Energy Efficiency of Backhauling Options for Future Heterogeneous Networks

Nasir Faruk, Abubakar Abdulkarim, Nazmat T. Surajudeen-Bakinde and Segun I. Popoola

Abstract Deployment of heterogeneous networks (HetNets) is a veritable solution to the challenges of coverage and capacity in meeting the unprecedented future mobile data traffic. However, the high density of small base stations (SBS) in future HetNets may increase the complexity of backhauling with higher capital expenditure (CAPEX), operating expenditure (OPEX), and energy cost. In this paper, a comprehensive review of various backhauling options for future HetNet is provided. For a HetNet system of seven SBS scenario, the efficiencies of the backhauling technologies are evaluated based on power consumption analysis. The implementation of energy-efficient microwave communication links is also considered based on realistic power consumption. Findings show that massive MIMO (M-MIMO) backhauling system consumes the highest power at maximum load. Power consumption in M-MIMO tends to rise as the number of transmitting antennas increases. In the same vein, power consumption in self-backhauling is relatively high when compared with conventional backhauling systems such as the microwave point-to-point (P2P) and point-to-multipoint (P2MP). On the other hand, total power consumed by satellite hub site, fiber optics, and cloud radio access network (CRAN) technologies are found to be relatively low (271.0571, 96.8083 and 90.1920 W, respectively). Fiber optics, CRAN, satellite hub site, and P2MP backhauling options proved to be more energy efficient in a decreasing order, when coverage and capacity are considered. The con-

N. Faruk (✉)
Department of Telecommunication Science, University of Ilorin, P.M.B 1515, Ilorin, Kwara State, Nigeria
e-mail: faruk.n@unilorin.edu.ng

A. Abdulkarim · N. T. Surajudeen-Bakinde
Department of Electrical and Electronics Engineering, University of Ilorin, P.M.B 1515, Ilorin, Kwara State, Nigeria
e-mail: abdulkarim.a@unilorin.edu.ng

N. T. Surajudeen-Bakinde
e-mail: deenmat@unilorin.edu.ng

S. I. Popoola
Department of Electrical and Information Engineering, Covenant University, P.M.B 1023, Ota, Ogun State, Nigeria
e-mail: segun.popoola@covenantuniversity.edu.ng

169

tribution of this work will help mobile network operators (MNO) in better decision making toward achieving a sustainable backhauling in future HetNet deployments.

Keywords Backhaul technologies · Small cells · Heterogeneous networks · Energy efficiency

1 Introduction

In this era of Internet of Things (IoT), the unprecedented and continuous growth in the demand for mobile data services by wireless devices and sensor nodes has compelled mobile network operators (MNOs) to seek for how to significantly increase their network capacity while decreasing the cost per bit of data delivered [1]. The traditional cellular architectures cater for large coverage area but they often fail in achieving the expected throughput due to high inter-cell interference, bandwidth, and backhauling air interface and network configuration [2]. Hence, the need for disruption in the network architecture of future mobile communication system so as to meet the ever-increasing mobile data traffic. Meanwhile, most of the methods proposed in the literature seek to increase network capacity and fill coverage gaps at the expense of increased network energy consumption. The bulk of the energy is consumed by the active nodes such as the macrobase stations (MBSs) and cooling systems. Therefore, the cost of energy consumed may introduce new challenges in the bid to finding traditional network energy solutions [3].

Several methods have been proposed to reduce the high power consumption in future mobile networks. For instance, network densification can be achieved through cell shrinking, wherein a large number of low power base stations are deployed to complement existing MBSs. The deployment of these SBS (femto-, micro-, and pico-base stations) have small coverage areas, may be exploited to improve the spectral efficiencies and to achieve low path losses and low power consumption. This low power can be as small as 500 W, which is feasible and sustainable, especially when renewable energy sources are employed. The 4 kW power consumed by the MBS is quite high when compared to that of SBS [3–5]. The resulting network consists of various types of base stations each with different coverage areas, typically referred to as heterogeneous network (HetNet) [1, 2].

