Comparative Analysis of V-Band and E-Band mmWaves for Green Backhaul Solutions for 5G Ultra-Dense Networks

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***Abstract*—5G Ultra-Dense Networks (UDNs) will involve massive deployment of small cells which in turn form complex backhaul network. This backhaul network must be energy efficient for the 5G UDN network to be green. V-band and E-band mmWave technologies are among the wireless backhaul solutions tipped for 5G UDN. In this paper, we have compared the performance of the two backhaul solutions to determine which is more energy efficient for 5G UDN. We first formulated the problem to minimize power, then proposed an algorithm to solve the problem. This was then simulated using Network simulator 3. The first scenario made use of V-band mmWave while the second was E-band mmWave. The performance metrics used were power consumption and energy efficiency against the normalized hourly traffic profile. The performances of the two solutions were compared. The results revealed that E-band mmWave outperformed V-band mmWave in backhauling traffic in 5G UDN. It can be concluded that E-band green backhaul solution is recommended over V-band mmWave for 5G UDN.**

***Index Terms*—Green backhaul solutions, E-band mmWave, V-band mmWave, Ultra-Dense Networks UDNs, 5G**

I. Introduction

Number of mobile network users, devices, applications and services have been increasing exponentially and taking new dimensions. Consequently, mobile networks have evolved from generation to generation with performance improvement to meet this ever-increasing demand. Fifth Generation, 5G Network is the present network which is expected to handle 1000 times more capacity than the preceding 4G by providing data rates in the region of 100 Mbps to users and must be done with very high energy efficiency [1]. Ultra-Dense Network (UDN) is one of the scenarios in 5G expected to deliver its specifications through massive deployment of small cell networks (SCNs) [2].

Femtocells, picocells, relays, Remote Radio Head (RRH) and microcells are types of small cells to be deployed in 5G UDN [3], in order to bring the base station resources close to the users. Typically, hundreds of these SCNs are to be deployed in one square kilometre to serve over 2500 users. Interference, energy efficiency and backhauling management are some of the major challenges of 5G UDN [4], [5]. The backhauling challenge is due to large number of SCNs which needs to be backhauled to the core network. It has been stated that backhaul could be the major bottleneck for 5G UDN to deliver the expected performance. The backhaul choice must ensure that it can handle the expected data traffic without compromising the overall power consumption of the network [3], [6].

There are several backhaul technologies recommended for 5G as presented in Table I. The options can be broadly categorised into fixed and wireless. Fixed technologies have dominated the backhaul network over the years, but there are suggestions for more deployment of wireless backhaul most especially in the millimetre wave, (mmWave) region.

Microwave (7-40 GHz) will scarcely be deployed due to proof of bandwidth availability in the future and the favourable parameters it possesses in terms of low cost of deployment, suitability for access and backhaul networks, support of mesh/ring topology and the large coverage range of 5 to 30 Km. However, this paper did not study this technology in 5G UDN scenario because of the limited interference immunity [7]. This is particularly important as interference problem is associated with dense deployment in 5G UDN scenario [8].

For the two fixed networks presented in Table I, fibre-optics is better suited to 5G UDN scenario than Copper [9]. However, detailed deployment types of fibre-optics will need to be considered in determining how suitable it is to serve as green backhaul solution for 5G UDN. This is part of our future research as the focus of this paper is on wireless backhaul technology.

Most of the parameters in Table I suggest that Satellite technology might not be a good option for 5G backhauling [10].

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TABLE I: PROPERTIES OF POSSIBLE MOBILE BACKHAUL TECHNOLOGIES FOR 5G UDN [11]

Segment	Microwave (7-40 GHz)	V-Band (60 GHz)	E-Band (70/80 GHz)	Fibre-optic	Copper (Bonded)	Satellite
Future-Proof Available Bandwidth	Medium	*High	*High	*High	Very Low	Low
Deployment Cost	*Low	*Low	*Low	*Medium	Medium/High	High
Suitability for Heterogenous Networks	*Outdoor Cell-Site / Access Network	*Outdoor Cell-Site / Access Network	*Outdoor Cell-Site/Access Network	*Outdoor Cell-Site / Access Network	Indoor Access Network	Rural only
Supporting for Mesh / Ring Topology	*Yes	*Yes	*Yes	Yes, where available	Indoors	Yes
Interference Immunity	Medium	*High	*High	*Very High	*Very High	Medium
Range (Km)	*5-30, ++	*1	*3	*<80	<15	Unlimited
Time to Deploy	Weeks	Days	Days	Months	Months	Months
License Required	Yes	*Light Licensed / Unlicensed	*Light Licensed / licensed	*No	No	No

Note - * indicates preferred choice for 5G Network

TABLE II: COMPARISON BETWEEN UDN AND THE TRADITIONAL CELLULAR NETWORK

Parameter	UDN	Traditional Cellular Network	Ref.
Deployment Scenario	Indoor, Hotspot	Wide coverage	[12]
Minimum user throughput	10 – 20 Mbps	4 Mbps	[4]
Spectrum	2×160 MHz	2×100 MHz	[4]
Spectrum band	> 3 GHz (up to mmWave)	< 3 GHz	[12]
AP Style	Small-cell, Pico, Femto, UE relay, Relay	Macro, Micro Base Station	[12]
AP backhaul	Ideal/non-ideal, Wired/ Wireless	Ideal, wired	[12]
Site/Km2	93 (Pico) 1000 (Femto)	7 (Micro) 3 -5 (Macro	[4]
Inter Site Distance ISD	112m (Pico) 10m (Femto)	Several hundred meters	[12] [4]
Subscriber Data	20 - 50 GB/month	1 GB/month	[4]
Traffic Volume Density	~ 40 Gb/s/km2	~1 Gb/s/km2	[4]
Active Users	~2500	250	[4]
User Mobility	Low	High	[12]

The two wireless technology which have suitable parameters for backhauling 5G UDN scenario are V-band and E-band mmWaves. These two technologies are the focus of this paper

Therefore, in this paper, we have investigated the performance of V-band and E-band mmWaves in serving as green backhaul solution for 5G UDN scenario.

II. LITERATURE REVIEW

The section contains the explanation of the topic concept as well as the review of related research.

A. Theoretical Background

Technical details of 5G UDN scenario and description of the millimeter wave technologies are presented here.

5G Ultra-Dense Network (UDN): This can be defined as a network in which low-power small cells (Micro, Pico and Femto cells) are massively deployed to serve large number of users [5], [12]. Table II summarizes the features of UDN compared to traditional network.

