Integrated Access and Backhauling with Energy Harvesting and Dynamic Sleeping in HetNets

Abdullah Alqasir*,Khalid Aldubaikhy*,Ahmed E. Kamal†
*Department of Electrical Engineering, College of Engineering, Qassim University, Qassim, Saudi Arabia
(a.alqasir,khalid)@qec.edu.sa
†Dept. of Elec. & Comp. Eng., Iowa State University (ISU), Ames, Iowa, USA
kamal@iastate.edu

***Abstract*—Due to the dense deployment of a small base station (SBS), wired backhauling is not always available, nor it is efficient. Therefore mmWaves are introduced to serve as backhauling links that offer high backhauling throughput and low CAPEX. However, mmWaves suffer from a high attenuation rate as the distance between SBSs and a macro base station (MBS) increases, which can severely degrade the system performance. Therefore, it is more efficient to use some SBSs to aggregate from different SBSs to MBS. On the other hand, densely deployed SBSs with wireless backhauling can cause high energy consumption in the system. In this work, we present a new network model in which SBSs are able to harvest energy from a renewable source and utilize it for backhauling and their associate UEs. A mathematical Optimization problem is formulated to solve UEs association, dynamic sleeping, backhauling, and transmission power. Moreover, due to the complexity of the formulated problem, a heuristic algorithm is introduced. Namely, a heuristic backhauling and dynamic sleeping (HBDS) algorithm is introduced to decomposes the formulated problem into two parts and solve it iteratively. Finally, computer simulation results that demonstrate the model's performance are presented for comparison between optimal solution and HBDS, which shows that HBDS has better computation efficiency with minimum performance difference.**

I. INTRODUCTION

In recent years, there has been increasing acknowledgment of the need for ultra-dense networks (UDNs) by utilizing SBS deployments to improve capacity gain by utilizing the enhanced area spectral efficiency of the system. However, mobile network operators face fundamental challenges, such as the operative expenditure (OPEX) and capital expenditure (CAPEX), in order to deliver the target capacity for the 5G/6G system as the tremendous growth in the SBS deployment and the need for backhauling [1], [2]. The Integrated Access and Backhaul (IAB) in the 5G/6G millimeter wave (mmWave) network can lower the OPEX and CAPEX, and the 3GPP identifies it as a practical alternative to the traditional fiber infrastructure. IAB enables wireless backhaul by utilizing mmWave spectrum to backhaul base stations while only a few of them are connected to fiber infrastructures.

Although UDN deployment is considered as one of the promising solutions in the 5G/6G to enhance capacity gain, energy consumption can be significant for mobile network operators and users [3], [4]. The energy efficiency can be decreased significantly in dense deployment scenarios because of the energy consumption of the SBSs at idle mode. Therefore, power consumption may increase the OPEX to mobile network operators, where the CAPEX can also be increased due to the cost of power wiring per SBS. Recently, different energy harvesting schemes have generated worldwide interest in the development of green communication networks. Thanks to the smart grid's continued deployments, renewable energies, such as solar and wind, can be utilized in green communication networks to increase energy efficiency [3], [5].

The literature proposes several approaches that enable the 5G/6G backhaul and access with mmWave transmission to reduce costs, interference, and complexity [1]–[7]. In [1], different topology setup strategies for realistic IAB deployment scenarios at mmWave are adopted to demonstrate the latency and overall throughput performance. In [2], an IAB approach based on mmWave frequencies is developed for SBSs, where a combination of fiber, non-line-of-sight (NLOS) microwave links, and line-of-sight (LOS) mmWave links are utilized to provide low-latency high capacity backhauling connections. In [3], a renewable energy allocation issue is studied for a cellular backhaul network to allocate and price renewable energy storage for the sake of forwarding the traffic. In [4], an integrated fiber-wireless access network with an energy conservation scheme is proposed for EPON-WLAN to minimize the total energy consumption. In [6], a spectrum allocation approach in the IAB architecture is proposed by developing a framework based on deep reinforcement learning. In [7], an IAB's energy-saving scheme is also considered to minimize energy consumption while satisfying the throughput requirements. However, the surveyed IAB schemes do not consider the energy efficiency issue, even though the energy consumption needs to be jointly considered in the UDN. Thus, energy consumption can be significant for mobile network operators. The scheme in [7] is explicitly proposed to minimize energy consumption in the IAB by formalizing an optimization problem to find the optimal power transmission. However, none of the previous works consider the potential benefits of harvesting energy from renewable sources to minimize the network's reliance on the traditional power supply.

