traditional multi-hop wireless networks. An adaptive backhaul topology for small cell networks, utilizing millimeter-wave bands and dynamic changes based on graph theory to han-

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dle fluctuating network traffic efficiently is proposed in [9]. Additionally, the authors introduce a dynamic optimization model for uplink/downlink decoupled non-orthogonal multiple access (NOMA) heterogeneous networks that optimizes the user association and power usage, demonstrating significant improvements in network throughput, energy efficiency, and user satisfaction compared to static architectures. The challenge of providing high-capacity backhaul solutions for ultra-dense mobile networks, focusing on the IAB technology is addressed in [10], based on a semi-centralized resource allocation scheme. The proposed scheme utilizes a modified Maximum Weighted Matching problem on an IAB network's spanning tree, demonstrating significant improvements in cell-edge user throughput, energy efficiency, and network congestion reduction compared to existing distributed approaches in 3GPP-compliant simulations.

B. Contributions and Outline

Despite prior research works in enhancing the energy efficiency of mm-wave IAB networks, the predominant approaches have leaned toward centralized or semi-centralized methods, resulting in significant signaling overhead for the network. Furthermore, existing studies have primarily tackled fragmented optimization challenges, such as user association, power control, and rate maximization [11], [12]. Consequently, the challenge of formulating optimal bandwidth allocation schemes for both access and backhaul links, alongside power management for both IAB nodes and the users to maximize their energy efficiency, while maintaining a distributed framework, remains an open research challenge.

This paper aims to comprehensively address these issues and fill the aforementioned research gap. The proposed SynergyWave framework empowers the IAB nodes and the users to independently optimize their transmission power levels, and facilitates the IAB nodes in achieving optimal bandwidth splitting across the access and backhaul links, thereby optimizing the energy efficiency of each participating entity in a decentralized and autonomous manner.

This research work stands out from the existing literature due to its distinct contributions, which are outlined below.

1) An analysis of a mm-wave IAB network is performed using the channel modeling framework established by the 3rd Generation Partnership Project (3GPP) [13]. The objective of this analysis is to derive the achieved data rates in both the access and backhaul links, which in turn enables the derivation of the energy efficiency formulas for the users (at the access link), as well as for the IAB nodes (at the backhaul link).
2) Subsequently, we introduce the SynergyWave framework, that treats a two-stage energy efficiency optimization problem aiming at comprehensively modeling and optimizing resource allocation in a mm-wave IAB network architecture. This formulation encompasses the determination of the optimal bandwidth splitting factor for partitioning the available bandwidth between the access and backhaul links, in addition to optimizing the uplink transmission power levels for both the IAB nodes and the users served by these IAB nodes. The solution to this joint resource orchestration problem is achieved through the application of a Stackelberg game-theoretic approach.
3) An assessment of the SynergyWave framework is performed via modeling and simulation in order to present the performance enhancements achieved in the energy efficiency of both the users and the IAB nodes in the mm-wave IAB network. These improvements are attributed to the synergistic utilization of the meticulous channel modeling, the mm-wave communication technology, and the integration of the IAB network architecture.

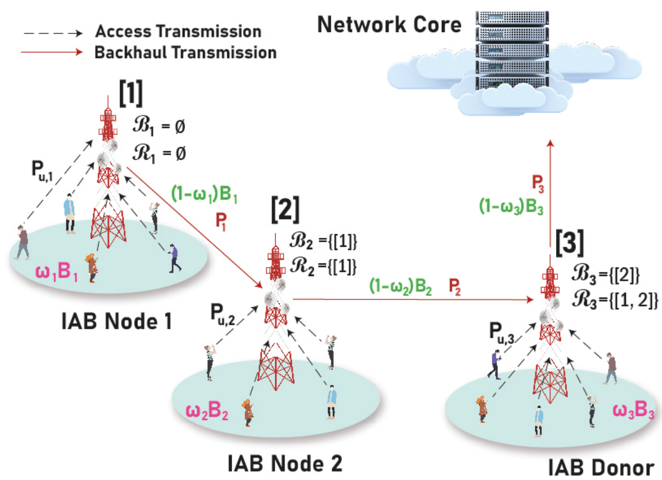

Fig. 1: Overview of the SynergyWave framework.