Interestingly, an energy-efficient operation can be achieved by the deployment of SBS since they consume less power. However, the high-capacity backhaul connection between the SBS and the mobile core network since more SBS would be required to complement a single high-powered MBS. These SBS-backhaul links may in turn increase the energy consumption of the overall SBS sites beyond what could be supported with low-cost renewable energy solutions. An extensive deployment of SBS will eventually increase the overall energy consumption due to SBS backhauling energy requirements [3]. Therefore, it is of paramount necessity to provide a holistic and comprehensive approach toward achieving a more energy-efficient and sustainable green backhauling for future HetNets.

This paper, therefore, explores and provides a critical and systematic review of the various backhauling options available today for future HetNet. Considering a HetNet system of seven SBS scenario, the efficiencies of the backhauling technologies are evaluated based on power consumption analysis. The implementation of energy-efficient microwave communication links is also considered based on realistic power consumption. The backhauling options covered in this paper include: massive MIMO (M-MIMO), satellite hub site, fiber optics, and cloud radio access network (CRAN) technologies. The contribution of this paper will help mobile network operators (MNO) in better decision making toward achieving a sustainable backhauling in future HetNet deployments. The descriptions of the mathematical notations used in this paper are provided in Table 1.

Table 1 Mathematical notations and their descriptions

Notation	Description
H	Efficiency
$\sum$	Summation
Δ	Delta
α	Alpha
φ	Quotient
P_{PA}	Power of transceiver
P_{RF}	Power amplifier
P_{DSP}	Power of baseband processing
P_{cool}	Power of cooling unit
W	Transmission bandwidth
P_{BB}	Baseband engine
P_{RF}	Small-signal transceiver
n_{PA}	PA efficiency
δ_{feed}	Feeder cable loses
P_{max}	Maximum transmission power
P^{SBS}	Power consumption of the SBS
N_j and N_v	Represent the total number of MBS and SBS, respectively
P_j^{MBS} and P_v^{SBS}	The power consumption of each MBS and SBS
f, f_a and f_b	The instantaneous load on the HetNet, MBS and SBS, respectively
n	Power amplifier efficiency
P_t	Transmit power
M	Number of transmit antennas
P_c	Circuit power of the corresponding RF chain

(continued)

Table 1 (continued)

| Notation	Description
P_{o}	Determined by the non-transmission power consumption
f_{a}	The load factor representing the number of active users served by MBS network
P_{t}	Transmit power
P_{c}	Power consumption of the transceiver
$P_{\mathrm{c,t}}^{\mathrm{bh}}$, $P_{\mathrm{SBS,t}}^{\mathrm{bh}}$	Power consumption of microwave unit(s) at the wireless hub and SBS, respectively
$P_{\mathrm{tot,t}}^{\mathrm{bh}}$	Total power consumption of microwave radio link (RRL)
SBS(C_j^{SBS})	Aggregate backhaul capacity of the RRL at the SBS at site j.
$N_{\mathrm{k}}^{\mathrm{SBS}}$	Total number of microwave at SBS
P_{lc}, P_{hc}	Power consumption of the microwave antennas associated with low and high-capacity demand, respectively.
$P_{\mathrm{Switch}}^{\mathrm{SBS}}$, $P_{\mathrm{Switch}}^{\mathrm{c}}$	Power consumption of the switches used at SBS and the hub site, respectively
C_j^{SBS} and C_j^{c}	Total backhaul capacity at the SBS and hub site
$N_{\mathrm{k}}^{\mathrm{SBS}}$ and $N_{\mathrm{k}}^{\mathrm{c}}$	Number of microwave links at the SBS and hub site, respectively
$C_{\mathrm{Max - Switch,t}}$	Maximum capacity of the switch of type t
$P_{\mathrm{Switch,t}}$	Fixed power consumed by switch type t irrespective of the load
φ_{bh}	Backhaul type (either P2P or P2MP)
N	Number of base station types used in the network
Mi	Total number of base stations of a specific type i
$P_{\mathrm{bh}}^{\mathrm{sat}}$	Entire backhaul power consumption
$P_{\mathrm{hub}}^{\mathrm{sat}}$	The power consumption of the area hub node
M_{bs}	Total number of base stations in the entire area
P_j^{sbs}	Power associated with satellite backhaul operations at the base station site j
C_{th}	Threshold capacity
V_{low} and V_{high}	Power consumption of the very small aperture terminal associated with low and high-capacity demand, respectively

