

GPON and V-band mmWave in green backhaul solution for 5G ultra-dense network

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ABSTRACT

Ultra-dense network (UDN) is characterized by massive deployment of small cells which resulted into complex backhauling of the cells. This implies that for 5G UDN to be energy efficient, appropriate backhauling solutions must be provided. In this paper, we have evaluated the performance of giga passive optical network (GPON) and V-band millimetre wave (mmWave) in serving as green backhaul solution for 5G UDN. The approach was to first reproduce existing backhaul solutions in very dense network (VDN) scenario which served as benchmark for the performance evaluation for the UDN scenario. The best two solutions, GPON and V-band solutions from the VDN were then deployed in 5G UDN scenario. The research was done by simulation in MATLAB. The performance metrics used were power consumption and energy efficiency against the normalized hourly traffic profile. The result revealed that GPON and V-band mmWave outperformed other solutions in VDN scenario. However, this performance significantly dropped in the UDN scenario due to higher data traffic requirement of UDN compared to VDN. Thus, it can be concluded that GPON and V-band mmWave are not best suited to serve as green backhaul solution for 5G UDN necessitating further investigation of other available backhaul technologies.

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1. INTRODUCTION

The Third and fourth generation network (3G and 4G) have shown that mobile networks can provide broadband access [1]. However, users' numbers and service applications are increasing and changing. This according to forecast [2, 3] users' data and traffic requirements will overwhelm the capacity of the existing mobile networks. Thus, there is need for a network that can handle 1000x more data traffic and this network is known as the fifth generation network (5G) [4, 5]. Capacity consideration was not the only advancement expected of 5G network compared to existing networks [1]. The other expected features of 5G network is as shown in Table 1. In order to achieve its targeted performance, [1] identified evolution of existing radio access technologies (RATs), Hyperdense small-cell deployment, Self-organising network (SON), Machine type communication (MTC), Developing millimetre wave (mmWave) RATs, allocation of new spectrum for 5G, Spectrum sharing, Radio access network (RAN) virtualisation, Energy efficiency (EE) and Redesigning backhaul links as the 10 pillars of 5G network.

Table 1. Expectation from the 5G framework [6]

Parameters	Support
Data Rates	10-100x more than LTE data rates
Mobility	Support for high speed users (~500Km/h)
Heterogeneous Networks	Mobility support in heterogeneous Radio Access Technologies along with multi-connectivity capabilities
CAPEX/OPEX	Sustainable
New deployment capabilities	Easy
Wireless device density	Support for 10-100x more devices
End-to-End latency	<1ms
Quality of Experience	Context based (flow, mobility profile, etc.)
Energy efficiency	High
Data Rates	10-100x more than LTE data rates

The 10 pillars are related, and most time researches complementarily solve problems to address two or more of these key features simultaneously. Energy efficiency, millimetre wave (mmWave), backhaul and Hyperdense Small-Cell Deployment in other words, ultra-dense networks (UDN) are some of the concept on focus in this research. The concept of Ultra-Dense Networks in 5G is about densification of small cells and the exploitation of spatial reuse of spectrum to meet the high number of users, machine and services [7]. UDNs boost capacity and enhance coverage with low-cost and power-efficient infrastructure in 5G networks. 5G UDN deployments are envisaged to be heterogeneous and dense, primarily through the provisioning of small cells such as picocells and femtocells. In UDN, users can be within the vicinity of multiple cells, which implies high interferences if not managed [8]. In addition to interference issue, UDN will most likely face the problem of redundant small cells, SCs energy consumption, and limited backhaul capacity. Therefore, there is need to do extensive research into 5G UDN energy consumption and its backhauling solution [9]. Airports, open gathering, campuses, apartments, mall, rail stations are examples of places where 5G UDN is expected to be deployed [10]. Table 2 contains the properties of UDN compared to the previous networks.