The rest of the paper is organized as follows. The system model is presented in Section II, while the SynergyWave framework is analyzed in Section III. Section IV presents the performance evaluation of the proposed approach and Section V concludes the paper.

II. System Model

We consider a mm-wave IAB network with a set of gNBs acting as the IAB nodes, as presented in Fig. 1. We define the set of IAB nodes as $\mathcal{N} = \{1, \ldots, n, \ldots, |\mathcal{N}|\}$, where each one of them serves the uplink communication of a set of users denoted by $\mathcal{U}_n = \{1, \ldots, u_n, \ldots, |\mathcal{U}_n|\}$ within the IAB node's n coverage area. It is noted that in the rest of the analysis the notation n will be used interchangeably to denote the IAB node n and the corresponding access network that the IAB node n serves. Given the support for multi-hop backhaul within the 3GPP standard [14], our study examines the collaborative functionality of each gNB, acting as an IAB node. The IAB nodes collaborate to gather data from their respective users at the access network and forward the collected data via the backhaul link to the core network via the IAB donor (see Fig. 1). Specifically, in this research work, this transmission occurs over a wireless multi-hop backhaul infrastructure following a predetermined route within the IAB network.

A. Path Loss Model

To determine the stochastic path loss between any user u_n and the corresponding IAB node n serving the user u_n residing in the IAB node's coverage area, we resort to the channel model developed by 3GPP [13] to account for both the path losses occurring from the Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) signal components. The LoS and NLoS path losses, denoted by PL^{LoS}_{n,u_n} [dB] and PL^{NLoS}_{n,u_n} [dB], respectively, between a user u_n and its corresponding IAB node n located at a 2D and 3D distance of d^{2D}_{n,u_n} and d^{3D}_{n,u_n}, respectively, from the user u_n are given by,

$$PL^{LoS}_{n,u_n}[dB] = \begin{cases} PL_1, & \text{if } 10m \le d^{2D}_{n,u_n} \le d_{BP} \\ PL_2, & \text{if } d_{BP} < d^{2D}_{n,u_n} \le 5km \end{cases} \quad (1a)$$

$$\begin{aligned} PL^{NLoS}_{n,u_n}[dB] = \max(&PL^{LoS}_{n,u_n}, 13.54 + 39.08\log_{10}(d^{3D}_{n,u_n}) \\ &+20\log_{10}(f_c) - 0.6(h_{u_n} - 1.5)) \end{aligned} \quad (1b)$$

where, $PL_1 = 28 + 22\log_{10}(d^{3D}_{n,u_n}) + 20\log_{10}(f_c)$ and $PL_2 = 28 + 40\log_{10}(d^{3D}_{n,u_n}) + 20\log_{10}(f_c) - 9\log_{10}[d^2_{BP} + (h_{gNB} - h_{u_n})^2]$, where, h_{gNB} is the height of the IAB node in meters with an effective height of $h'_{gNB} = h_{gNB} - h_E$, h_{u_n} is the height of the user u_n in meters with an effective height of $h'_{u_n} = h_{u_n} - h_E$ with $h_E = 1m$ if $h_{u_n} < 13m$, f_c is the center frequency, and $d_{BP} = \frac{4h'_{gNB}h'_{u_n}f_c}{c}$, where c [m/s] denotes the speed of light.

The resulting path loss is calculated as, $PL^{Tot}_{n,u_n} = Pr^{LoS}_{n,u_n}PL^{LoS}_{n,u_n} + (1 - Pr^{LoS}_{n,u_n})PL^{NLoS}_{n,u_n}$, Pr^{LoS}_{n,u_n} is the probability of experiencing LoS communication, defined as follows:

$$Pr^{LOS}_{n,u_n} = \begin{cases} 1, & \text{if } d^{2D}_{n,u_n} \le 18m \\ [(\frac{18}{d^{2D}_{n,u_n}} + e^{-\frac{d^{2D}_{n,u_n}}{63}}(1 - \frac{18}{d^{2D}_{n,u_n}}))(1 + C'(h_{u_n}) & \\ \times \frac{5}{4}(\frac{d^{2D}_{n,u_n}}{100})^3 e^{-\frac{d^{2D}_{n,u_n}}{150}})], & \text{if } 18m < d^{2D}_{n,u_n} \end{cases} \quad (2)$$

where $C'(h_{u_n}) = 0$ if $h_{u_n} \le 13m$, or, $C'(h_{u_n}) = \frac{h_{u_n} - 13}{10}^{1.5}$ if $13m < h_{u_n} \le 23m$.