Table 1 (continued)

Notation	Description
p_i	Wireless transmission power of the RRH
η	Power amplifier efficiency
P_{RF}	Circuit power consumption for a RRH
P_0 and P_{max}	Power consumption of BBU in idle mode and in full usage mode, respectively
Δp	Slope of the equivalent linear power model
k	Relevant coefficient
X_{cap}	Baseband processing capacity of one BBU in the BBU pool
P_{tx}	Average radiated power
a_i	Power consumption that scales with the transmit power due to RF amplifier and feeder losses
b_i	Models the power consumed independently of the transmit power due to signal processing and site cooling
c_i	Power consumption of the SFP used to transmit over the backhauling fiber
P_{bh}	Power consumed by the backhaul
P_i	Power consumption of a base station of type i
P_{dl}	Power consumed by one downlink interface in the aggregation switch used to receive the backhauled traffic
N_{ul} and P_{ul}	Total number of uplink interfaces and the power consumption of one uplink interface
P_s	Power consumed by a switch
P_{max}	Maximum power consumption of the switch when all the downlink interfaces are in use
Ag_{max}	Maximum amount of traffic a switch can handle

2 Heterogeneous Networks (HetNets)

HetNet architecture involves the interconnection of different base station types (macro-, micro-, pico-, and femto-base stations) with varying coverage footprints and power requirements. The primary aim of introducing HetNet is to increase the network capacity while ensuring higher Quality of Service (QoS) and bandwidth usage in an energy-efficient manner. Table 2 presents the different base stations, their coverage distances, power radiated, and consumed with the various backhauling technologies for connecting the base stations and the core networks. Figure 1

Table 2 Various base station types [3–5]

Base station type	Coverage distance (m)	Radiated power (kW)		Consumed power (kW)	Backhaul type
		Indoor	Outdoor		
Macrocell	<35,000	N/A	0.005–0.040	1–5	Fiber or microwave
Microcell	<2000	N/A	0.0005–0.002	0.1–0.3	Microwave
Picocell	<200,000	0.0001	0.00025–0.002	0.009–0.015	Microwave or fiber or DSL
Femtocell	10,000–15,000	>0.0001	N/A	6–14	Fiber/DSL
RRH-cell	<2000	N/A	5–20	550–760	Fiber
Relay-cell	<2000	<0.001	0.25–7	10–120	via DeNB
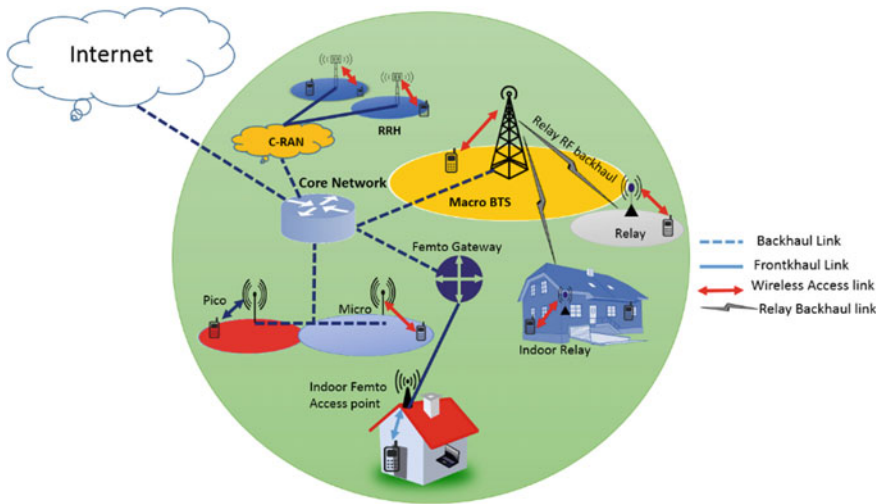
Fig. 1 Typical HetNet deployment scenario

is a schematic diagram which shows how the SBS are connected to the MBS. The figure also shows the different links vis-à-vis backhaul, fronthaul, wireless access, and relay backhaul links. This is a typical scenario of how the core network, which accesses the Internet, can be connected to the various SBS.