UDNs will be used in places such as offices, apartments, open-air gathering, airports, campuses and railway stations. UDN is characterised by very high density. According to [4], in UDN scenario, there will be about 2500 users per kilometre square (Km^2). This will result in high traffic density which could reach 10 megabits per seconds per metre square, ($Mbps/m^2$) [13]. In addition, 5G UDN is expected to use higher spectrum frequency and wider bandwidth [14]. UDN will be heterogenous in nature that is contains different types of network deployed, base stations and or technologies [15]. This deployment will be irregular and will require flexible, high capacity and energy efficient backhaul [16].

Possible Backhaul Solution for 5G UDN: Mobile backhaul is the transport network that connects the Radio Access Network, RAN to core network [10]. In 5G, backhaul can refer to the link between two or more 5G eNode Bs as well as the connection of these eNode Bs to the core network. Also, in UDN scenario where small cells are being used, backhaul networks include connection between the small cells, small cells to the Macro Base Station and connection between small cells to the core network.

Fibre optics and mmWave are tipped as possible technologies to be deployed in UDN scenario [17]–[20]. The investigation of mmWaves to serve as green backhaul solution for 5G UDN is the focus of this paper as the fibre optics option will be feature in our future paper.

Millimeter waves (mmWaves): There has been increased interest in mmWaves in the last decade as many see it as a promising candidate for 5G small cells in dense urban areas [21]–[24].

There are very wide channels available at this band which will enable high data rates. For instance, in the 60GHz band, the Federal Communications Commission (FCC) allocated 7GHz of spectrum from 57 GHz to 64 GHz for unlicensed use [25]. Other countries also have similar allocations in the 60GHz band, with bandwidth varying from 5GHz to 7GHz. In the 70 GHz and higher millimetre-wave bands, there is a total of 13GHz bandwidth available worldwide; that is, 71–76GHz, 81–86GHz and 92–95GHz. Backhaul links using these bands are well suited to supporting 5G due to their 10 Gbps to 25 Gbps data throughput capabilities [11].

Millimetre waves is a cheap mobile backhaul option and deployments are easily done without license or light licensing.

TABLE III: PROPERTIES OF V-BAND AND E-BAND MMWAVES

Characteristic	V-Band	E-Band
Frequency range	57 – 64 GHz	71 -76, 81-86 GHz
Licensing	Unlicensed	Licensed
Maximum Power Transmit	27 dBm	35 dBm
Maximum Antenna Gain		43 bBi
Data rate for 2GHz bandwidth	> 4 GBps	12.8 GBps
Configuration (indicative)	200 MHz	500 MHz – 2 GHz
Backhaul Capacity	1 Gbps	3 – 10 Gbps
Backhaul Latency (One way)	< 500 µs	< 50 – 100 µs
Area	Dense urban/urban	Dense urban/urban

Millimetre bands (V-band (60GHz) and E-band (70/80 GHz)) are recommended for heterogenous network backhaul because it allows for outdoor cell site and access network aggregation of traffic from several base stations, which can then be handed off to the mobile switching centres and finally the core network [10]. They are also preferred in 5G UDN due to their high interference immunity and this allow high capability of frequency reuse. These extremely high frequency signals enable the installation of many antenna elements within a small area which enable high antenna array gain. The wider channel bandwidth offered by mmWave spectrum and high directivity can provide multi-Gbps data rates. The 60Hz (V-band) and 70/80GHz (E-band) have excellent characteristics for small cell wireless backhaul, in particular for short link distances, allowing for spectrum re-use and very wide channel sizes to permit data throughputs [9]. They mostly require Line of Sight, LOS.

Atmospheric attenuation is a major issue with mmWaves because they are vulnerable to high propagation losses due to rain attenuation, oxygen or other molecular absorption. However, these environmental factors may not cause significant propagation loss when considered for short-range communications, for example, ultra-dense small-cell networks. Penetration losses is another challenge with the mmWave frequencies as they experience high penetration loss on the exterior surfaces of urban buildings whereas the penetration loss for indoor materials is relatively low [26]. Thus, the outdoor BSs in the mmWave network can hardly serve indoor users. Despite the drawbacks, the two bands are well fitted for 5G UDN scenario.

Table III summarises difference between V-Band and E-Band mmWaves. These properties are considered in the network simulation to determine which of the two bands has a better performance in serving as green backhaul solution for 5G UDN.

B. Related Work

Mowla, Ahmad, Habibi, & Viet Phung [27] proposed a green communication network for 5G in order to tackle the increase in power consumption envisaged for this network. They proposed a green communication model which considered both access and backhaul network. They formulated an analytical model used to calculate the optimum number of small cells that need to be kept active at various times of the day in order to minimize power consumption while meeting users' quality of service demands. They further presented two backhauling solutions based on Passive Optical Network (PON) and V-band mmWaves. The simulation result showed that their model can save up to 48% more power than other existing models.

Mowla *et al*. [18] tackled the problem of increase in power consumption of backhauling traffic 5G UDN. They investigated green backhauling challenge in 5G UDN using PON and mmWave backhauling to support its diverse groups of customers and applications. This approach was based on the facts that different technologies perform better under different load condition. They formulated an optimization problem which considered the estimated hourly traffic load and determined the most energy efficient backhauling strategy for various hours of the day. They also proposed an energy efficient heuristic solution to solve the complexity problem of the backhaul optimization problem formulated. Their simulation results indicated that the proposed solution provided up to 32% more energy savings than the existing solutions.

R. K. Saha [28] proposed a spectrum sharing technique of both licensed and unlicensed spectrum in 5G UDN to solve it spectral and energy efficiency problems. The scenario was a 3-dimensional (3D) multi-storey building. They used non-orthogonal spectrum sharing. The Small Cells (SCs) in each building was modelled to form 3D clusters of SCs subject to a minimum distance between co-channel SCs. This clustering was to allow multiple spectrum reuse per building. They explored Licensed Shared Access (LSA) to share the licensed space-satellite spectrum and Licensed Assisted Access (LAA) to share the 60 GHz unlicensed spectrum with SCs based on assumptions that the SCs can use multiband. They derived a system-level capacity, spectra and energy efficiency metrics. Their study was through simulation. Their result showed that the proposed non-orthogonal spectrum sharing had a better performance in terms of spectral and energy efficiency compared to orthogonal spectrum sharing and therefore recommended for 5G UDN.

Huang & Psounis [23] attempted to optimise the use of mmWaves in backhauling of 5G UDN with dense deployment of small cells, SCs. They wireless backhaul architecture of the SCs was made in cluster in which one of the SCs was made the cluster head. All the other SCs were connected to the cluster head, which was then connected to the Macro Base Station, MBS using mmWave link combined with multiple-input and multiple output (MIMO) link. They formulated the problem of jointly selecting the cluster heads and the number of BS antennas dedicated to each mmWave MIMO link between the BS and each cluster head to maximize system throughput as an integer linear program (ILP) and prove its NP-hardness. They proposed an algorithm to solve the ILP. The simulation result showed that their solution had a better performance compared to the existing solutions.