Table 2. UDN properties in comparison to older networks [11]

	Traditional Networks	Denser Networks	Very Dense Networks VDN	Ultra-Dense Networks UDN
Period	Before 2014	2015 – 2017	2017 – 2020	Beyond 2020
Subscribed data	1 GB / month	2 – 5 GB / month	5 – 10 GB / month	20 -50 GB / month
Minimum user throughput	4 Mbps	8 Mbps	10 Mbps	10 – 20 Mbps
Spectrum	2 x 100 MHz	2 x 120 MHz	2 x 140 MHz	2 x 160 MHz
Site / Km ²	7 sites	21 sites	26 sites	93 sites
Inter Site Distance ISD	395 m	237 m	209 m	112 m

There are numerous backhaul technologies (wired and wireless) available for backhauling the telecommunication networks. According to Rony et al. [12], backhaul is the link between one Base Station/eNode B (BS/eNB) to another. Also, in the centralized approach, i.e. Centralized radio access network (CRAN), backhaul connects baseband unit (BBU) and the core network. Additionally, in 5G networks, backhaul will carry large amount of traffic to/from the core network where both distributed radio access network (DRAN) (RAN processing is distributed to BSs), and CRAN co-exist. Backhaul in 5G is expected to have low latency and low power consumption [13]. Different technologies have been considered for 5G backhaul to be able to meet the requirements. Each of these technologies have their advantages and disadvantages.

Broadly backhaul solutions can be divided into wired and wireless solutions [12]. Wired solutions have dominated the backhaul network in the past when the base station was majorly macro base station (MBS). Copper and Fibre optics are the two popular options for wired backhauling. It is however believed that copper-based solution will not be able to serve as backhaul for 5G and beyond due to its limited capacity [14]. This is not issue with fibre optics as it has high capacity, low latency which can meet the quality of service (QoS) requirement of 5G and beyond. High cost of deployment and scalability are the major issues associated with fibre optics based backhaul solution. In order to address these issues, there has been evolution of passive optical network (PON) technology to improve the performance of fibre based solutions [15, 16].

Wireless solution has recently gained attention as many researches [17-20] recognized it as possible viable option for backhauling 5G and beyond. Aside the present sub 6 GHz and microwave frequency presently in use, other higher frequencies wireless options which provide larger link capacity but are very

vulnerable to environmental effects will be greatly explored. For instance, mmWave operating in three different bands, 60 GHz (V-band), 70/80 GHz (E-band) has been described as an attractive option for future wireless backhaul and access network technology, as it offers very large capacity (up to 10Gbps) compared to other wireless options [19]. Apart from environmental losses, most mmWaves band also requires line of sight (LOS) [21].

Finding an energy efficient and environmentally friendly (green) solutions for present and future telecommunication networks is one of the most important concept to research on now according to [22]. The present generation, fifth generation (5G) is built on green concept. There are efforts [23-29] from researchers to make 5G greener than the previous networks despite increase in densification and data rates [30]. For 5G and beyond to be meet its energy efficiency expectations, both the access and the backhaul parts of the networks must be carefully designed and operated [31]. Particularly, choosing the right technology to achieve the best result in terms of energy efficiency and power consumption is an open problem which needs more effort most especially when it comes to 5G UDNs whose backhaul will be very complex due to high number of small cells [32].

In response to the environmental challenge that comes from the emissions of the mobile network, many researches [30, 33-35] have been done in order to make the network more environmentally friendly and energy efficient. While there are different ways to achieve green network, Tombaz [36] was one of the leading authors who argued that backhaul power consumption contributes significantly to the overall power consumption and energy efficiency of the mobile network. Since, there has been many backhaul solutions [36-38] for different generations of the mobile network using different technologies. Tombaz et al. [36] proved that backhaul has significant impact in the overall power consumption and energy efficiency of the network. They proposed Optical Point-to-point Ethernet backhaul solution for the 3G UMTS networks. Their solution showed improved green performance of the network. Their solutions were based on 3G network and after the emergence of 4G network there was need to get better backhaul solutions to cope with the complexity of the new network.

Tombaz et al. [39] further assessed the impact of backhaul on the overall energy consumption of the cellular networks using different data traffic requirements from 2014 to 2020. They proposed three (3) backhaul architectures using three (3) different technologies (copper, fibre and microwave). Two (2) of the proposed architectures are hybrid thereby making use of two technologies simultaneously. Fibre-to-the-node (FTTN) using VDSL2, Microwave Only and Fibre-to-the-Building (FTTB) + Microwave are their three (3) architectural implementations. Their result showed that backhaul can be responsible for up to 50% of the power consumption on the network. The hybrid backhaul made up of Fibre-to-the-Building (FTTB) option and microwave links had better performance compared to the other architectures.