3 Backhaul Technology Options

HetNet is described as the combination of different types of base stations with various building components, form factor, coverage area, operation, and cost of procurements. The coverage footprints of the SBS are called small cells while those of

Table 3 Copper cables available for backhaul [7]

Cable	Standard	Types	Maximum downstream (Gbps)	Maximum upstream (Gbps)
Data over cable service interface specification (DOCSIS)	ITU DOCSIS 1.0	1.0	0.01	0.01
		1.1	0.01	0.01
		2.0	0.03	0.03
		3.0	0.2	0.2
		3.1	1–2	1–2
		3.1 full duplex	10	10
Digital subscriber line (DSL)	ITU G992	SADSL	0.012	0.0018
		ADSL 2	0.012	0.0035
		ADSL 2+	0.024	0.0013
		ADSL 2 + M		0.0033
		VDSL	0.055	0.003
		VDSL 2+	0.055	0.003
		G. FAST	1	1
Fiber optics cable	ITU G.707, G.783, G.784, and G.803	Single mode	>10	>10
		Multimode		
		Plastic		

MBS are referred to as macrocells [6]. Backhauling, which is of two types, wired and wireless, is the connection between the SBS and the MBS. It also links the MBS to the core network.

3.1 Wired Backhauling

Wired backhauling is a type of backhauling that uses cables to connect nodes together. It is the most suitable solution for dense urban deployment due to its high reliability, high data rate, and high availability. However, these advantages come with an extra cost [6]. The two types of wired backhauling are copper and optical fiber cables. Table 3 presents the different types of copper cables available for backhauling with their corresponding maxima downstream and upstream data rates.

3.1.1 Wired Backhauling

Copper cables are in different kinds; they can be the E1/T1 or the Digital Subscriber Line (DSL). E1/T1 cables are the ancient backhaul medium between base transceiver stations (BTS) and base station controller (BSC). They operate using time division

multiplexing techniques known as plesiochronous digital hierarchy (PDH). There are two standard PDH delivering different bit rates: the T-carriers (T1–T4) and E-carriers (E1–E5). Leased T1/E1 copper lines dominate the backhaul solutions in the 1G and 2G networks as they provide suitable support for voice traffic, deterministic QoS, low latency, and low delay variations (jitter). However, the increase in the required backhaul capacity with the later generations of mobile networks has caused a huge growth in the number of T1/E1 connections and cost. As a result, leased T1/E1 is not a suitable backhaul option for future networks [8]. DSL over existing copper infrastructure is a good backhaul option for short distances. This is mostly used for indoor backhauling and for broadband applications [8]. However, its backhaul capacity depends on the technology and the distance from the exchange. The continuous improvements in DSL technology led to the evolution of ADSL2+, GSHDSL.DOC, VDSL2, VDSL2+, etc. making them viable for mobile backhaul in future networks [9].

3.1.2   Optical Fiber Cable

An optical fiber cable comprises of a transparent core and a cladding with rays of light kept in the core by total internal refraction, while information is transmitted as rays of light from one point to another within the cable. Fiber, which is widely used for a shorter length, can support multiple propagation paths known as multimode Fiber (MMF). A single-mode fiber (SMF) has a single path, and it provides high-speed connectivity, making it suitable for future networks because any backhaul capacity can be served [10]. On the other hand, a huge capital expenditure (CAPEX) of up to $100,000 per km is incurred by the MNOs. It also requires permits, trenching, boring, and ducting leading to high deployment duration [11]. Direct fiber could be used to connect SBS or a hybrid or fiber and any other backhauling technologies such as microwave. Figure 2 shows a typical fiber optics backhaul architecture.