Hussein [29] worked on a dynamically controlling power-saving modes in 5G UDN in order to address the problem of increase energy demand of the network. They proposed a cooperative energy management framework for 5G UDN using graph theory. They modelled the 5G network as graph then applied graph theory method to determine the order of nodes at which power-off/on procedure is applied. They also showed that significant power savings were achievable by considering only a subset of network nodes and thus reduce traffic migration and control plane signalling. They evaluated the proposed algorithm at different network densification levels and several load factors including two real-life networks. Also, they presented the convergence of the proposed algorithm and the robustness of networks optimized using it. In their result, their proposed algorithm saves power up to 25% at full load and 65% during off-peak.

Aboagye, Ibrahim, & Ngatched [30] set out to solve the problem of extreme pathloss and unreliable transmission of mmWaves over a long distance when used as 5G heterogenous network backhaul. They also considered problem of energy efficiency in 5G UDN. They proposed a multi-hop mmWave transmission as the backhaul solution and two optimization frameworks for maximizing the EE of HetNets. Joint EE, power and flow control (JEEPF) and joint EE, power, flow and throughput (JEEPFT) were their proposed framework for maximizing energy efficiency in 5G HetNet. In JEEPF, a strict throughput requirement is enforced on all user equipment (UEs) and maximizing the network EE via the joint optimization of power and BH flows while in JEEPFT, an acceptable range of throughput requirements were allowed for each UE and maximized the network EE via the joint optimization of power, BH flows, and UEs' achievable throughputs. Their simulation result revealed that JEEPFT framework outperformed JEEPF and other existing frameworks. They attributed this to consideration of throughput in JEEPFT and concluded that throughput is an important parameter to be considered in designing an energy efficient framework for 5G HetNet.

Li *et al.* [31] recognized that tuning off Small cells, SCs in 5G UDN in order to improve it energy efficiency can cause degradation of delay performance. They therefore developed a theoretical framework for Energy-Delay Trade-off (EDT). Association probabilities of UEs and transmission probabilities of BSs were investigated. They derived expressions for energy consumption and network packet delay and used these expressions to analyse the impact of BS sleeping ratio on energy consumption and packet delay. They then formulated the EDT problem as a cost minimization problem to select the optimal set of sleeping small cells. Using the dynamic gradient iteration algorithm, they obtained a locally optimal sleeping ratio for EDT which can converge to the global optimal sleeping ratio. They further proposed queue-aware and channel-queue-aware sleeping strategies to find the optimal set of sleeping small cells according to the optimal sleeping ratio. Their simulation and numerical results showed that their proposed scheme is effective for EDT.

Dai *et al.* [32] study was to solve problem of high energy consumption and severe inter-cell interference (ICI) in 5G UDN. Their major concern was to maintain network coverage while avoiding degradation of the quality of service (QoS) of user equipment (UEs) while adopting Small cell SC on/off control to solve the problem of energy consumption and Inter Cell Interference (ICI). They formulated Energy Efficiency (EE) optimization problem in stochastic geometry-based network and took into consideration the QoS of UEs and ICI to maximize the EE. The solution to the optimization problem was obtained by dividing the problem into SCs clustering and intra-cluster SC on/off control. They used an improved K-means clustering algorithm to divide the SCs into discrete clusters based on distance and number of SCs. Each cluster had a cluster head responsible for SCs on/off control subject to the constraint of UEs minimum required data rate. They also used Heuristic Search Algorithm (HAS) for intra-cluster SC on/off control. Their simulation result showed that their proposed scheme improved the energy efficiency of 5G UDN and reduces the effect of interference.

Ajani, Oduol and Adeyemo [33] suggested in their work that V-Band mmWave might not be the best mmWave green backhaul solution for 5G UDN, thereby necessitating investigation of other band to reveal which is best in UDN scenarios. Therefore, in this research we decided to apply E-Band mmWave as green backhaul solution in order to compare it with the performance of the V-Band Solution.

While some work has been concentrated on mmWaves technologies [21], [23], [34], some on 5G UDN [3], [35]–[37] others on green backhaul solutions [6], [27], [38] there has not been any research which investigated the 2 bands of mmWaves from energy efficiency and power consumption perspective in 5G UDN and this is the gap filled in this paper.

III. RESEARCH METHOD

The section contains the explanation of how the research was conducted including the simulation scenarios, parameters and performance metrics.

A. 5G UDN Model

The specific objective here is to develop a mathematical optimization problem to make UDNs most energy efficient without losing the expected Quality of Service (QoS) Requirement.

The following sets of notations has been adopted in this paper:

Q as set of *Q* for a 5G multi-tier heterogenous network, index *q*.

J as set of *J* SCN base stations, index *j*.

T as set of *T* Traffic class, index *t*.

U as set of *U* Users, index *u*.

The energy efficiency of the ultra-dense network ($\mathrm{EE}_{\mathrm{HetNet\ UDN}}^{\mathrm{AN+BH}}$) with respect to the access and backhaul network can be given in equation (1)

$$\mathrm{EE}_{\mathrm{HetNet\ UDN}}^{\mathrm{AN+BH}} = \frac{\sum_{q=1}^{Q}\sum_{j=1}^{J} d_{q,j}}{P_{\mathrm{HetNet\ UDN}}^{\mathrm{AN+BH}}} \tag{1}$$

where $\sum_{q,=1}^{Q}\sum_{j=1}^{J} d_{q,j},\ \forall q \in Q,\ \forall j \in J$ is the total data rate by every base station. $P_{\text{HetNet UDN}}^{\text{AN+BH}}$ is the total power consumption of the network (considering both access and backhaul network)

The set up consist of a central Macro base station, MBS and several picocells (as the small cells network, SCN) for UDNs scenario. Thus, total power consumption ($P_{\text{HetNet UDN}}^{\text{AN+BH}}$) is the sum of power consumptions of MBS and SCN, i.e. P_{MBSTotal} (total power consumption due to MBS) and P_{SCNTotal} (total power consumption due to SCN):

$$P_{\text{HetNet UDN}}^{\text{AN+BH}} = P_{\text{MBSTotal}} + P_{\text{SCNTotal}} \tag{2}$$

Since UDN is heterogenous in nature, q>1, the MBS exist at q = 1 and the SCN is at q = 2, ∀q ∈ Q.