B. Channel and Communication Model

Let us denote the total available bandwidth for IAB node n as B_n, which is divided in a ratio denoted as $\omega_n B_n$ for the access link, and $(1 - \omega_n)B_n$ for the backhaul link, communicating with the next IAB node or with the IAB donor, as depicted in Fig. 1. Assuming an ordered arrangement of users' channel gains denoted as $g_{u_n} = \frac{1}{10^{\frac{PL^{Tot}_{n,u_n}}{10}}}$, where $g_1 \le \cdots \le g_{u_n} \le \cdots \le g_{|\mathcal{U}_n|}$, the uplink data transmission from multiple users to the IAB node can be efficiently multiplexed by incorporating the principles of Non-Orthogonal Multiple Access (NOMA) and Successive Interference Cancellation (SIC) technique implemented at the receiver. The resulting achieved data rate $R^{AC}_{u_n}$ at the access link is [15]:

$$R^{AC}_{u_n} = \omega_n B_n \log_2(1 + \frac{g_{u_n}P_{u_n}}{\sum_{u'_n=1}^{u_n-1} g_{u'_n}P_{u'_n} + \omega_n B_n N_0}) \quad [bps] \quad (3)$$

while the corresponding data rate of the IAB node n at the backhaul link is derived as follows [16]:

$$R^{BH}_n = (1 - \omega_n)B_n \log_2(1 + \frac{g_n P_n}{(1 - \omega_n)B_n N_0}) \quad [bps] \quad (4)$$

where P_{u_n} [W] and P_n [W] are the uplink transmission powers of user u_n and IAB node n, respectively, g_n is the channel gain of IAB node n with its next hop IAB node at the backhaul link, and N_0 is the Additive White Gaussian Noise (AWGN) with zero mean [17].

The IAB node n receives data both from the users belonging to its access network, as well as from other IAB nodes $n' \in \mathcal{B}_n$ that are utilizing the IAB node n as a relay to ultimately forward their data to the IAB donor in a wireless manner (refer to Fig. 1). The set $\mathcal{B}_n$ represents the IAB nodes forwarding their data to the IAB node n to ultimately communicate with the IAB donor. Thus, by following the principles of proportional fairness, the achieved data rate of a user $u_n \in \mathcal{U}_n$ or any backhaul connection from IAB node $n' \in \mathcal{B}_n$, is given as follows:

$$R^{BH}_k = \frac{R_k}{\sum_{u_n=1}^{|\mathcal{U}_n|} R^{AC}_{u_n} + \sum_{\forall n' \in \mathcal{B}_n} R^{BH}_{n'}} R^{BH}_n \quad [bps] \quad (5)$$

where $R_k, \forall k \in \mathcal{U}_n \cup \mathcal{B}_n$ indicates the rate at which the data are received at the IAB node n, i.e., $R_k = R^{AC}_{u_n}$ for any access user $u_n \in \mathcal{U}_n$ or $R_k = R^{BH}_{n'}$ for any IAB node $n' \in \mathcal{B}_n$ forwarding its data through the IAB node n.

III. SynergyWave Framework

In this section, we introduce the SynergyWave framework, which addresses a two-stage optimization problem towards enhancing the energy efficiency in mm-wave IAB networks. The proposed framework provides a comprehensive way of optimizing the allocation of resources, i.e., bandwidth and transmission power, within the network, by determining the optimal splitting of the available bandwidth between the access and the backhaul links, while simultaneously optimizing the uplink transmission power levels for both the IAB nodes and the users (Section III-A). The solution to this integrated resource management problem is achieved through the application of a game-theoretic approach, and in particular by employing a Stackelberg game framework (Section III-B).