Suarez et al., [37] studied energy efficiency of backhaul in heterogenous network. They proposed two (2) hybrid backhaul architectures: Fibre-to-the-building (FTTB) + 10Gbps passive optical network (10GPON) technologies and FTTB + microwave. Their analyses were based on Area Power Consumption [W/km²]. Their result showed that the two proposed architectures had better performance than the conventional backhaul in terms of area power consumption [W/km²]. Mowla et al. [38] presented energy-efficient communication model for 5G heterogeneous networks (HetNets). They considered both access and backhaul. They investigated power consumption of various backhaul designs, then proposed two backhaul solutions. Wired passive optical network (PON) and wireless V-band millimetre wave (mmWave). The performance evaluation was done through simulation using network simulator 2 (NS-2). They showed how to connect passive optical network units/terminals with 5G access units to reduce the overall power consumption in the first solution. The second solution integrated mmWave backhaul units with 5G SCN units to reduce power consumption. Backhaul power consumption in Watt and Backhaul Energy Efficiency Mbps/ Watt were the performance metrics used. The result revealed that their solution can save up to 48% power consumption. Their solutions outperformed the previous solution in terms of power consumption and energy efficiency.

In this paper, we have evaluated all this solution in the pre 5G network scenario to determine which is best of the existing green backhaul solutions. Furthermore, we analysed the performance of the best solutions in 5G UDN scenario through simulation in MATLAB using an improved 5G model and algorithm. This is to determine if the best two solutions (giga passive optical network (GPON) and V-band millimetre wave (mmWave)) are well suited to serve as green backhaul solution for 5G UDN network. We have presented the model and improved algorithm in section 2 and the simulation description in section 3. Section 4 contains the result and discussion while section 5 has the conclusions from the analysis.

2. PROPOSED MODEL

This section presents the approach used for this research. It includes the requirement analysis, definition of concepts and tools, performance parameters and metrics as well as definition of scenarios.

2.1. 5G UDN model

This section contains the derivations of the mathematical optimization problem to make UDNs most energy efficient without losing the expected quality of service (QoS) Requirement. The 5G UDN model proposed here consist of a central macro base station (MBS) and several randomly distributed Small cells. The choice of this paper for small cell is picocells because we are investigating an outdoor scenario.

The following set 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 ($EE_{HetNet\ UDN}^{AN+BH}$) with respect to the access and backhaul network can be given in (1)

$$EE_{HetNet\ UDN}^{AN+BH} = \frac{\sum_{q=1}^Q \sum_{j=1}^J d_{q,j}}{P_{HetNet\ UDN}^{AN+BH}} \quad (1)$$

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. $P_{HetNet\ UDN}^{AN+BH}$ is the total power consumption of the network including power consumed by both access and backhaul network. The total power consumption ($P_{HetNet\ UDN}^{AN+BH}$) is the sum of power consumptions of MBS ($P_{MBS\ Total}$) and SCs ($P_{SCN\ Total}$) and this is as defined in (2)

$$P_{HetNet\ UDN}^{AN+BH} = P_{MBS\ Total} + P_{SCN\ Total} \quad (2)$$

Since UDN is heterogenous in nature, $q > 1$, the MBS exist at $q = 1$ and the SCN is at $q = 2$, $\forall q \in Q$. For $q = 1$ (MBS).

$$P_{MBS\ Total} = P_{MBSAN} + P_{MBSBH} \quad (3)$$

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 (5)).

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.

$$P_{MBSAN} = P_{MBS}^{fixed} + \Delta_{MBS} P_{tx}^{dynamic} \quad (4)$$

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

For the MBS backhaul which using PON, the power consumption of the backhaul is as given is (5).

$$P_{MBSBH} = N_{MBS} P_o + N_g P_g + N_{ul} P_{SFP+} \quad (5)$$

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_{SFP+} is the power consumption of SFP+ module.