For q = 1 (MBS)

$$P_{\text{MBSTotal}} = P_{\text{MBSAN}} + P_{\text{MBSBH}} \tag{3}$$

where P_{MBSAN} is the power consumption of the access network for MBS (as defined in (4), P_{MBSBH} is the power consumption of the backhaul network for MBS (as defined in 10).

P_{MBSAN} has both fixed and load dependent parameters. The fixed power consumption is the total power consumed by the MBS irrespective of whether there is data traffic or not. On the other hand, the load dependent consumption depends on the parameters of the traffic being passed and this is usually in addition to the fixed.

$$P_{\text{MBSAN}} = P_{\text{MBS}}^{\text{fixed}} + \Delta_{\text{MBS}} P_{\text{tx}}^{\text{dynamic}} \tag{4}$$

where $P_{\text{MBS}}^{\text{fixed}}$ is the fixed power consumption, Δ_{MBS} is the load dependent parameter, $P_{\text{tx}}^{\text{dynamic}}$ is the dynamic power of base station, it is defined as

$$P_{\text{tx}}^{\text{dynamic}} = \sum_{u=1}^{U} P_{\text{tx,qj}}(u),\ \forall q \in Q,\ \forall j \in J \tag{5}$$

where $P_{\text{tx},q,j}(u)$ is the transmission power for a single user u, expressed as:

$$P_{\text{tx},q,j}(u) = \left[\left(2^{(e_{q,j})} - 1\right)\frac{I_{q,j}(u) + \sigma^2}{g_{q,j}}\right] \tag{6}$$

where $e_{q,j}$ is the spectral efficiency, $I_{q,j}(u)$ is the interference of a user, σ^2 is the noise level, $g_{q,j}$ is the corresponding channel gain.

It should be noted that $P_{\text{tx,z}}(u)$ should be limited within a maximum limit $P_{\text{tx}}^{\max}$ (43 dBm for MBS and 21 dBm for SCN i.e. picocell):

$$P_{\text{tx},q,j}(u) \le P_{\text{tx}}^{\max},\quad \forall u \in U,\ \forall q \in Q,\ \forall j \in J \tag{7}$$

The spectral efficiency (e_{qj}) is defined in equation (8)

$$e_{\text{qj}} = \frac{\eta_{q,j}}{N_c^{q,j}(u)\, f_{\text{sc}}},\quad \forall u \in U,\ \forall q \in Q,\ \forall j \in J \tag{8}$$

where $N_c^{q,j}(u)$ is the number of assigned sub-carriers per user u, f_{sc} is the sub-carrier frequency, and $\eta_{q,j}$ is the achievable downlink throughput for a user (which is defined in equation (9)

$$\eta_{q,j} = \frac{N_c^{q,j}(u) R_c' N_{\text{sym}} \log_2(L)}{T_f} \cdot \left(1 - P_{\text{block}}\right) \tag{9}$$

where R_c' is the adapted modulation and coding scheme rate, N_{sym} is the downlink orthogonal frequency-division multiple access (OFDMA) symbol numbers, L is the modulation order, T_f is OFDMA frame duration, and P_{block} is the block error probability.

For the MBS backhaul which is through NG-PON 2, the power consumption of the backhaul is as given is equation (10).

$$P_{\text{MBSBH}} = N_{\text{MBS}} P_o + N_g P_g + N_{\text{ul}} P_{\text{SFP+}} \tag{10}$$

where N_{MBS} is the number of MBS, P_o is the power consumption of an ONU, N_g is the number of GPON port in an OLT, P_g is the power consumption of the GPON port, N_{ul} is the number of uplink interface, and $P_{\text{SFP+}}$ is the power consumption of SFP+ module.

For q=2, (SCN), we define P_{SCNAN} is the power consumption of the access network for SCN and P_{SCNBH} is the power consumption of the backhaul network for SCN. The total power consumptions of SCN is then

$$P_{\text{SCNTotal}} = P_{\text{SCNAN}} + P_{\text{SCNBH}} \tag{11}$$

where

$$P_{\text{SCNAN}} = P_{\text{SCN}}^{j,\text{fixed}} + H_s \Delta_{\text{SCN}} P_{\text{SCN,tx}}^{j,\text{dynamic}} \tag{12}$$

$$P_{\text{SCNBH}} = \sum_{m_k \in M} \left(P_{m_k}^{\text{bh,fixed}} + P_{m_k}^{\text{bh,tx}}\right) \tag{13}$$

where $P_{\text{SCN}}^{j,\text{fixed}}$ is the fixed power consumption of SCN, ∀j ∈ J, H_s is the traffic load for SCN (this is equal to zero in sleep mode), Δ_{SCN} is the slope of load-dependent power consumption, $P_{\text{SCN,tx}}^{j,\text{dynamic}}$ is the transmission power for the SCN (picocell=21 dBm), $P_{m_k}^{\text{bh,fixed}}$ is the fixed power consumption of each SCN mmWave backhaul link, and $P_{m_k}^{\text{bh,tx}}$ is the load dependent radio frequency transmit power consumption of the SCN mmWave backhaul link.

From (1), $\text{EE}_{\text{HetNet UDN}}^{\text{AN+BH}}$ will increase with decrease in $P_{\text{HetNet UDN}}^{\text{AN+BH}}$ without giving up the expected quality of service. This implies that minimizing power consumption will indirectly maximizes the energy consumption. Thus, this leads to a minimization problem as

$$\begin{aligned} \text{minimize } P_{\text{HetNet UDN}}^{\text{AN+BH}} = {} & \text{P}_{\text{MBS}}^{\text{fixed}} + \Delta_{\text{MBS}} P_{\text{tx}}^{\text{dynamic}} + \\ & N_{\text{MBS}} P_o + N_g P_g + N_{\text{ul}} P_{\text{SFP+}} + \\ & P_{\text{SCN}}^{\text{j,fixed}} + H_s \Delta_{\text{SCN}} P_{\text{SCN,tx}}^{j,\text{dynamic}} + \\ & \sum_{m_k \in M} \left(P_{m_k}^{\text{bh,fixed}} + P_{m_k}^{\text{bh,tx}}\right) \end{aligned} \tag{14}$$