A. Problem Formulation

Functioning as an IAB node responsible for forwarding user data towards the IAB donor, it is critical for each IAB node to calculate the optimal bandwidth splitting parameter ω^*_n and the optimal transmission power P^*_n while considering the uplink transmission power of the users $u_n \in \mathcal{U}_n$ and any incoming connections from other IAB nodes $n' \in \mathcal{B}_n$. This is important to guarantee that each IAB node operates in the most energy-efficient manner. The corresponding problem, seeking to maximize energy efficiency, formulated and solved independently by each IAB node n, is expressed as follows:

$$\max_{\omega_n, P_n} EE_n = \frac{R_n^{BH}}{P_n + \sum\limits_{\forall n' \in \mathcal{B}_n} P_{n'} + \sum\limits_{\forall u_n} P_{u_n}} \tag{6a}$$

$$s.t. \quad 0 \leq \omega_n \leq 1 \tag{6b}$$

$$0 < P_n \leq P_n^{max} \tag{6c}$$

$$R_n^{BH} \geq |\mathcal{U}_n| * R^{min} + \sum_{\forall n' \in \mathcal{R}_n} |\mathcal{U}_{n'}| * R^{min} \tag{6d}$$

where $\mathcal{R}_n$ is a set of IAB nodes n' that have the IAB node n in their routing table to reach the network core, where $\mathcal{B}_n \subseteq \mathcal{R}_n$, $P_n^{max}[W]$ is the maximum transmission power of the IAB node and R^{min} is the minimum data rate required to satisfy specific constraints for a given requested service scenario. The physical meaning of the constraints of the optimization problem in Eq. 6a – 6d are as follows. Eq. 6b provides the feasible range of splitting factors (i.e., ω_n), Eq. 6c provides the feasible transmission power range of the IAB node n, and Eq. 6d provides the assurance of satisfying the users' end-to-end data rate Quality of Service (QoS) requirement.

Having determined the optimal bandwidth splitting factor and the transmission power of each IAB node n, the users residing in the IAB node's coverage area n begin, in a distributive manner, the process of optimizing their own energy efficiency by strategically setting their uplink transmission power, given the optimal bandwidth splitting factor ω_n^*, the optimal IAB node transmission power P_n^*, and the uplink transmission power of all the other users being served by the same IAB node n denoted by the vector $\mathbf{P}_{-u_n} = [P_1, \ldots, P_{u_n-1}, P_{u_n+1}, \ldots, P_{|\mathcal{U}_n|}]$. The distributed energy efficiency optimization problem of the users in the access network of each IAB node n is formulated as follows:

$$\max_{P_{u_n}} EE_{u_n}(P_{u_n}, \mathbf{P}_{-u_n}) = \frac{R_{u_n}^{AC}}{P_{u_n} + P_c} \tag{7a}$$

$$s.t. \quad 0 < P_{u_n} \leq P_{u_n}^{max} \tag{7b}$$

$$R_{u_n}^{AC} \geq R^{min} \tag{7c}$$

where $P_c[W]$ denotes the power consumed by the communication module, which we refer to as the circuit power. Eq. 7b captures the feasible uplink transmission power range of user u_n, and Eq. 7c reassures the satisfaction of the user's data rate constraint.

B. Problem Solution

The joint resource optimization problems in Eq. 6a – 6d and Eq. 7a – 7c are addressed in a game-theoretic approach in the form of a Stackelberg game, where, the IAB node n, having control over the bandwidth allocation, acts as the leader and optimizes its own energy efficiency, while the users being served by the IAB node n optimize their own energy efficiency by participating in a non-cooperative game among each other. Toward solving the Stackelberg game to determine the equilibrium point, we first analyze the nature of the optimization problems as follows.

Lemma 1: The IAB node's energy efficiency function given by Eq. 6a is strictly quasi-concave with respect to the IAB node's n transmission power P_n.

Proof: For any function $f : \mathbb{R}^n \to \mathbb{R}$, it qualifies as strictly quasi-concave if, for all values of λ, its sublevel set $S_\lambda = \{\mathbf{x} | \mathbf{x} \in dom f, f(\mathbf{x}) \geq \lambda\}$ is strictly convex. Here, $\mathbf{x}$ denotes the vector of relevant variables [18]. Applying this concept to the energy efficiency function of the IAB node, expressed as Eq. 6a, we find that its sublevel set S_λ can be represented as $S_\lambda = \{P_n | P_n \in dom EE_n, \frac{g(P_n)}{P_n+b} \geq \lambda\}$, where $g(P_n) = R_n^{BH}$ (a concave function with respect to P_n), and b is a constant greater than zero, defined as $b = \sum\limits_{\forall u_n \in \mathcal{U}_n} P_{u_n} + \sum\limits_{\forall n' \in \mathcal{B}_n} P_{n'}$. Consequently, when $\lambda \leq 0$, S_λ exhibits convexity on P_n. However, for $\lambda > 0$, S_λ can be expressed as $S_\lambda = \{P_n | P_n \in dom EE_n, \lambda(P_n+b) - g(P_n) \leq 0\}$, where $\lambda(P_n+b)$ increases linearly with respect to P_n due to the constants λ and b, and the linearity of P_n+b in terms of P_n. Additionally, the function $-g(P_n)$ is strictly convex with respect to P_n as $g(P_n)$ is strictly concave with respect to P_n. Hence, it follows that the sublevel set S_λ is strictly convex. This establishes the proof that the energy efficiency function EE_n of IAB node n, involving its transmit power P_n, is quasi-concave. ■