The contribution of this paper is as follows:

1) A mathematical optimization problem is formulated to optimally solve the IAB backhauling, UEs-SBSs association, transmission power, and energy transfer.

The authors gratefully acknowledge Qassim University, represented by the Deanship of Scientific Research, on the financial support for this research under the number (10081-qec-2020-1-1-W) during the academic year 1442AH / 2020 AD"

2) A heuristic algorithm is proposed,namely HBDS, which is based on decomposing the mathematical problem into two parts: First, binary variables are solved using a modified version of Base Station Centrality (BSC). Second, continuous variables are solved by a nonlinear problem (NLP) approximation based on the mathematical optimization problem.
3) Finally, a validation and a comparison between the heuristic approach and the optimal solution are presented using computer simulation, which shows significant computation efficiency improvement.

The paper is organized as follows: Section II describes the proposed IAB and energy harvesting system model. The formulation of the optimization problem is introduced in Section III. In section IV, a decomposition of the original problem is presented with a heuristic algorithm, that shows the detailed steps for providing the solution. User association and dynamic sleeping are proposed using centrality analysis. Section V discusses the selected numerical results of the simulation. Finally, the paper is concluded in Section VI.

II. SYSTEM MODEL

In this section, we introduce a system model for HetNet with mmWave backhauling. We consider a HetNet comprised of a set of SBSs and a single MBS, denoted by $(b = 0, 1, ..., B)$ where $b = 0$ denotes MBS. The SBSs are deployed densely and can interfere with each other. Every SBSs is backhauled, using mmWave, to the MBS, which uses optical fiber technology to connect to the core network. Fig. 1 shows the topology of the network, where SBSs and UEs follow homogeneous Poisson Point Processes (PPPs) Φ_{SBS} and Φ_{UE} whose densities are λ_{SBS} and λ_{UE}, respectively. We assume that UEs and SBSs are both equipped with directional antennas that have steering capability, where beamforming is performed between UEs, SBSs, and MBS. All SBSs share the same spectrum and connect to the MBS with constrained mmWave backhaul links. The MBS is connected to the core network with fiber-optic links.

A. Model of mmWaves Backhauling Network

Let $(m = 1, ..., M)$ denotes the set of point-to-point line-of-sight backhaul links that SBSs are using to backhaul their traffic to MBS. Let z_{ij}^{m} denotes a binary indicator for backhauling links between any BSs, and equals 1 if SBS i is using this link to backhaul its data to BS j and zero otherwise and since MBS is using fiber optics for backhauling, $z_{0j}^{m} = 0$. Moreover, assume ϵ^{m} indicates the maximum capacity of link m, therefore the total aggregated rate in link m:

$$R_{ij}^{m} = \sum_{i=1}^{B}\sum_{j=1}^{B} \mathcal{W}_{ij}^{m} log_{10}(1 + SINR_{ij}^{m}) \leq \epsilon^{m} \tag{1}$$

where $\mathcal{W}_{ij}^{m}$ is the backhaul bandwidth, and $SINR_{ij}^{m}$ is the signal to interference and noise ratio. Due to the high attenuation rate in mmWaves, interference can be negligible and assume $SINR = SNR$. With:

$$SNR_{ij}^{m} = \frac{p_{ij}^{m} h_{ij}^{m}}{\mathcal{W}_{ij}^{m} N_0} \tag{2}$$

where p_{ij}^{m} is backhauling transmission power between SBS i and any BS (SBS or MBS)j using link m and h_{ij}^{m} is backhauling channel gain. The backhauling channel can be modeled by the flat-top model, which has a constant gain in the main lobe and zero gain outside. This model is an ideal case, where in practice, the main lobe gain varies, and side lobes have non zero values. However, 3GPP presented simple and practical two-dimensional directional antenna with gain $G(\theta)$ [8]:

$$G(\theta) = \begin{cases} G_{main} 10^{-\frac{3}{10}(\frac{2\theta}{\omega_{main}})} & |\theta| \leq \frac{\theta_{main}}{2} \\ G_{side} & \frac{\theta_{main}}{2} \leq |\theta| \leq \pi \end{cases} \tag{3}$$

where ω_{main} denotes half-power beamwidth, and θ_{main} is the main lobe beamwidth. G_{main} and G_{side} are the main lobe and side lobes gains, respectively. Backhauling channel gain between SBS i and any BS j is as follows [9]:

$$h_{ij}^{m} = G(\theta, i) G(\theta, j) \frac{\lambda^2 d^{-\alpha}}{d_0^3 (4\pi)^2} \tag{4}$$

where $G(\theta, i)$ and $G(\theta, j)$ represent transmit and receive directional antenna gains, respectively. d and α denote the propagation distance and the path loss exponent, respectively. λ is the wavelength, and d_0 is the free space reference distance.