Subject to

$$S_{q,j}^{t}(u) \in \{0,1\}, \quad \forall u \in U,\ \forall t \in T,\ \forall q \in Q,\ \forall j \in J \quad (15)$$

$$\sum_{t=1}^{T}\sum_{j=1}^{J} S_{q,j}^{t} = 1, \quad \forall u \in U,\ \forall q \in Q,\ \forall j \in J \quad (16)$$

$$\gamma(u) \geq \gamma^{\text{th}}(u)\sum_{t=1}^{T} S_{\text{qj}}^{t}(u), \quad \begin{matrix}\forall u \in U,\ \forall t \in T \\ \forall q \in Q,\ \forall j \in J\end{matrix} \quad (17)$$

$$\sum_{t=1}^{T} S_{q,j}^{t}(u) \geq \sum_{t=1}^{T} S_{q,j'}^{t}(u), \quad \begin{matrix}\forall u \in U,\ \forall q' \in Q \\ \forall j \in J,\ qj < qj'\end{matrix} \quad (18)$$

$$\eta_{q,j}(u) \geq \eta_{q,j}(u)^{\text{qos}}, \quad \forall u \in U,\ \forall q' \in Q,\ \forall j \in J \quad (19)$$

$$\sum_{j=1}^{J} W_{\text{SCN}}^{j} N_{\text{SCN}}^{j} \geq W_m^r - W_m,\ \forall q > 1,\ \forall q' \in Q,\ \forall j \in J \quad (20)$$

Equation (7) has to do with the limitation of transmission power with respect to the maximum value $P_{\text{tx}}^{\max}$. For MBS the $q = 1$, $j = 1$ and the value is 41 dBm while for SCN (picocells), $q = 2$, $j > 1$ and the value is 21 dBm.

In equation (15), $S_{q,j}^{t}(u)$ denotes user's association to particular base station j at tier q and it assumes binary variable, taking 1, if user u is associated with particular base station q, j with traffic type t or 0 otherwise. Equation (16) is the scheduling constraint ensuring that a user is connected to a single base station at a particular instance. Equation (17) (where $\gamma(u)$ is the user's SINR and γ^{th} is the threshold SINR) ensures that each user is connected to a base station where the SINR is greater than the threshold. Equation (18) ensures that user is associated to the nearest base station. Equation (19), (where $\eta_{q,j}(u)^{\text{qos}}$ is the least achievable downlink throughput for a user which meets the QoS requirement of the user) ensures the standard qos is being met at all time. In equation (20), W_{SCN}^{j} is the bandwidth of SCN, N_{SCN}^{j} is the number of j SCNs needed, W_m^r is the required bandwidth and W_m is the bandwidth of the MBS and the equation shows that the assigned bandwidth of the SCN must be greater or equal to the excess bandwidth which the MBS cannot take care of.

B. Enhanced Energy Efficient Resource Management and Planning for 5G Ultra Dense Networks Algorithm

To solve the problem in (14), an enhanced energy efficient resource management and planning for 5G UDN algorithm was developed.

Algorithm: Enhanced Energy Efficient Resource Management and Planning for 5G Ultra-Dense Networks (UDN)

Input: Set of users, $u \in U$; set of traffic class, $t \in T$; set of macrocell zone/SCNs $qj \in QJ$
Output: Set of active SCNs that minimizes power consumption and still satisfies the traffic demand: $j \in J; N_{\text{SCN}} = n(J)$
for each hour, $h \in 1, 2, \ldots, 24$ **do**
    while the set of users is not empty: $U \neq \varnothing$ **do**
        User u computes the SINR $\gamma_{q,j}(u)$ from each SCN or MBS and connects/associates to the SCN or MBS qj that satisfies $\gamma_{q,j}(u) \geq \gamma^{\text{th}}(u)$ based on QoS requirements.
    end while
    Calculate W_m^r (amount of required bandwidth in the macrocell)
    if $W_m^r \leq W_m$ (MBS available bandwidth/spectrum) **then**
        for each SCN $j \in J$ **do**
            $N_{\text{SCN}}^{j} = 0$ (all SCNs are turned to sleep mode)
        end for
        Handover all users to the MBS
    else
        Calculate $W_e = W_m^r - W_m$
        Set of SCNs is empty: $J \neq \varnothing$; $N_{\text{SCN}} = n(J)$;
        Compute total power consumption model P_{SCN} for all SCNs.
        Add the SCN qj that gives the lowest/minimum P_{SCN} to the set: $J = J \cup \{qj\}$; $N_{\text{SCN}} = n(J)$;
        Using the current set of SCNs J, compute the current network power consumption $P_{\text{HetNet/UDN}}^{\text{AN-BH}}$ subject to the constraints
        while $W_e > \sum_{j=1}^{J} W_{\text{SCN}}^{j} N_{\text{SCN}}^{j}$ **do**
            Temporarily add next SCN qj with the lowest P_{SCN} to the set: $J = J \cup \{qj\}$; $N_{SCN} = n(J)$;
            Using the current set of SCNs J, compute temporary network power consumption $P_{\text{HetNet/UDN}}^{\text{AN-BH}}(\text{temp})$ subject to the constraints.
            if $P_{\text{HetNet/UDN}}^{\text{AN-BH}}(\text{temp}) \leq P_{\text{HetNet/UDN}}^{\text{AN-BH}}$ **then**
                Accept the SCN as it does not increase the total network power consumption $P_{\text{HetNet/UDN}}^{\text{AN-BH}} = P_{\text{HetNet/UDN}}^{\text{AN-BH}}(\text{temp})$
            else
                Reject the SCN as it increases the total network power consumption $J = J \setminus \{qj\}$; $N_{\text{SCN}} = n(J)$;
            end if
        end while
    end if
end for

This algorithm is responsible for the addition of new SCNs to cater for excess bandwidth needed in the UDN scenario. This is being simulated in the next section.

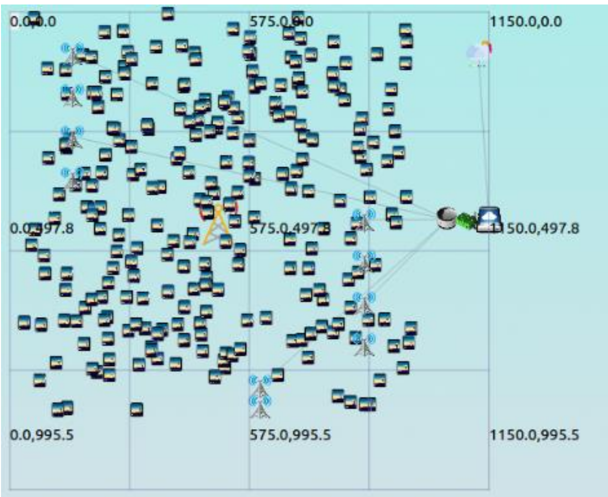
C. 5G UDN Simulation

The research has been done using simulation. This is because 5G UDN is still evolving and setting up a real life 5G UDN scenario will be expensive and unrealistic at this moment. Network simulator 3 (NS 3) [39] was the desired simulator because it has all the building block needed to design the 5G UDN and has been used by related researches[18], [27].