3.1.3   Cloud Radio Access Network (C-RAN)

Cloud RAN (C-RAN) is a network architecture which maximizes baseband unit (BBU) utilization by pooling network resources into a centralized, virtual pool called the BBU/DU pool/hotel. These resources are then shared between the remote radio heads (RRH). This architecture was first referred to as wireless network cloud by IBM, but its name was later changed to C-RAN where the letter "C" could mean "Cloud" or "Centralized." However, in massive deployment, its high-speed fronthaul connection makes it less cost-effective. Also, the latency requirements for the BBU, real-time requirement for the operating system, clock synchronization, and capacity requirement are its major limitations [12].
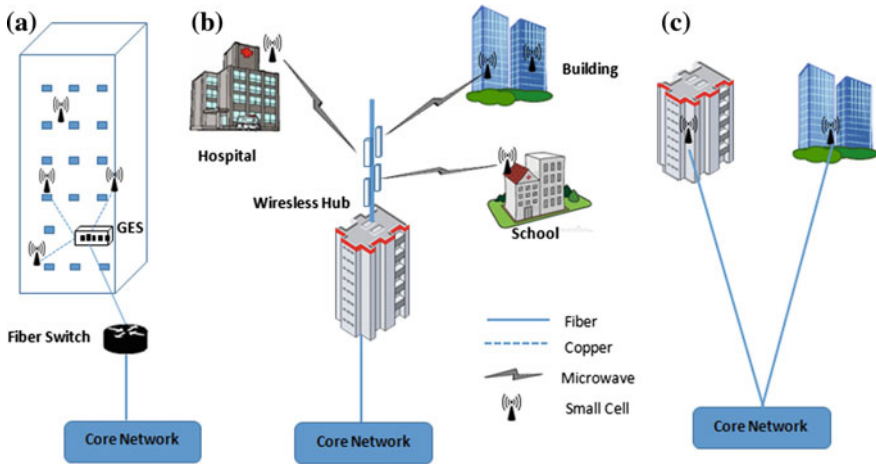
Fig. 2 Fiber optic backhaul architecture **a** fiber–copper architecture, **b** fiber–microwave, **c** direct fiber

3.2 Wireless Backhauling

Although wireless backhauling, when compared to the wired counterpart, has lesser capacity and reliability, it becomes useful in areas where wired backhauls are difficult to deploy in terms of location or cost [10]. Wireless backhauls are of two major types: line of sight (LoS) and non-line of sight (NLoS). LoS backhaul requires that both communicating antennas have clear visibility to each other for communication to be made, while the NLoS does not require clear visibility to establish information exchange [13]. Wireless backhaul includes microwave, satellite, TV white space, self-backhauling, etc. Parameters such as communication channel, spectrum efficiency, cost of the backhauling, and backhaul capacity among others, for the two types of wireless backhauls, are compared in Table 4.

3.2.1 Self-backhauling System

Self-backhauling system uses the existing cellular network infrastructures to provide backhaul traffic. It involves the use of existing macro-RAN to provide backhaul to SBS as shown in Fig. 4. Its merits include flexible deployment in dense SBS scenarios using NLoS requirement, cost saving through reusing of macrocell infrastructures such as spectrum, and leveraging the existing macrosite management and control (such as security management, resource management, and fault management) [14].