B. Model of UEs Association and Achievable Rate

Let $(u = 1, 2, ...U)$ denotes mobile UEs that employ one or more of the available channels to associate with SBSs. A time slotted system with fixed duration slots $(n = 1, 2, ..., N)$ is used where UEs are considered stationary during this time.

Let $x_{ub}[n]$ be a binary indicator that is equal to 1 if UE u and SBS b are associated in n, or 0 otherwise. On the other hand, let $y_b[n]$ denotes the SBS on/off status, where it is 0 if the SBS is OFF during the time slot n and 1 if the SBS is ON, where the channel gain $h_{ub}[n]$ between UE u and SBS b is defined as follows:

$$h_{ub}[n] = \frac{\beta_0}{d_{uf}^{\alpha}[n]} \tag{5}$$

where β_0 denotes the channel gain at the reference distance of $d_0 = 1$m, and α_0 is the path loss exponent. Thus, the interference at a UE u which is associated with SBS b from all other SBSs at a time slot n will be:

$$I_{ub}[n] = \sum_{i \neq b}^{B} p_{iu}[n] h_{ui}[n], \tag{6}$$

Then, the signal to interference and noise ratio SINR for every user is:

$$SINR_{ub}[n] = \frac{p_{ub}[n] h_{ub}[n]}{I_{ub}^{c}[n] + \mathcal{W}_{ub} N_0}, \tag{7}$$

where N_0 is the channel noise spectral density, which is assumed to be Additive White Gaussian Noise AWGN, and $\mathcal{W}_{ub} N_0$ is the noise variance σ^2. Thus, the data rate for every UE u during a time slot is as follow: T

$$R_{ub}[n] = \mathcal{W}_{ub} \log(1 + SINR_{ub}[n]) \tag{8}$$

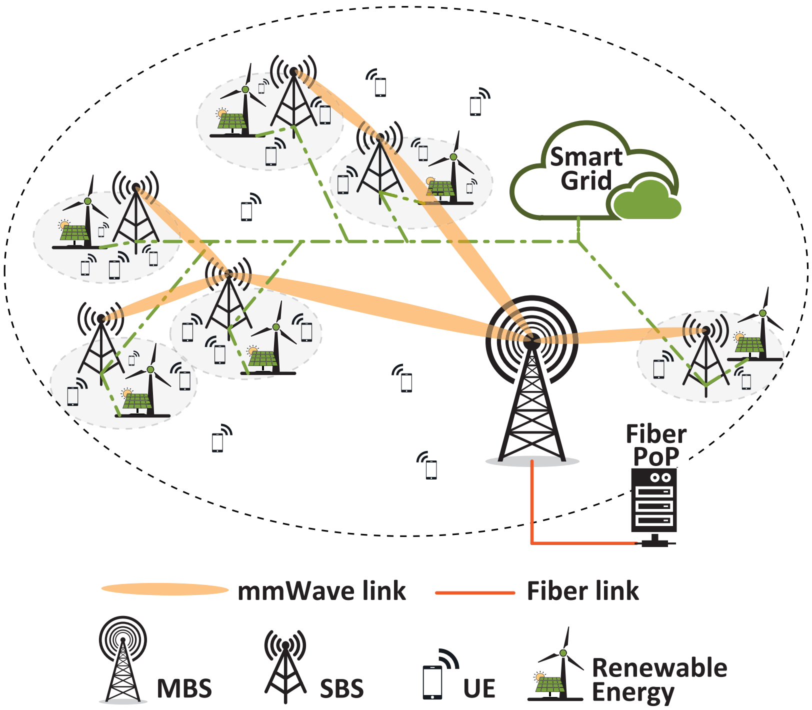

Fig. 1: A network with SBSs powered by renewable energy and connected to a smart grid.

C. Model For SBS Energy Harvesting

In this subsection, a model for energy harvesting for SBSs is presented, where every SBS is equipped with two power sources: non-renewable power from a smart grid (SG) and power from renewable sources. Renewable energy is not a reliable source since the amount of harvested energy for each SBS depends on several factors such as location, time of the day, and weather forecast. Therefore, the grid power source is utilized to work as a backup power supply if the renewable source does not provide enough power. On the other hand, there is a possibility that some SBSs harvest energy more than their requirement in a given time slot. Hence, in this section, we will model an energy harvesting model and energy transfer model using SG to transfer energy from an SBS with excessive renewable energy supply to another SBS suffering from an energy shortage. In other words, every SBS is set to use the energy from a renewable source first and then request power from the grid. However, because SG technology allows a two-way flow of power [10], it can be used here to transfer HE between SBSs.