Lemma 2: The constraints of the energy efficiency optimization problem for each IAB node n, as represented by equations 6b through 6d, collectively define a compact and convex set.

Proof: Towards proving Lemma 2, we show that the constraints in Eq. 6b – 6d form a closed and bounded, and convex set. Eq. 6b generally forms a closed and bounded set, i.e., a compact set. To analyze the rest of the constraints (Eq. 6c – 6d, we consider the following functions:

$$h_1 = P_n - P_n^{max} \tag{8a}$$

$$h_2 = (|\mathcal{U}_n| + \sum_{\forall n' \in \mathcal{R}_n} |\mathcal{U}_{n'}|) R^{min} - R_n^{BH} \tag{8b}$$

The function h_1 is evidently convex with respect to P_n, and h_2 also exhibits convexity with respect to P_n given that the channel gain g_n is greater than zero. Consequently, the level sets derived from these functions, generally defined as $S_0 = \{\mathbf{x} | \mathbf{x} \in \mathrm{dom} f, f(\mathbf{x}) = 0\}$, where f represents any arbitrary function with its corresponding vector of variables $\mathbf{x}$, are convex sets. ■

Towards solving the complex double-variable quasi-concave optimization problem Eq. 6a – 6d, the optimization operation is decomposed into (i) an exhaustive search of the optimal value of ω_n over its discretized strategy space, and (ii) an optimization problem with respect to the optimal value of P_n, given the optimal splitting factor ω_n.

Moving on to the users' energy efficiency optimization, similar to the analysis of Lemma 1 and 2, it can be proven that the energy efficiency function of a user $u_n \in \mathcal{U}_n$ is also quasi-concave with respect to the user's transmission power P_{u_n}. We define the non-cooperative game among the users served by the IAB node n as $G = [\mathcal{U}_n, \{\mathcal{P}_{u_n}\}_{\forall u_n \in \mathcal{U}_n}, \{EE_{u_n}\}_{\forall u_n \in \mathcal{U}_n}]$, where $\mathcal{U}_n$ is the set of users served by the IAB node n,

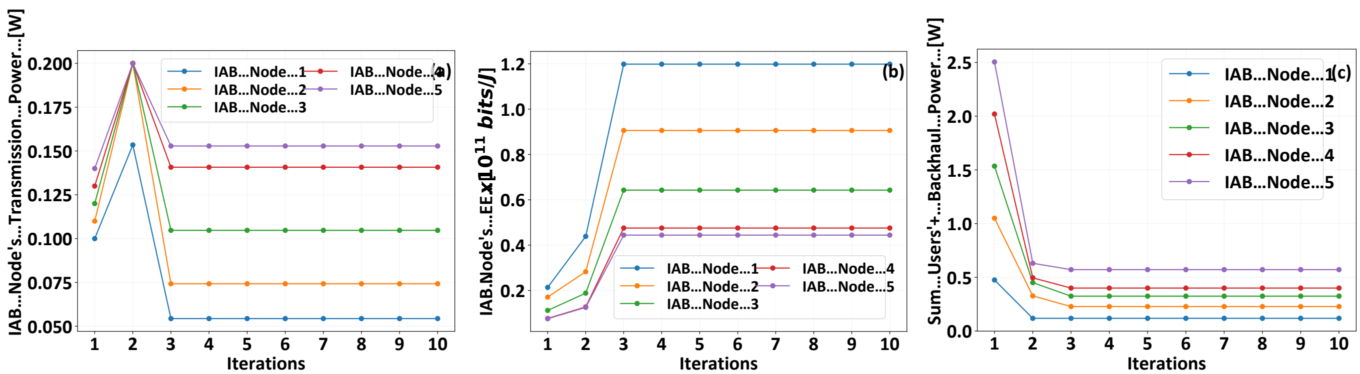

Fig. 2: IAB nodes' transmission power, energy efficiency, and total access users' and backhaul links transmission power.