The 5G UDN model used for this research was based on 3GPP release 16 specification [40]. The scenario was modelled after a dense urban outdoor situation like airports, railway station, stadium and campus.

The network was planned as two-tier network. At tier 1, is the Macro Base Station (MBS) which is at the centre of 1 Km^2 area. Then at tier 2 are the small cells. The choice of small cell for this study is picocell. This picocells are backhauled using the two bands of the mmWave to the MBS which is then backhauled by fibre optics to the core. The setup is as depicted in Fig. 1.

Table IV contains the summary of the simulation parameters used for the research.



Legend: : Macro Base Station MBS; : Picocell; : Optical Line Terminal OLT; : Splitter; Optical Network Unit ONU; : Cloud; : 5G User Equipment, UE

Fig. 1. 5G UDN Scenario using MBS and PBS.

TABLE IV: SUMMARY OF SIMULATION PARAMETERS USED

Parameter	Value
Access Network Carrier Frequency f_c	2.0 GHz
Macro-tier spectrum Wm	10 MHz
Dynamic power of microcell base station	43 dBm
Dynamic transmission power for picocell	21 dBm
Fixed power consumption of microcell base station	130 W
Fixed power consumption of picocell	7 W
Load-dependent Parameter	4.7
Slope of load-dependent power consumption	8
Spectrum Allocation	Partitioned
Traffic Model Capacity	Full Buffer
Environment	Dense Urban
Maximum number of downlink interface	24
Weighting parameter A	0.9
Power consumption of OLT/ONU	2.9 W/5 W
Number of ports per Splitter	16
Backhaul frequency / Backhaul bandwidth link (V-band)	60 GHz/1.76 GHz
Backhaul frequency / Backhaul bandwidth link (E-band)	73 GHz/4.75 GHz
Length of each backhaul link *d*	100 m
Tolerable pathloss	108 dB
Path loss at 1 m distance	68 dB
Implementation loss	4 dB
Shadowing loss	1 dB
Attenuation loss	3.2 dB
Number of OLT	1
Number of Line Card	9
Number of GPON ports	72
Capacity per GPON Ports	2.5 Gbps
Uplink Interface Maximum Capacity	10 Gbps
Power Consumption of GPON port	2.9 W
Power Consumption of SFP+ module, PSFP+	1 W

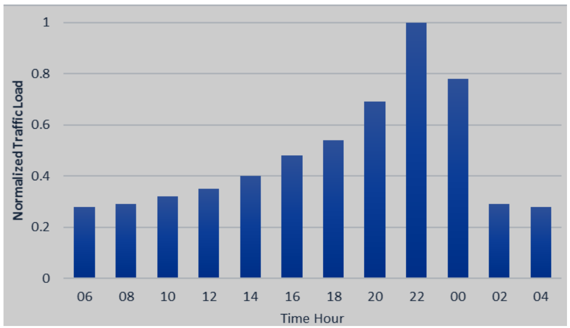


Fig. 2. Normalised traffic load hourly profile [41].

D. Performance Metrics

The two major metrics used in assessing the performance of V-Band and E-Band mmWaves are power consumption and energy efficiency.

Energy efficiency is defined as the ratio of total throughput (system capacity) to the total power consumed (bits/Joule):

$$\eta_{EE} = \frac{\text{Total datarate (bits/sec)}}{\text{Total power consumption (W)}} \quad (21)$$

Energy efficiency can be enhanced by increasing the throughput or decreasing the power consumption. The total power consumption is the overall power of the device (or the BS), including the circuit power consumption. The power consumption is measured in watts.

These metrics are plotted against the normalized traffic data obtained from cisco as shown in Fig. 2.

The simulation was run based on assumption that both V-Band and E-Band mmWave performed to the theoretical backhaul capacity of 1 Gbps and 10 Gbps respectively [7]. It was also assumed that an additional traffic requirement of 40 Gbps is expected to be delivered by the picocells in the 1 km^2 to meet the Traffic Volume Density requirement of 40 $Gbps/km^2$ expected of 5G UDN [4].

IV. RESULTS AND DISCUSSION

As stated earlier in Section III it was assumed that the UDN scenario can deploy up to 91 picocells per kilometre square [4]. This implies that all the picocells will be always if the sleep / on algorithm in Section III is not used. This algorithm ensures that only the picocells needed to cater for the excess bandwidth are on while others are put to sleep. For instance, at hour 22, the excess bandwidth to cater for is 40Gbps. Numerically, this will require 4 picocells in E-band scenario with each capacity of 10Gbps and 40 picocells in the V-band scenario with limited capacity of 1Gbps each. Fig. 3 shows the number of active picocells in each scenario based on the hourly traffic load profile.

Fig. 3 shows that adapting numbers of active cells based on traffic will save energy. Usually up to 93 picocells will be deployed in 1 km^2 of a 5G UDN [4]. This implies that if sleep/on strategy [31], [42], [43] is not in use, the 93 picocells and the MBS will always require maximum power even when there is low traffic requirement. Also, it can be observed from the graph that there are more active cells in V-Band scenario than E-band scenario. This is due to the backhaul capacity limit of V-Band compared to the E-band link.

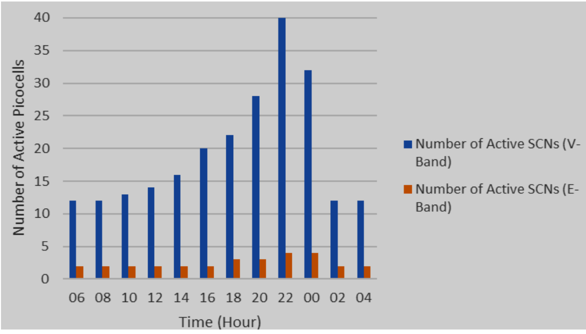


Fig. 3. Number of active picocells used per hour.

According to [2], E-band backhaul consumes 35dBm (3.16W) compared to V-band backhaul which consumes 27dBm (3.16W). This when considered with the number of active picocells and the MBS for both scenarios gives total power consumed to support the excess traffic in each hour. This is as presented in Fig. 4.

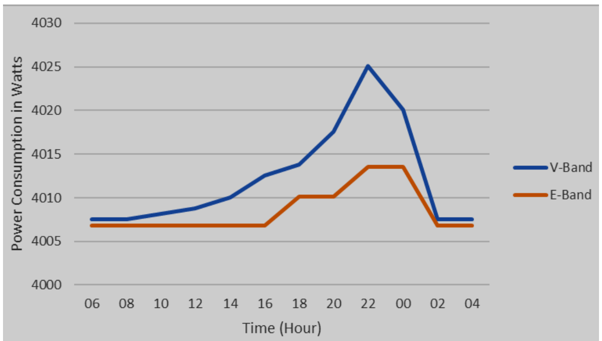


Fig. 4. Power consumption of V-Band vs E-Band backhaul solutions in 5G UDN.