The SBSs harvest energy from a renewable source, where the amount of HE for every SBS b and time slot n is denoted by $H_b[n]$, and it follows a normal distribution. Therefore, at the end of every time slot, an SBS will either transfer the surplus of its harvested energy or request energy from other SBSs to compensate for its deficit. If the energy surplus of the other SBSs cannot match the energy demand of the SBS with the shortage, then the SBS will request non-renewable energy from the smart grid directly.

The HE is utilized for transmission between SBS and its associated UEs and for backhauling transmission. Therefore, the transmission power between UE u and BS b during the time slot n is [11]:

$$p_{ub}[n] = p_{ub,g}[n] + p_{ub,r}[n] \tag{9}$$

where $p_{ub,g}[n]$ is the power drawn from the grid and $p_{ub,r}[n]$ is the power drawn from the renewable source including HE transferred from other SBSs.

Similar to [11], at every time slot, each SBSs will either inject its excessive harvested energy or request energy equals its energy shortage. Let $\beta_b[n]$ and $\kappa_b[n]$ denote the amount of the harvested energy SBS b is injecting into or receiving from the SG at the end of slot n, respectively. SG will provide storage for the excessive harvested energy that SBSs are injecting into the SG (however, the storage should not be actual storage; instead, SG will keep records of all injected energy and keep these records as virtual storage). Then, the amount of the harvested energy transferred into the SG equals the harvested energy drawn from the SG, where η is the transfer efficiency.

$$\sum_{b=1}^{B}\sum_{n=1}^{n}\kappa_b[i]\eta \leq \sum_{b=1}^{B}\sum_{n=1}^{n}\beta_b[i] \tag{10}$$

III. PROBLEM FORMULATION

In this section, a mathematical optimization problem is presented to minimize the energy consumption of the system model by performing the UEs association, SBSs active sleeping strategy, and backhauling association. The optimization problem will work on forcing all SBSs to first use harvested renewable energy for transmission and backhauling and then request energy from the SG. The problem will also force as many SBSs to deactivate and keep harvesting energy to transfer it to other SBSs that require more energy than it can harvest. This approach guarantees that the network employs the harvested energy first. After depleting all the harvested energy, the network will request energy from the traditional power grid to compensate for any energy shortage.

The optimization problem is presented as follows:

P1 :

$$\underset{p_{ub}[n],\kappa_b[n],\beta_b[n],y_b[n],z_{ij}^m,x_{ub}[n],p_{ij}^m}{\text{Minimize}}$$

$$\sum_{b,u,n=1}^{B,U,N} p_{ub,g}[n]\tau + \sum_{i,j,m=1}^{B,B,M} p_{ij}^m\tau + \sum_{b=1}^{B}\sum_{n=1}^{N} E_b y_b[n]$$

subject to

$$\text{C1} : R_{min} \le \sum_{b=1}^{B} R_{ub}[n] \quad \forall u, \forall n,$$

$$\text{C2} : \sum_{i=1}^{B} R_{ib}^m + \sum_{u=1}^{U} R_{ub}[n] \le \epsilon^m \quad \forall m, \forall n, \forall b,$$

$$\text{C3} : H_B[n] = \beta_b[n] + \sum_{u=1}^{U} p_{ub,r}[n]\tau \quad \forall n, \forall b$$

$$\text{C4} : \sum_{u=1}^{U} p_{ub,r}[n]\tau = \sum_{i=1}^{n} \eta\kappa_b[i] + \sum_{i=1}^{n} H_B[i] \quad \forall b, \forall n,$$

$$\text{C5} : \sum_{u=1}^{U} p_{ub}[n] \le \sum_{u=1}^{U} x_{ub}[n] P_b^{max} \quad \forall b, \forall n,$$

$$\text{C6} : \sum_{j=1}^{B}\sum_{m=1}^{M} p_{bj}^m \le \sum_{j=1}^{B}\sum_{m=1}^{M} z_{bj}^m P_b^{max} \quad \forall b,$$

$$\text{C7} : \sum_{j=1}^{B}\sum_{m=1}^{M} p_{bj}^m + \sum_{u=1}^{U} p_{ub}[n] \le y_b[n] P_b^{max} \quad \forall b, \forall n,$$

$$\text{C8} : \sum_{b=1}^{B} x_{ub}[n] \le 1 \quad \forall u, \forall n,$$

$$\text{C9} : \sum_{j=0}^{B}\sum_{m=1}^{M} z_{bj}^m = 1 \quad \forall b \ne 0,$$

$$\text{C10} : \frac{\sum_{u=1}^{U} x_{bu}[n]}{\#ofUEs} \le y_b[n] \le \sum_{u=1}^{U} x_{bu}[n], \quad \forall\, b, \forall n,$$