$\mathcal{P}_{u_n} = [0, P_{u_n}^{max}]$ is each user's strategy set, and EE_{u_n} is each user's energy efficiency function.

Theorem 3: (**Existence of Nash Equilibrium**): The non-cooperative game G admits at least one Nash equilibrium.

Proof: Towards proving the existence of at least one Nash equilibrium, we need to show that the non-cooperative game G is a concave n-person game [19]. Thus, the necessary and sufficient conditions are: (i) the strategy set $\mathcal{P}_{u_n}$ is a convex, closed, and bounded set; the payoff function $EE_{u_n}(P_{u_n}, \mathbf{P}_{-u_n})$ is (ii) continuous in P_{u_n} and (iii) quasi-concave in $P_{u_n}, \forall u_n \in \mathcal{U}_n$. The first condition holds true following a similar analysis as Lemma 2. The second condition also holds true since the energy efficiency function of a user is continuous in the user's strategy space $\mathcal{P}_{u_n}$. Finally, the last condition also holds true following the analysis in Lemma 1 adapted to the energy efficiency equation of a user. ■

IV. Numerical Results

This section conducts a comprehensive evaluation of the proposed resource management framework's performance and efficacy, via modeling and simulation. We initially assess the pure performance of the resource allocation model (Section IV-A), followed by an analysis of its scalability considering an increasing number of users associated with each IAB node (Section IV-B). Subsequently, we provide indicative comparative results to highlight the advantages of the SynergeWave framework. It is noted that, unless otherwise explicitly specified, we consider the following set of simulation environment parameters throughout our evaluation: $|\mathcal{N}| = 5$, $|\mathcal{U}_n| = \{5, 10, 15, 20, 25\}$, $h_{gNB} = 25$ m, $h_{u_n} \in [1.5, 20]$ m, $d_{n,u_n}^{3D} \in [11, 45]$ m, $f_c = 73.5$ GHz, $P_n^{max} = 0.2$ W, $P_{u_n}^{max} = 0.1$ W, $P_c = 0.001$ W, $N_0 = 10^{-22}$, $\omega_n = [0.05, 0.1, 0.15, \ldots, 0.95]$, $B_n = 5$ GHz, $\mathcal{B}_n = [-, [1], [2], [3], [4]]$, $\mathcal{R}_n = [-, [1], [1,2], [1,2,3], [1,2,3,4]]$, where $[n]$ denotes the IAB node's ID.

A. Pure Performance Evaluation

To analyze the pure performance of the SynergyWave framework, we initially present the Stackelberg game's convergence to find the optimal resource allocation including the IAB node's optimal uplink transmission power P_n^*, bandwidth splitting factor ω_n^*, and the user's uplink transmission power $P_{u_n}^*$. Fig. 2a depicts the convergence of each IAB node's n transmission power, where it is observed that the higher the ID

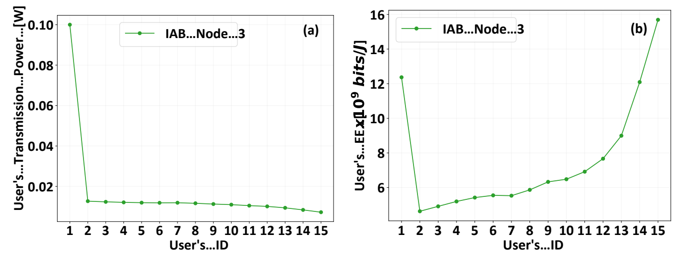

Fig. 3: Users' transmission power and energy efficiency.