For $q = 2$, (SCN), we adopted P_{SCNAN} as the power consumption of the access network for SCN and P_{SCNBH} as the power consumption of the backhaul network for SCN. The total power consumptions of SCN is defined in (6) while P_{SCNAN} and P_{SCNBH} are defined in (7) and (8) respectively.

$$P_{SCN\text{Total}} = P_{SCNAN} + P_{SCNBH} \quad (6)$$

$$P_{SCNAN} = P_{SCN}^{j,\text{fixed}} + H_s \Delta_{SCN} P_{SCN,tx}^{j,\text{dynamic}} \quad (7)$$

$$P_{SCNBH} = \begin{cases} \sum_{m_k \in M} (P_{m_k}^{bh,\text{fixed}} + P_{m_k}^{bh,\text{tx}}), & mmWave \\ P_o N_{SCN-ONU}, & PON \end{cases} \quad (8)$$

where $P_{SCN}^{j,\text{fixed}}$ is the fixed power consumption of SCN, $\forall j \in J$, 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, $P_{SCN,tx}^{j,\text{dynamic}}$ is the transmission power for the SCN (picocell = 21 dBm), $P_{m_k}^{bh,\text{fixed}}$ is the fixed power consumption of each SCN mmWave backhaul link, $P_{m_k}^{bh,\text{tx}}$ is the load dependent radio frequency transmit power consumption of the SCN mmWave backhaul link, P_o is the power consumption of an Optical Network Unit (ONU) and $N_{SCN-ONU}$ is the number of linking between the SCN and the ONU.

Equation (1) can be modified to minimization of power consumption instead of maximization of the energy efficiency. This is to avoid fractionality in the optimization problem. This is possible according to equation where it can be inferred that if the expected data rate is being delivered, minimizing power consumption will result in maximizing EE. Thus, problem formulation to minimize power consumption is as given in (9)

$$\text{Minimize } P_{HetNet\ UDN}^{AN+BH} = P_{MBS}^{\text{fixed}} + \Delta_{MBS} \cdot P_{tx}^{\text{dynamic}} + N_{MBS} P_o + N_g P_g + N_{ul} P_{SFP+} + P_{SCN}^{j,\text{fixed}} + H_s \cdot \Delta_{SCN} \cdot P_{SCN,tx}^{j,\text{dynamic}} + *P_{SCNBH} \quad (9)$$

* P_{SCNBH} can assume take two definitions depending on whether mmWave or PON is being used. This (9) can be further stated as (9a) which make use of mmWave and (9b) when PON is used.

$$\text{Minimize } P_{HetNet\ UDN}^{AN+BH} = P_{MBS}^{\text{fixed}} + \Delta_{MBS} \cdot P_{tx}^{\text{dynamic}} + N_{MBS} P_o + N_g P_g + N_{ul} P_{SFP+} + P_{SCN}^{j,\text{fixed}} + H_s \cdot \Delta_{SCN} \cdot P_{SCN,tx}^{j,\text{dynamic}} + \sum_{m_k \in M} (P_{m_k}^{bh,\text{fixed}} + P_{m_k}^{bh,\text{tx}}) \quad (9a)$$

$$\text{Minimize } P_{HetNet\ UDN}^{AN+BH} = P_{MBS}^{\text{fixed}} + \Delta_{MBS} \cdot P_{tx}^{\text{dynamic}} + N_{MBS} P_o + N_g P_g + N_{ul} P_{SFP+} + P_{SCN}^{j,\text{fixed}} + H_s \cdot \Delta_{SCN} \cdot P_{SCN,tx}^{j,\text{dynamic}} + P_o N_{SCN-ONU} \quad (9b)$$