The optimization problem P1 is minimizing the total energy consumption by forcing lightly utilized SBSs to deactivate and implementing the harvested energy first, then using grid source power. C1 assures a quality of service QoS with minimum throughput for each UE. C2 is enforcing a cap on backhaul links where the total amount of data that is transmitted through it cannot exceed a maximum threshold ϵ^m for each m. C3 and C4 are for energy causality where transmission power from renewable source and energy injected into the grid must not exceed the total harvested energy. Constraints C5, C6 and C7 set the limit for the maximum transmission power for each SBS that is used for backhauling and data transmission to its associated UEs.Constraints C8, C9 and C10 are binary variables constraints for UEs association, backhauling and dynamic sleeping, respectively.

Problem P1 is a mixed-integer nonlinear problem (MINLP), which is an NP-hard problem and is extremely difficult to solve. Moreover, the SINR term in constraint C2 is causing the constraint to be non-convex, which increases the complexity of the problem. Therefore, a new heuristic approach is presented in the following section to present an efficient solution to the problem.

IV. PROBLEM DECOMPOSITION AND HEURISTIC APPROACH

This section presents a heuristic approach to solve problem P1. Problem P1 is decomposed into two parts: Binary variables part (UEs association, backhauling, and SBSs dynamic sleeping) and continuous variables part (transmission power and energy transfer). The binary variables are solves in two steps. First, the backhauling association variable z_{ij}^m is solved according to the best initialized SNR_{ij}^m. Second, the UEs association and dynamic sleeping are solved according to a modified version of the BSC approach [11]. The BSC is a method that assigns each SBS a value according to its position within a network, where an SBS at the center of the network, which is surrounded by many SBSs that have higher BSC value than an SBS that is at the edge of the network. BSC helps in deciding which SBS can be deactivated and which is not, since SBS that is at the middle of the network (hence, has higher BSC) is more probable on being deactivated without affecting the performance of the network than an SBS that is at the edge of the network.

The candidate solution of the binary variables from BSC, $(\bar{y}_b[n], \bar{z}_{ij}^m, \bar{x}_{ub}[n])$ is utilized to solve the following problem:

P2 :

$$\underset{p_{ub}[n],\kappa_b[n],\beta_b[n],p_{ij}^m}{\text{Minimize}} \quad \mathbb{P} =$$

$$\sum_{b,u,n=1}^{B,U,N} p_{ub,g}[n]\tau + \sum_{i,j,m=1}^{B,B,M} p_{ij}^m\tau + \sum_{b=1}^{B}\sum_{n=1}^{N} E_b \bar{y}_b[n]$$

subject to

$$\text{C1} - \text{C4},$$

$$\text{C11} : \sum_{u=1}^{U} p_{ub}[n] \le \sum_{u=1}^{U} \bar{x}_{ub}[n] P_b^{max} \quad \forall b, \forall n,$$

$$\text{C12} : \sum_{j=1}^{B}\sum_{m=1}^{M} p_{bj}^m \le \sum_{j=1}^{B}\sum_{m=1}^{M} \bar{z}_{bj}^m P_b^{max} \quad \forall b,$$

$$\text{C13} : \sum_{j=1}^{B}\sum_{m=1}^{M} p_{bj}^m + \sum_{u=1}^{U} p_{ub}[n] \le \bar{y}_b[n] P_b^{max} \quad \forall b, \forall n,$$

Problem P2 is NLP and is less complex than P1. All binary variables in P2 are treated as constants and are provided from the first step. Algorithm 1 is presenting the detailed steps for the heuristic method.

Algorithm 1 can be divided into three parts: initialization and association, backhauling, and association using BSC, and the third is evaluating the continuous variables by solving P2.