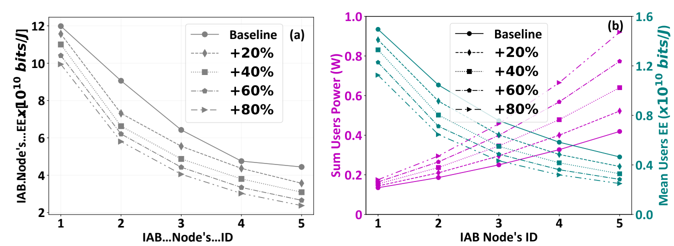

Fig. 4: Scalability analysis.

of the IAB node, the higher the transmission power, as the IAB node with a higher ID serves more users, hence, it is required to transmit with higher transmission power. Fig 2b shows the corresponding energy efficiency of each IAB node. The results reveal that higher transmission power - stemming from the higher number of served users - results in lower energy efficiency for the IAB nodes. Fig 2c depicts the sum of the users' uplink transmission power from the IAB node's access network and other IAB nodes' n' uplink transmission power to the IAB node n. It can be seen that the higher the number of users associated with an IAB node, the higher is the required transmission power of a user to combat the interference from the other users and the backhaul connection.

Moving into the microscopic analysis of the access network of each IAB node, we can see from Fig. 3a that the higher the ID of the user, the lower its uplink transmission power, since the users with higher IDs have better channel gain conditions g_{u_n}. Thus, the users with higher IDs in an IAB node's access network, achieve higher energy efficiency. Moreover, it should be noted that the user with ID #1 gains some benefit due to the application of NOMA, where the user with the lowest channel gain does not experience interference from any other user given the SIC technology applied at the receiver.

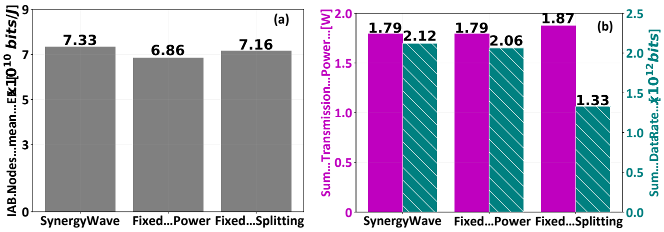

Fig. 5: Comparative analysis.

B. Scalability Analysis

A detailed scalability analysis is provided both from the access networks and backhaul links' perspective. Supported by the argument provided earlier for the continual decrease in energy efficiency with increased number of users to be served, it can be seen from Fig. 4a that a gradual step increase of 20% from the baseline scenario continually decreases the IAB energy efficiency. This is due to the fact that the increasing number of user data forces the increasing transmission power of the IAB nodes. Fig 4b demonstrates the effect of increasing the number of users in the access network performance. It is observed that the presence of more transmitting users forces the users in the access network to raise their transmission power to overcome the inherent interference from the coexistence of a large number of users associated with the same IAB node. Specifically, increasing the number of users from the baseline scenario by 80% drove the users connected to IAB node #1 to #5 to increase the users' transmission power by 30%, 58.6%, 83%, 103%, and 120%, respectively. This results in a continual decrease in the users' energy efficiency associated with the corresponding IAB node.

C. Comparative Analysis

The proposed SynergyWave framework is compared against two alternative energy efficiency maximization models in mm-wave IAB networks, where in each one of them only one optimization is applied: (i) Fixed transmission power but optimal bandwidth splitting factor, and (ii) Fixed bandwidth splitting but optimal uplink transmission power. The results reveal that optimizing both the uplink transmission power and the bandwidth splitting factor results in the highest IAB node's energy efficiency (Fig. 5a). It can also be seen that even though the total transmission power achieved in the SynergyWave framework is quite similar to the Fixed Power scenario (Fig. 5b), our framework still achieves considerably higher data rate. It is also highlighted that determining the optimal bandwidth splitting factor is critical for the network's data rate since the Fixed Bandwidth splitting scenario resulted in the worst performance in terms of achieved data rate.

V. Conclusion

In this paper, the SynergyWave framework is introduced to optimize the energy efficiency in mm-wave IAB networks, by jointly offering optimal bandwidth allocation for both access and backhaul links, and power management for both IAB nodes and the users. In particular, the SynergyWave framework introduces a two-stage optimization framework following a Stackelberg game-theoretic approach. A thorough numerical evaluation demonstrates the benefits of the SynergyWave framework compared to existing alternative energy efficiency optimization approaches. Part of our current and future work includes the investigation of the downlink connection in mm-wave IAB networks, aiming at optimizing the network's capacity in terms of the number of served users, and communication blockages which are challenging in mm-wave IAB networks.

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