In Fig. 4, Simulation result showed that E-Band mmWave backhaul scenario consumed less power compared to V-Band mmWave backhaul scenario. This is because of more active picocells involved in V-Band scenario. It was observed that the performances were close when off peak and more obvious at peak. This implies E-Band performs better as the traffic requirement increases but the performance drop and tends to converge as the traffic requirement reduces. The energy efficiency output is also similar to the pattern of the power consumption. This is as presented in Fig. 5.

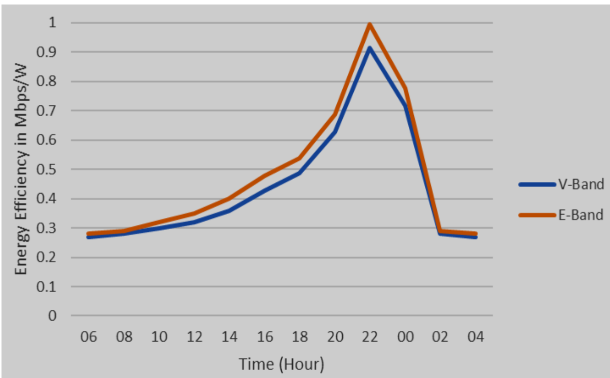


Fig. 5. Energy efficiency of V-Band vs E-Band backhaul solutions in 5G UDN.

In Fig. 5, EE profile was obtained according to equation (1). For instance, at hour 14, the excess traffic was 16Gbps and the total power consumed were 4010W and 4006W for V-band and E-band scenario respectively. Thus, the EE could be obtained numerical using equation (21) as 0.36Mbps/W for V-band scenario and 0.4Mbps/W for E-band mmWave. Similar to power consumption performance, E-Band has better energy efficiency than V-Band. There is also observation of the pattern that the energy efficiency of E-Band improves with increase in capacity compared to V-Band backhaul link.

V. Conclusion

Conclusively, this paper has shown that E-Band mmWave is a better backhaul solution for 5G UDN scenario based on the power consumption performance in Fig. 4 and energy efficiency graph in Fig. 5 However, V-Band will be preferred where the data rates are not up to the scale used in this research.

It is therefore recommended for further investigation to know what traffic range will suits V-Band over E-Band. Also, the performance of the combination of the two either as hybrid solution or switching the backhaul.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Ayodeji conducted the research while Professor Oduol and Professor Adeyemo both supervised the process adding technical inputs. Carine assisted in the paper preparation.

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References

[1] J. Rodriguez, *et al.*, "Fundamentals of 5G mobile networks," in *Fundamentals of 5G Mobile Networks*, vol. 136, no. 1, John Wiley & Sons Ltd, 2015, p. 336.

[2] S. Chen, F. Qin, B. Hu, X. Li, Z. Chen, and J. Liu, "5G Requirement and UDN," in *User-Centric Ultra-Dense Networks for 5G*, Springer US, 2018, pp. 5–9.

[3] I. B. Sofi and A. Gupta, "A survey on energy efficient 5G green network with a planned multi-tier architecture," *J. Netw. Comput. Appl.*, vol. 118, no. May, pp. 1–28, 2018.

[4] Nokia, "Ultra Dense Network (UDN) white paper," *Nokia*, 2016.

[5] M. Filo, "5G Ultra-Dense cellular networks - performance analysis and MAC protocol design," Thesis to University of Surrey, 2019.

[6] S. Tombaz, P. Monti, F. Farias, M. Fiorani, L. Wosinska, and J. Zander, "Is backhaul becoming a bottleneck for green wireless access networks?" in *Proc. IEEE Int. Conf. Commun*, 2014, pp. 4029–4035.

[7] Y. Niu, *et al.*, "Energy-Efficient scheduling for mmWave backhauling of small cells in heterogeneous cellular networks," *IEEE Trans. Veh. Technol.*, vol. 66, no. 3, pp. 2674–2687, 2017.

[8] M. Ding, D. López-Pérez, H. Claussen, and M. A. Kaafar, "On the fundamental characteristics of ultra-dense small cell networks," *IEEE Netw.*, vol. 32, no. 3, pp. 92–100, 2018.

[9] A. L. Rezaabad, H. Beyranvand, J. A. Salehi, and M. Maier, "Ultra-Dense 5G small cell deployment for fiber and wireless backhaul-aware infrastructures," *IEEE Trans. Veh. Technol.*, vol. 67, no. 12, pp. 12231–12243, 2018.

[10] G. Zhang, T. Q. S. Quek, M. Kountouris, A. Huang, and H. Shan, "Fundamentals of heterogeneous backhaul design - analysis and optimization," *IEEE Trans. Commun.*, vol. 64, no. 2, pp. 876–889, 2016.

[11] J. Saunders and N. Marshall. (2018). Mobile backhaul options - spectrum analysis and recommendations. September. GSM Association. [Online]. 38–52. Available: https://www.gsma.com/spectrum/wp-content/uploads/2019/04/Mobile-Backhaul-Options.pdf

[12] A. Othman, "User ultra-dense networks TM for 5G in urban areas," Technical Report at Open University Malaysia, Kuala Lumpur, September 2018, pp. 1-74.

[13] E. Kim, J. Lee, and Y. Kim, "Analysis of the optimal number of clusters in UDN environment," in *Proc. IEEE VTS Asia Pacific Wirel. Commun. Symp.*, 2019, pp. 1–4.

[14] ETSI ISG-mWT, White Paper No. 25. (2018). 5G Wireless Backhaul/X-Haul. [Online]. 1. pp. 1–24. Available: https://www.etsi.org/deliver/etsi_gr/mWT/001_099/012/01.01.01_60/gr_mWT012v010101p.pdf

[15] T. Q. Duong, X. Chu, and H. A. Suraweera, Eds., *Ultra-Dense Networks for 5G and Beyond Modelling, Analysis, and Applications*, John Wiley & Sons Ltd, United Kingdom, 2019.

[16] X. Ge, S. Tu, G. Mao, C. X. Wang, and T. Han, "5G ultra-dense cellular networks," *IEEE Wirel. Commun.*, vol. 23, no. 1, pp. 72–79, 2016.

[17] M. Tornatore, C. Gee-Kung, and G. Ellinas, *Fiber-Wireless Convergence in Next-Generation Communication Networks*, Cham: Springer International Publishing, USA, 2017 pp 230-235.