Algorithm 1 starts by randomly initializing transmission power and dynamic sleeping variables. Then, steps 4 and 5

Algorithm 1 Heuristic Backhauling and Dynamic Sleeping.

```
1: Input:$H_B[n]; h_{ub}[n]; h_{ij}^m; R_{min}; P_b^{max}; \mathcal{W}_{ub}; N_0; \epsilon^m;$
2: Initialize: $p_{ub}^{[0]}[n]; p_{ij}^{m[0]}; y_b^{[0]}; k = 0$
3: while True do
4:     Calculate $SINR_{ub}[n]$ $\forall u, \forall b$, and associate users with active BSs according to the highest SINR.
5:     Calculate $SNR_{ij}^m \quad \forall i, \forall j \in B$, and set $z_{ij}^m = 1$ for SBS $i$ and BS $j$ with the highest SNR.
6:     if $\sum_{u=1}^{U} x_{bu}[n] = 0 \quad \forall u \forall n$ then
7:         $y_b := 0 \quad \forall b$
8:     end if
9:     Utilize BSC algorithm in [11] to find $\bar{y}_b[n]$ and $\bar{x}_{ub}[n]$
10:    Solve problem 2 and the solution is: $[\bar{p}_{ub}^{[k]}[n], \bar{p}_{ij}^{m[k]}, \bar{\kappa}_b^{[k]}[n], \bar{\beta}_b^{[k]}[n]]$
11:    if $\bar{\mathbb{P}}^{[k]} \leq \bar{\mathbb{P}}^{[k-1]}$ then
12:        $\mathbb{T}^* := [\bar{p}_{ub}^{[k]}[n], \bar{p}_{ij}^{m[k]}, \bar{\kappa}_b^{[k]}[n], \bar{\beta}_b^{[k]}[n]]$
13:        $x_{ub}^*[n] := \bar{x}_{ub}^{[k]}[n]$
14:        $y_b^*[n] := \bar{y}_b^{[k]}[n]$
15:        $z_{ij}^{*m} := \bar{z}_{ij}^{[k]m}$
16:    else if problem 1 is infeasible then
17:        Go back to 9
18:    end if
19:    k:=k+1
20:    Break after calculating BSC for all SBSs.
21: end while
22: Output: $\mathbb{T}^*, y_b^*[n], x_{ub}^*[n], z_{ij}^{*m}$
```

Table I: List of used parameter values for simulation.

Parameter	Value	Parameter	Value
N	5	λ	4.10675mm
U	20	ϵ^m	50Gbps
E_B	10J	G_{side}	-2dBm. [13]
B	10	G_{main}	20dBm.
M	5	P_{max}	30dBm. [13]
R_{min}	10Mbps.	α	1.2
η	0.9	τ	1s
N_0	-174dBm/Hz	$\mathcal{W}_{ub}$	20MHz
$\mathcal{W}_{ij}^m$	5GHz.	d_0	1m

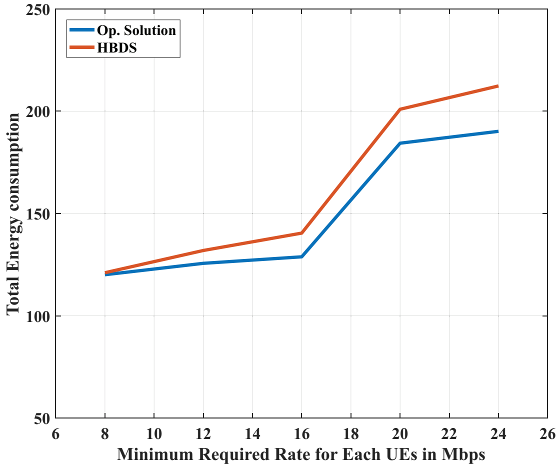

Fig. 2: A Comparison between Optimal solution and HBDS algorithm.

are to calculate SNR_{ub} and SNR_{ij}^m and associate UEs with SBS that offer the highest SINR and backhaul each SBS with BS that has the highest SNR. Steps 6 and 7 are for dynamic sleeping where each SBS with no associated UEs is deactivated and used for harvesting and backhauling. Step 9 is invoking the BSC algorithm to calculate the association and dynamic sleeping. The solution from BSC is utilized to solve P2 for the continuous variables. If the provided solution is better than the previous solution, the candidate solution is assigned as the optimal solution. If P2 is infeasible, BSC is invoked again to provide a new solution. After calculating BSC for all SBSs, $\mathbb{T}^*, y_b^*[n], x_{ub}^*[n], z_{ij}^{*m}$ will be the final optimal solution.

V. SIMULATION RESULTS

This section provides simulation results that demonstrate the performance of the system model shown in Fig. 1 to minimize energy consumption. The parameters in all simulations, unless stated otherwise, are presented on Table I.