Subject to

$$P_{tx,qj}(u) \leq P_{tx}^{\text{max}}, \quad \forall u \in U, \forall q \in Q, \forall j \in J \quad (10)$$

$$S_{qj}^t(u) \in \{0,1\}, \quad \forall u \in U, \forall t \in T, \forall q \in Q, \forall j \in J \quad (11)$$

$$\sum_{t=1}^T \sum_{j=1}^J S_{qj}^t = 1, \quad \forall u \in U, \forall q \in Q, \forall j \in J \quad (12)$$

$$\gamma(u) \geq \gamma^{\text{th}}(u) \sum_{t=1}^T S_{qj}^t(u), \quad \forall u \in U, \forall t \in T, \forall q \in Q, \forall j \in J \quad (13)$$

$$\sum_{t=1}^T S_{qj}^t(u) \geq \sum_{t=1}^T S_{qj'}^t(u), \quad \forall u \in U, \forall q' \in Q, \forall j \in J, qj < qj' \quad (14)$$

$$\eta_{qj}(u) \geq \eta_{qj}(u)^{\text{qos}}, \quad \forall u \in U, \forall q' \in Q, \forall j \in J \quad (15)$$

$$\sum_{j=1}^J W_{SCN}^j N_{SCN}^j \geq W_m^r - W_m, \forall q > 1, \forall q' \in Q, \forall j \in J \quad (16)$$

Equation (10) ensures the maximum transmission power is with the maximum value (P_{tx}^{max}). The maximum values for MBS and picocells are 41 dBm and 21 dBm respectively. $S_{qj}^t(u)$ represents user's association to a particular base station j at tier q in (11). This takes binary values '0' or '1' with '1' when user u is associated with particular base station q,j with traffic type t or 0 otherwise.

Equation (12) ensures that a user is connected to a single base station at an instance. Equation (13) is responsible for making sure users are connect with a particular Signal to Interference to Noise Ratio (SINR, $\gamma(u)$) value which greater than the threshold SINR (γ^{th}). Equation (14) is for user's association to the nearest base station. Equation (15), is to ensure the QoS requirement is met by the achievable downlink throughput for a user ($\eta_{qj}(u)$) is greater than or equal to the least achievable downlink throughput for a user which meets the QoS requirement of the user ($\eta_{qj}(u)^{QoS}$).

Equation (16) ensures that the assigned bandwidth (W_{SCN}^j) to Number of SCNs needed (N_{SCN}^j) is greater than or at least equal to the excess bandwidth required. The excess bandwidth required is the difference between the total bandwidth required (W_m^r) and the bandwidth of the MBS (W_m). This model has included backhaul power consumption for each of the solutions in the problem formulation unlike the one adopted by [38]. This is particularly important in UDN scenario. To solve the problem in (9), we used an improved 5G UDN energy efficient algorithm.

2.2. Improved 5G UDN energy efficiency algorithm

An algorithm to solve the problem in (9) is presented here. This improved algorithm is to allow mathematical solution programming in MATLAB. This algorithm also expatiates on how the additions and putting to sleep of SCs are being done.

Algorithm: Improved 5G UDN Energy Efficiency

- 1: **Input:** Set of users, $u \in U$; set of traffic class, $t \in T$; Sets of 5G multi-tier Heterogenous Network, $q \in Q$; Set of Small cell base stations, $j \in J$.
- 2: **Output:** Set of active SCNs meets all the constraints in Equations (10 to 16) and fulfils the optimum value for Equation (9): $j \in J; N_{SCN} = n(J)$
- 3: **for** each hour of the day, $h \in 01, 02, \dots, 24$ **do**
- 4: **while** the set of users is not empty: $U \neq \emptyset$ **do**
- 5: User u calculates the SINR $\gamma_{qj}(u)$ from each SCN or MBS then associates to the SCN or MBS q,j that satisfies $\gamma_{qj}(u) \geq \gamma^{th}(u)$ based on QoS requirements.
- 6: **end while**
- 7: Calculate W_m^r (total required bandwidth)
- 8: **if** $W_m^r \leq W_m$ (MBS available bandwidth/spectrum) **then**
- 9: **for** each SCN $j \in J$ **do**
- 10: $N_{SCN}^j = 0$ (all SCNs are turned to sleep mode)
- 11: **end for**
- 12: Handover all users to the MBS
- 13: **else**
- 14: Calculate $W_e = W_m^r - W_m$
- 15: Set of SCNs is empty: $J \neq \emptyset$; $N_{SCN} = n(J)$;
- 16: Compute total power consumption model P_{SCN} for all SCNs.
- 17: Add the SCN q,j that gives the minimum P_{SCN} to the set: $J = J \cup \{qj\}$; $N_{SCN} = n(J)$;
- 18: Using the current set of SCNs J , compute the current network power consumption $P_{HetNet\ UDN}^{AN-BH}$ subject to the constraints
- 19: **while** $W_e > \sum_{j=1}^J W_{SCN}^j N_{SCN}^j$ **do**
- 20: Temporarily add next SCN q,j with the lowest P_{SCN} to the set: $J = J \cup \{qj\}$; $N_{SCN} = n(J)$;
- 21: Using the current set of SCNs J , compute temporary network power consumption $P_{HetNet\ UDN}^{AN-BH}(\text{temp})$ subject to the constraints.
- 22: **if** $P_{HetNet\ UDN}^{AN-BH}(\text{temp}) \leq P_{HetNet\ UDN}^{AN-BH}$ **then**