Table 4 Comparison of LoS and NLoS wireless backhauls

Parameters	LoS	NLoS
Communication channel	Requires a clear unobstructed visibility between antenna	Requires only to be placed within range of the backhaul radio unit
Multipath fading and signal interference	A highly directional beam transmits the data in a straight line with little or no fading or multipath radio interference	NLoS systems using OFDM present a level of tolerance to multipath fading and other wireless channel impairments not possible with LoS systems
Spectrum efficiency	This is a highly efficient use of spectrum, as multiple microwave transceivers can function within a close proximity to each other and reuse the frequency band for transmitting separate data streams	It has limited spectrum efficiency; hence, frequency planning would have to be planned to avoid too much interference
Areas of application	Mainly used for high-bandwidth applications for outdoor small cell deployments rather than indoor cells	It can provide coverage for various types of small cell setups with proper design
Tolerance to environment changes	Pole tilting or swaying are problems for deploying small cell backhaul on structures like utility, lighting, and traffic poles. Also, environments with many trees, such as park, could block LoS making them impractical location for small cells backhauled through LoS technology	A single NLoS base station can provide coverage for multiple small cells within the coverage area without the need for an unobstructed path between the transceivers, this makes the technology highly helpful for future planning and upgrades
Cost of the backhauling	The cost of the backhaul rises quickly when compared to NLoS in cases of huge deployment especially if daisy chains are involved as significant number of skilled technicians are usually required for antenna alignment for LoS technologies	NLoS technologies are easy to deploy as they are mostly "plug and play" and can be set up in a short time with reduced labor costs
Backhaul capacity	LoS technologies have no upper limit lower than that offered by the network	NLoS technology has an upper limit to the amount of data that each coverage area can backhaul

3.2.2 Microwave and Millimeter Wave Backhaul

Microwave and millimeter wave backhauls have dominated mobile networks for years, especially in challenging geographical areas. They are easy to deploy and they support a distance of up to 50 km. New innovations (such as adaptive coding and modulation (ACM), compression accelerators) are being made so as to increase the bandwidth on both links, hence making them operate in both LoS and NLoS (but microwave is mostly used in LoS backhaul) using point-to-point (P2P) or point-to-multipoint (P2MP) topologies [15]. The setback to microwave is that operating in the licensed band increases the CAPEX while operating in the unlicensed band and E-band takes less CAPEX (which is lightly licensed and relatively easy permission, with frequency ranging from 70 to 80 GHz). However, it suffers attenuation from atmospheric effects and other signals. In addition, it has been established that the operating frequency and bandwidth of E-band are inversely proportional to coverage distance. This makes the E-band mostly used in small cell backhauling and short distance links. Also, when the gap between coverage areas is large and unpopulated, it is not economically feasible to add towers to bridge the distance.

3.2.3 Satellite Backhauling

This type of backhaul is preferred in remote areas where other backhaul solutions are uneconomical to deploy [6]. Backhaul over satellite was demonstrated in 2012 to deliver a speed of 10 Mbps at download speed and 7 Kbps upload speed [7]. In many areas where terrestrial infrastructure is limited satellite becomes the primary option for transporting voice and data services. Satellite communication is not affected by topological variations such as distance, terrain or LoS, making it the most viable option for backhauling. Although satellite might be more expensive than other wireless solutions, it is scalable, highly reliable and can be deployed quickly, even under the most challenging geographical and climatic conditions. Also, the invention of small cell technology has motivated some MNOs to consider the use of carrier-class satellite backhaul as a viable option to more traditional backhaul types. Compared to macrocell solutions, these small cell networks are less expensive; when coupled with a low-cost satellite MODEM/router. Moreover, it enables MNOs to expand coverage into rural areas quickly and economically or operate smaller networks on board ships, in aircraft, or in remote mining areas [16]. In future network, the satellite will contribute in areas like coverage extension, enhanced spectral utilization integrated signaling systems, and providing resilience [17–19].

3.2.4 Wireless Fidelity (Wi-Fi) Network Technology

Wi-Fi has been modified from its initial indoor usage to feasible backhaul connectivity of up to 38 km. It is based on the IEEE 802.11 standard using 5.8 and 2.4 GHz unlicensed band. This feature, together with its low cost and flexible deployment,

makes it a good alternative for microwave backhaul. However, it has design limitations relevant to the achieved throughput, distance coverage, packet overhead, timing, and synchronization [8, 9].

3.2.5 Massive Multiple-Input Multiple-Output (M-MIMO) Backhauling

Massive MIMO system involves scaling up the antenna system of MIMO whereby hundreds of MBS antennas serve thousands of Mobile terminals in the same time–frequency resource. With aggressive spatial multiplexing and array gain, massive MIMO could achieve capacity increase and energy efficiency improvement [20, 21]. However, M-MIMO provides limited throughput to mobile end users in high path loss channels, but this could be improved with the introduction of small cells. This results in M-MIMO-based HetNet [22]. Other merits of M-MIMO include energy and cost efficient components, reduced air interface latency, and in-band wireless backhaul [23].