In this simulation we consider an area of $100 \times 100 m^2$ where SBSs and UEs are distributed using homogeneous Poisson point processes. In solving the optimal problem we used used Convex Over and Under ENvelopes for Nonlinear Estimation (Couenne) which is based on branch-and-bound framework [12].

Fig. 2 investigates the performance difference between the optimal solution in P1 and algorithm 1. In this scenario, the number of SBSs is 6 with $n = 4$, and the number of UEs in the network is $u = 8$. From the figure, we can see that as the minimum required rate increases, the total energy consumption increases too. This is understandable since a higher data rate requires higher transmission power. On the other hand, the sudden increase in energy consumption (from 140 to more than 200) is caused by the increase of active SBSs (from 3 to 4) since the active SBSs could not provide the minimum required data rate. Moreover, we can see the performance difference between the optimal solution and algorithm 1 where the performance difference is less than 12%.

Table II shows the computation time required to provide results for both approaches: optimal solution form P1 and algorithm 1. As the number of SBSs increases, the computation time for the optimal solution increases exponentially until it requires more computation resources than available. On the other hand, HBDS provided reasonable performance with a linear increase in computation time as the number of SBSs increases.

In Fig. 3, we show the advantage of utilizing SBSs as aggregators for other SBSs in comparison with each SBS that uses mmWave to backhaul directly to MBS. The results show

Table II: Required Computation Time for P1 and HBDS.

# of SBSs	Optimal comp. time (in hours)	HBDS comp. time (in hours)
4	5	0.01
6	16	0.03
8	Machine resources not enough	0.12
10	Machine resources not enough	0.22

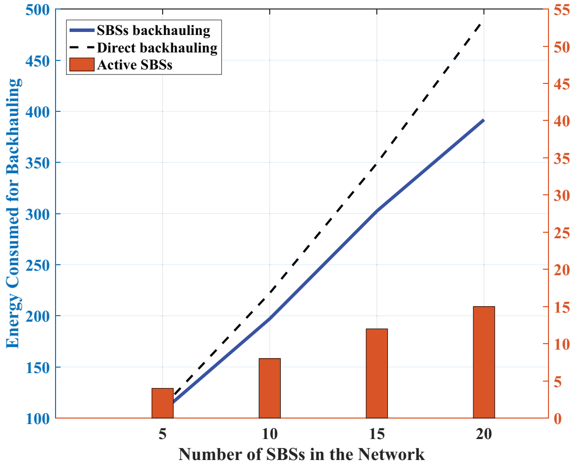

Fig. 3: The effect of the total number of SBSs on the backhauling.

significant energy saving in using aggregated backhauling in comparison with direct backhauling. Moreover, the energy-saving increases as the number of SBSs increases; this is understandable since the more the active SBSs, the more backhauling links are required, which consumes more energy.

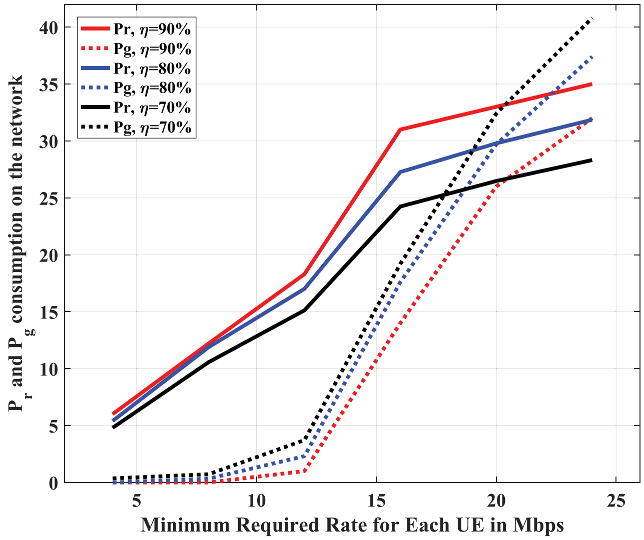

Fig. 4: The effect of increasing R_{min} on P_r and P_g.

Fig. 4 shows the minimum required rate effect on power consumption from the harvested energy, power grid, and energy transfer efficiency. For less R_{min}, algorithm 1 consumes energy for communication solely from the harvested energy and non from the grid. Further, when R_{min} increases, algorithm 1 starts requesting power from the power grid. For high R_{min}, p_r will saturate since algorithm 1 utilized all the available harvested energy, and p_g increases to support a higher data rate. Moreover, energy transfer efficiency plays an important role in minimizing energy consumption, where better η means better utilization of the harvested energy.