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23:   Accept the SCN as because it has not increased the power consumption of
      the network
       $P_{\text{HetNet UDN}}^{\text{AN-BH}} = P_{\text{HetNet UDN}}^{\text{AN-BH}}(\text{temp})$ 
24: else
25:   Reject the SCN because it has increased the power consumed by the network  $J = J \setminus \{qj\}$ ;
       $N_{\text{SCN}} = n(J)$ ;
26: end if
27: end while
28:   end if
29: end for
    
```

This algorithm ensures the addition of small cells where needed without compromising the power consumption of the network and makes other SCs sleep when not required. The simulation of the solution is done in MATLAB.

3. RESEARCH METHOD

Simulation descriptions are presented here, which includes the choice of parameters, performance metrics and the description of the scenarios.

3.1. Simulation of 5G UDN

The study involved different backhaul solutions using available technologies in 5G very dense network, VDN and UDN scenarios. Therefore, the research required design of 5G VDN and UDN scenarios and this was simulated in MATLAB. The simulation decision is inspired by work reviewed [36-39] and recent study in 5G UDN [32, 40-43]. The choice of simulation is because 5G UDN is still evolving and doing a live experiment was not available.

The simulation parameters used follows the work of [38]. The normalised hourly traffic profile from cisco was used to this effect as presented in Figure 1. The performance metrics used are power consumption in Watts and energy efficiency in Mbps/Watt. The full simulation parameters are as given in Table 3.

Table 3. Simulation parameters

Parameters	Parameters Description	Value
f_c	Access Network Carrier Frequency	2.0 GHz
W_m	Macro-tier spectrum	10 MHz
$P_{tx}^{dynamic}$	Dynamic power of microcell base station	43 dBm
$P_{q,tx}^{j,dynamic}$	Dynamic transmission power for femtocell	17 dBm
P_m^{fixed}	Fixed power consumption of microcell base station	130 W
$P_q^{j,fixed}$	Fixed power consumption of femtocell	4.8 W
Δ_m	Load-dependent Parameter	4.7
Δ_s	Slope of load-dependent power consumption	8
Spectrum Allocation		Partitioned
Traffic Model Capacity		Full Buffer
Environment		Sub-urban
N_{dl}^{max}	Maximum number of downlink interface	24
A	Weighting parameter	0.9
$P_{sw}^{max} / P_{sw}^{dl} / P_{sw}^{ul}$	Maximum power consumption of switch / Power consumption of one downlink interface / Power consumption of one uplink interface	300 / 1 / 1 W
$P_{modem} / P_{DSLAM} / P_{sw}^F$	Power consumption of VDSL2 modem/ DSLAM / Fibre switch	5 / 85 / 300 W
$P_{SFP} / P_{SFP+} / P_{low-c} / P_{high-c}$	Power consumption of SFP module / SFP+ module / Low / High power consumption region of a microwave antenna	1 / 1 / 37 / 92.5 W