[18] M. M. Mowla, I. Ahmad, D. Habibi, and Q. V. Phung, "Energy efficient backhauling for 5G small cell networks," *IEEE Trans. Sustain. Comput.*, vol. 4, no. 3, pp. 279–292, 2018.

[19] M. Song and H. Shan, "Backhauling for small-cell networks," in *Wiley, UK 5G Ref*, R. Tafazolli, C. L. Wang, and P. Chatzimisios, Eds., 2019. pp. 1-22.

[20] A. H. Jafari, D. López-Pérez, H. Song, H. Claussen, L. Ho, and J. Zhang, "Small cell backhaul: Challenges and prospective solutions," *Eurasip J. Wirel. Commun. Netw.*, vol. 2015, no. 1, pp. 1–18, 2015.

[21] J. G. Andrews, T. Bai, M. N. Kulkarni, A. Alkhateeb, A. K. Gupta, and R. W. Heath, "Modeling and analyzing millimeter wave cellular systems," *IEEE Trans. Commun.*, vol. 65, no. 1, pp. 403–430, 2017.

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

[23] P. Huang and K. Psounis, "Optimal backhauling for dense small-cell deployments using mmWave links ☆," *Comput. Commun.*, vol. 138, no. September 2018, pp. 32–44, 2019.

[24] R. Taori and A. Sridharan, "Point-to-multipoint in-band mmwave backhaul for 5G networks," *IEEE Commun. Mag.*, vol. 53, no. 1, pp. 195–201, 2015.

[25] M. A. Imran, S. A. R. Zaidi, and M. Z. Shakir, Eds., Fronthaul and Backhaul Networks for 5G & Beyond Edited by Muhammad Ali Imran, Syed Ali Raza Zaidi and Muhammad Zeeshan Shakir the Institution of Engineering and Technology, UK 2017.

[26] C. Han, J. Huo, Q. Gao, G. Su, and H. Wang, "Rainfall monitoring based on next-generation millimeter-wave backhaul technologies in a dense urban environment," *Remote Sens.*, vol. 12, no. 6, pp. 1–20, 2020.

[27] M. M. Mowla, I. Ahmad, D. Habibi, and Q. Viet Phung, "A green communication model for 5G systems," *IEEE Trans. Green Commun. Netw.*, vol. 1, no. 3, pp. 1–1, 2017.

[28] R. K. Saha, "A technique for massive spectrum sharing with ultra-dense in-building small cells in 5G era," in *Proc. IEEE 90th Veh. Technol. Conf.*, pp. 1–7, 2019.

[29] M. Hussein, "Energy management framework for 5G ultra-dense networks using graph theory," *IEEE Access*, vol. 7, pp. 175313–175323, 2020.

[30] S. Aboagye, S. Member, A. Ibrahim, and T. M. N. Ngatched, "Frameworks for energy efficiency maximization in HetNets with millimeter wave backhaul links," *IEEE Trans. Green Commun. Netw.*, vol. PP, no. c, p. 1, 2019.

[31] P. Li, Y. Shen, F. Sahito, Z. Pan, and X. You, "BS sleeping strategy for energy-delay tradeoff in wireless-backhauling UDN," *Sci. China Inf. Sci.*, vol. 62, no. 4, pp. 1–17, 2019.

[32] C. Q. Dai B. Fu, and Q. Chen, "A cluster-based small cell On/Off scheme for energy efficiency optimization in ultra-dense networks," *Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering*, vol. 312, pp. 385-401, Feb. 2020..

[33] A. A. Ajani, V. K. Oduol, and Z. K. Adeyemo, "GPON and V-band mmwave in green backhaul solution for 5G ultra-dense network," *Int. J. Electr. Comput. Eng.*, vol. 11, no. 1, pp. 101–112, 2021.

[34] C. Saha, M. Afshang, and H. S. Dhillon, "Integrated mmWave access and backhaul in 5G: Bandwidth partitioning and downlink analysis," in *Proc. IEEE Int. Conf. Commun.*, 2018, pp. 1–6.

[35] G. Chopra, R. K. Jha, and S. Jain, "A survey on ultra-dense network and emerging technologies: Security challenges and possible solutions," *J. Netw. Comput. Appl.*, vol. 95, no. July, pp. 54–78, 2017.

[36] I. Allal, K. Dhifallah, J. Penhoat, Y. Gourhant, and S. Senouci, "A green mesh routers' placement to ensure small cells backhauling in 5G networks," *IEEE Commun. Surv. Tutorials*, vol. 11, no. 2, pp. 56–62, 2017.

[37] Y. Teng, M. Liu, F. R. Yu, V. C. M. Leung, M. Song, and Y. Zhang, "Resource allocation for ultra-dense networks: A survey, some research issues and challenges," *IEEE Communications Surveys & Tutorials*, vol. 21, no. 3, pp. 2134-2168, 2019.

[38] L. Suarez, M. A. Bouraoui, M. A. Mertah, M. Morvan, and L. Nuaymi, "Energy efficiency and cost issues in backhaul architectures for high data-rate green mobile heterogeneous networks," in *Proc. IEEE Int. Symp. Pers. Indoor Mob. Radio Commun. PIMRC*, vol. 2015-Decem, 2015, pp. 1563–1568.

[39] NS-3 Project. {NS-3} Network Simulator. [Online]. Available: http://www.nsnam.org/ns-3-19/,%5Cnhttp://www.nsnam.org/ns-3-19/documentation/

[40] European Telecommunications Standards Institute (ETSI), TS 123 501 - V15.5.0 - 5G; System Architecture for the 5G System (5GS) (3GPP TS 23.501 version 15.5.0 Release 15), 2019, p. 353.

[41] Cisco Systems International. Cisco Annual Internet Report (2018–2023) White Paper. 2020. [Online]. Available: https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html

[42] U. K. Dutta, M. A. Razzaque, M. A. Al-Wadud, M. S. Islam, M. S. Hossain, and B. B. Gupta, "Self-Adaptive scheduling of base transceiver stations in green 5G networks," *IEEE Access*, vol. 6, pp. 7958–7969, 2018.

[43] L. Chen, F. R. Yu, H. Ji, B. Rong, X. Li, and V. C. M. Leung, "Green full-duplex self-backhaul and energy harvesting small cell networks with massive MIMO," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 12, pp. 3709–3724, 2016.

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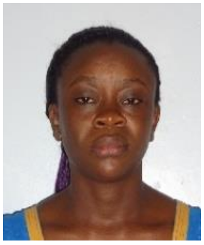

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