VI. CONCLUSION

In this work, HetNets with IAB, dynamic sleeping, and energy harvesting are investigated, where mmWave backhauling between SBSs is performed in order to minimize the total energy consumption in the network. Moreover, an optimization problem is formulated that provides UEs association, dynamic sleeping, and transmission power for the network. The optimization problem forces all SBSs to use first harvested energy for transmission and backhauling, then request energy from the SG. The problem also forces as many SBSs to deactivate and keep harvesting energy to transfer it to other SBSs. This approach guarantees that the network employs the harvested energy to its maximum before turning the power supply. However, due to the problem's complexity, a heuristic algorithm is introduced by decomposing the problem into two parts and invoking BSC to an efficient solution to the problem. Finally, computer simulation is performed to demonstrate the performance of HBDS in energy consumption and computation efficiency.

REFERENCES

[1] M. Polese, M. Giordani, T. Zugno, A. Roy, S. Goyal, D. Castor, and M. Zorzi, "Integrated access and backhaul in 5G mmWave networks: Potential and challenges," *IEEE Communications Magazine*, vol. 58, no. 3, pp. 62–68, 2020.

[2] C. Dehos, J. L. González, A. D. Domenico, D. Kténas, and L. Dussopt, "Millimeter-wave access and backhauling: the solution to the exponential data traffic increase in 5G mobile communications systems?" *IEEE Communications Magazine*, vol. 52, no. 9, pp. 88–95, 2014.

[3] D. Li, G. Zhang, Y. Xu, H. Zhao, and F. Tian, "Integrating distributed grids with green cellular backhaul: From competition to cooperation," *IEEE Access*, vol. 6, pp. 75 798–75 812, 2018.

[4] D. P. Van, B. P. Rimal, M. Maier, and L. Valcarenghi, "ECO-FiWi: An energy conservation scheme for integrated fiber-wireless access networks," *IEEE Transactions on Wireless Communications*, vol. 15, no. 6, pp. 3979–3994, 2016.

[5] N. Javaid, G. Hafeez, S. Iqbal, N. Alrajeh, M. S. Alabed, and M. Guizani, "Energy efficient integration of renewable energy sources in the smart grid for demand side management," *IEEE Access*, vol. 6, pp. 77 077–77 096, 2018.

[6] W. Lei, Y. Ye, and M. Xiao, "Deep reinforcement learning-based spectrum allocation in integrated access and backhaul networks," *IEEE Transactions on Cognitive Communications and Networking*, vol. 6, no. 3, pp. 970–979, 2020.

[7] D. Meng, X. Li, W. Pu, X. Yang, and D. Li, "An energy-saving scheme with multi-hop transmission for mmwave backhaul networks," in *2018 IEEE 87th Vehicular Technology Conference (VTC Spring)*, 2018, pp. 1–5.

[8] O. Semiari, W. Saad, M. Bennis, and B. Maham, "Caching meets millimeter wave communications for enhanced mobility management in 5G networks," *IEEE Transactions on Wireless Communications*, vol. 17, no. 2, pp. 779–793, 2018.

[9] K. Aldubaikhy, W. Wu, Q. Ye, and X. Shen, "Low-complexity user selection algorithms for multiuser transmissions in mmWave WLANs," *IEEE Transactions on Wireless Communications*, vol. 19, no. 4, pp. 2397–2410, 2020.

[10] X. Fang, S. Misra, G. Xue, and D. Yang, "Smart grid — the new and improved power grid: A survey," *IEEE Communications Surveys Tutorials*, vol. 14, no. 4, pp. 944–980, 2012.

[11] A. M. Alqasir and A. E. Kamal, "Cooperative small cell HetNets with dynamic sleeping and energy harvesting," *IEEE Transactions on Green Communications and Networking*, vol. 4, no. 3, pp. 774–782, 2020.

[12] P. Belotti, J. Lee, L. Liberti, F. Margot, and A. Wachter, "Branching and bounds tighteningtechniques for non-convex minlp," *Optimization Methods Software*, vol. 24, no. 4–5, p. 597–634, Aug. 2009. [Online]. Available: https://doi.org/10.1080/10556780903087124

[13] W. Wu, N. Zhang, N. Cheng, Y. Tang, K. Aldubaikhy, and X. Shen, "Beef up mmWave dense cellular networks with D2D-assisted cooperative edge caching," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 4, pp. 3890–3904, 2019.