$P_{GES}^{max} / P_{sw}^{MW} / P_g / P_o$	Maximum power consumption of GES / Power consumption of microwave switch / Power consumption of OLT / Power consumption of ONU	50 / 53 / 2.9 / 5 W
$n_{ports}^D / n_{ports}^F / n_{ports}^{GES} / n_{ports}^{splitters} / n_{sup}^{MW}$	Number of ports per DSLAM switch / Fibre switch / GES / splitter / microwave switch	16 / 24 / 12 / 24 / 16
$A_{g,max} / U_{int}^{max} / C_{sw}^{MW}$	Maximum traffic switch can handle / Maximum transmission rate of the interface / Maximum capacity of microwave switch	24 / 10 / 36 Gbps
f_{bh}^{mmWave} / W_{mk}	Backhaul frequency using mmWave / Backhaul link bandwidth	60 / 1.76 GHz
D	Length of each backhaul link	100 m
$L_p / L_{p0} / L_i / L_{sh} / L_a$	Tolerable pathloss / Path loss at 1 m distance / implementation loss / Shadowing loss / Attenuation loss	108 / 68 / 4 / 1 / 3.2 dB

The choice of adopting normalised hourly load traffic is to make the study easily adaptable to other situations. This means different study can use this without necessarily using the amount of traffic used here or even with different hourly profile.

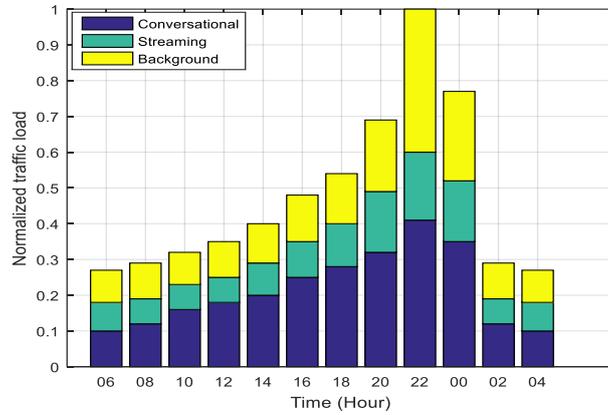


Figure 1. Normalised traffic load hourly profile [2]

3.2. Description of the simulation scenarios

There are 2 sets of scenarios implemented here. The first set is the reproduction of the solution reviewed in Very Dense Network scenario using each of the solutions highlighted in Section 1. This is for verification and validation purpose. The other set is to test the best 2 solutions in the UDN scenario to evaluate their performance. The scenario is modelled after an outdoor situation like a public concert, sport stadium, transportation hub or any other large gathering where the thousand users require high bandwidth simultaneously.

3.3. Performance metrics

The performance metrics used are power consumption in Watts per normalized hourly traffic for each of the solutions and energy efficiency in Mbps/Watt.

4. RESULTS AND DISCUSSIONS

The results of the simulation are being presented in this section as well as the detailed discussion of the results.

4.1. Result of existing solutions in 5G VDN

The reviewed solutions were implemented in VDN network for verification and validation purpose. The result of the simulation is as presented in Figure 2 and Figure 3

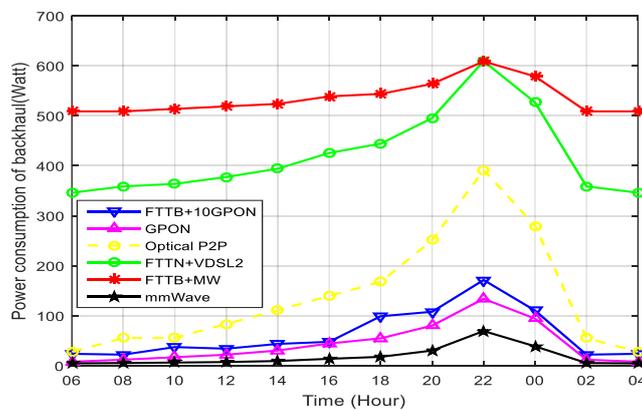


Figure 2. Graph of power consumption of the backhaul solutions