3.2.6 Worldwide Interoperability for Microwave Access (WiMAX)

WiMAX is a broadband broadcasting technology designed using IEEE 802.16 standards, and researches are done for outdoor purposes [8, 24]. It uses orthogonal frequency division multiplexing (OFDM) to provide higher throughput, guaranteed QoS, and larger coverage area than Wi-Fi. Theoretically, it can deliver data rates from 75 Mbps in a single channel and up to 350 Mbps via multiple channels). It can work in both unlicensed (typically 2.4 and 5.8 GHz) and licensed (typically 700 MHz, 2.3, 2.5, and 3.5 GHz) bands. Hence, the technology reduces the CAPEX more than microwave as it offers a cheaper license spectrum as well as unlicensed option. It uses the IEEE 802.16-2004 standard for backhauling in fixed connectivity applications, P2P, P2MP, and mesh topology. It also supports high-throughput data aggregation [6]. There are two main sets of WiMAX: the fixed WiMAX and the IEEE 802.6e-2005 [24].

The fixed WiMAX was originally designed using IEEE 802.16-2001 standard for fixed wireless broadband air interface with LoS and P2MP applications only but was modified in subsequent standards up to 802.16d-2014 to target NLOS and add WiMAX system profiles and Errata for 2–11 GHz. The 802.16e-2015 is an amendment of the fixed WiMAX for mobile wireless broadband providing up to vehicular speeds in licensed bands from 2 to 8 GHz. It also enables roaming for portable users (laptops, tablets, etc.) within and between service areas [25].

4 Performance Evaluation of Different Backhauling Options

Minimum delay and latency, low cost and time to deploy, high-energy efficiency, and availability of bandwidth for future improvements are the vital backhaul requirements to sustain a network for future HetNet. These requirements vary with the available backhaul options. Hence, there is a need to provide a critical and thorough comparison among the available backhauling options as shown in Tables 5 and 6.

5 System Concept

The system concept introduced in this paper, as illustrated in Figs. 2, 3, 4, 5, 6, and 7, consists of a conventional fixed microwave backhauling that is configured in P2P and P2MP topology, the self-backhauling, M-MIMO, satellite, fiber, and C-RAN. These are used to backhaul seven (7) SBS. For the microwave backhauls, we assume LOS clearance between the microwave units (wireless hubs) and the SBS due to operation in higher frequency bands. However, this LoS requirement can be relaxed by using alternative multihop topologies (e.g., mesh) to route the fixed wireless links around shadowing objects (e.g., buildings, mountains, etc.). For C-RAN, the SBS/RRHs are connected to the BBU. Then, a fronthaul fiber is used to link the BBU to the core network. In the case of fiber, we consider direct fiber connections to each SBS. The satellite system consists of VSAT hubs connecting remote SBS. The M-MIMO and self-backhaul require umbrella macrocells since the macroradio access link is used to backhaul the small cells. We assume the SBS to be distributed within the MBS cell coverage area. The MBS users (MBS UE) and SBS user (SBS UE) are randomly distributed within the MBS and SBS coverage areas, respectively, while the SBS are uniformly distributed. The MBS radio access link is used to transmit the backhaul traffic between the SBS and MBS. However, due to the capacity requirements of the traffic aggregates from multiple SBS within the coverage area of the MBS, all other UE traffics, both from the MBS and SBS, are routed to the core network via fiber links. For fairness, in all the scenarios, we assumed that all the SBS transmits on the same power level. Therefore, under normal condition, their power consumption and the sizes of their coverage footprint are expected to be the same.