V-band mmWave and PON solution had the least power consumed compared to other solutions. This is because there are components such as Ethernet switch, fibre switch, DSL access multiplexer, microwave switch, Gigabit Ethernet switch in the previous solutions responsible for their high-power consumption. Considering energy efficiency, which is the data rate per power consumed, high power consumption of backhaul solution will result in low energy efficiency and low data power consumption will mean high energy efficiency as shown in Figure 3.

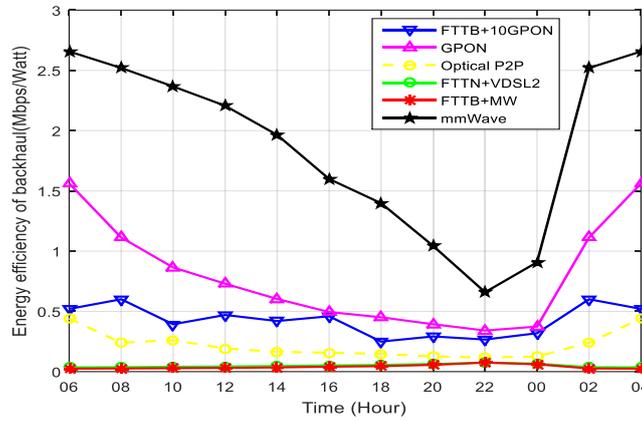


Figure 3. Graph of energy efficiency of the backhaul solutions

Similar to power consumption graph, V-band mmWave and PON solution had the better performance in terms of energy efficiency compare to others. This mean the two solutions are well suited for the scenario. The technologies employed had similar timeline with the network deployed in. Therefore, it is imperative to test the best solution in the new network scenario, UDN to evaluate it performance for suitability. The result of this evaluation is as presented in Section 4.2.

4.2. Result of the best two solutions (GPON and V-Band mmWave) in 5G VDN and UDN scenarios

The PON and mmWave solution was simulated in UDN scenario and was compared to the VDN scenario performance presented in 4.1. Figure 4 and Figure 5 show the power consumption and energy efficiency graphs of the two solutions in both VDN and UDN scenarios respectively.

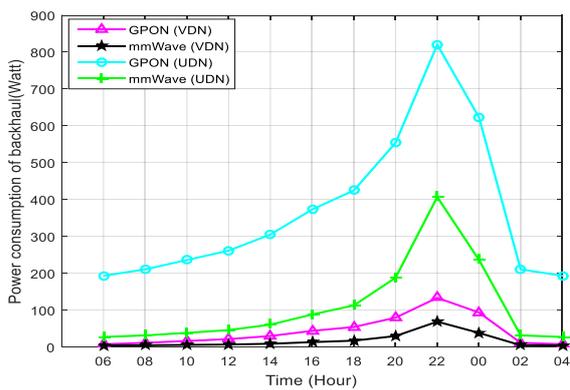


Figure 4. Graph of power consumption of PON and mmWave in VDN and UDN

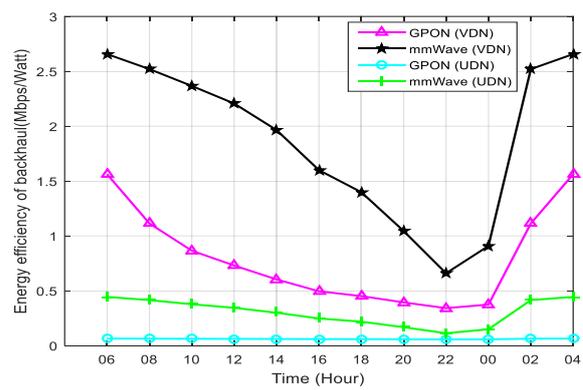


Figure 5. Graph of power consumption of PON and mmWave in VDN and UDN

As revealed in Table 2, the data rate, number of users and sites in UDN are greater than that of the VDN. Thus, there is an increase in the power consumed by the solutions to deliver the increased data rate thereby leading to drop in energy efficiency as shown in Figure 5. However, UDN network is expected to be

greener than VDN [44] that is less power consumption and higher energy efficiency. Thus, this open a research area to investigate other technologies like NG-PON 2 and E-Band mmWave in UDN scenario to know if they can deliver the desired performance.

5. CONCLUSION

GPON and V-band mmWave backhaul solutions were investigated in 5G UDN scenario. The result revealed that GPON and V-band mmWave solutions outperformed other existing solutions in VDN scenarios, but the performance dropped in UDN scenario thereby leading to a suggestion of investigation of other technologies in order to achieve greener performance in 5G UDN scenario. Further research is ongoing on investigation of NG-PON 2 and E-Band mmWave solutions in serving as green backhaul solution for 5G UDN.

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