6 Backhaul Power Consumption Models

6.1 Power Consumption in MBS

The power consumption of the MBS (in watts) is given in Eq. (1) [3]:

Table 5 Performance evaluation of fiber cable, copper cables, self-backhauling, and microwave and millimeter wave backhauling options

Parameters	Fiber cable	Copper cables	Self-backhauling	Microwave and millimeter wave
Cost	Huge CAPEX because it requires permits, trenching, boring and ducting	Low if already existing but the cost is high for new deployment or leasing	Low as existing cellular network infrastructures are used	Operating in the licensed band cost more CAPEX while operating in the unlicensed band and E-band requires lower cost
Energy efficiency	Highest	High	Moderate	Moderate but can be improved using energy-saving devices
Quality of Service (QoS)	Excellent	Guaranteed	Depends on the presence of a regulatory framework for sharing of network resources	Guaranteed
Delay and latency	Low	Low	Low	Low
Network capacity	Unlimited capacity	High with recent brands (10 Gbps)	Limited but can be improved by adding more carriers	High (2–170 Mbps)
Available bandwidth for future improvement	High	Not imminent as capacity depends on number of cables	Medium with modifications	High available spectrum especially in the V and E-band
Suitability for heterogeneous network	Aggregation and core	Indoor small sites and for low traffic MBS backhauling	Small cell backhauling	MBS and SBS backhauling
Duration of deployment	Months and possibly years	Months and possibly years	Days	Weeks
License required	No, but permit required for laying cables	No but permit required for laying cables	No new licensing is required as same licensing for RAN	Licensed for microwave but light licensed/unlicensed for V-band

(continued)

Table 5 (continued)

Parameters	Fiber cable	Copper cables	Self-backhauling	Microwave and millimeter wave
Synchronization and timing	Available	Available	Not available	Available
Power consumption	Least	Least	Low	Moderate
Ease of deployment	Difficult	Difficult	Easy	Easy

Table 6 Performance evaluation of Wi-Fi, M-MIMO, satellite, and WiMAX backhaul options

| Parameters	Wi-Fi	M-MIMO	Satellite	WiMAX
Cost	Low	Low	Small cell satellite requires low CAPEX	Low but standardization is expected to decrease the CAPEX
Energy efficiency	Moderate as it has low power, low consumption but low throughput also	Better spectral efficiency and energy efficiency	Energy-saving mechanism such as split architecture can improve the energy efficiency	Moderate but better than Wi-Fi as it offers greater throughput
QoS	Not guaranteed	Guaranteed	Suffers propagation delay	Guaranteed in P2MP model
Delay and latency	Low	Low	High	Low
Network capacity	High (11, 54 or 600 Mbps)	High as it multiplies the capacity without requesting for more spectrum	Medium (384 Kbps to 4.81 Mbps)	High (75–359 Mbps)
Available bandwidth for future improvement	High	Sufficient bandwidth using same frequency resources	Bandwidth depends on some parameters such as size of antenna, etc.	Higher than Wi-Fi
Suitability for heterogeneous network	Small cell backhauling	MBS and SBS backhauling	Geographically challenged areas and low density area backhauling	Outdoor and indoor Small cell
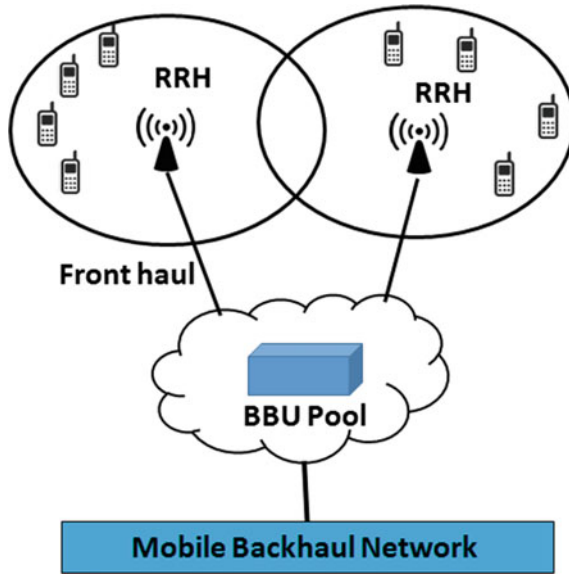
Fig. 3 Architecture of C-RAN HetNet
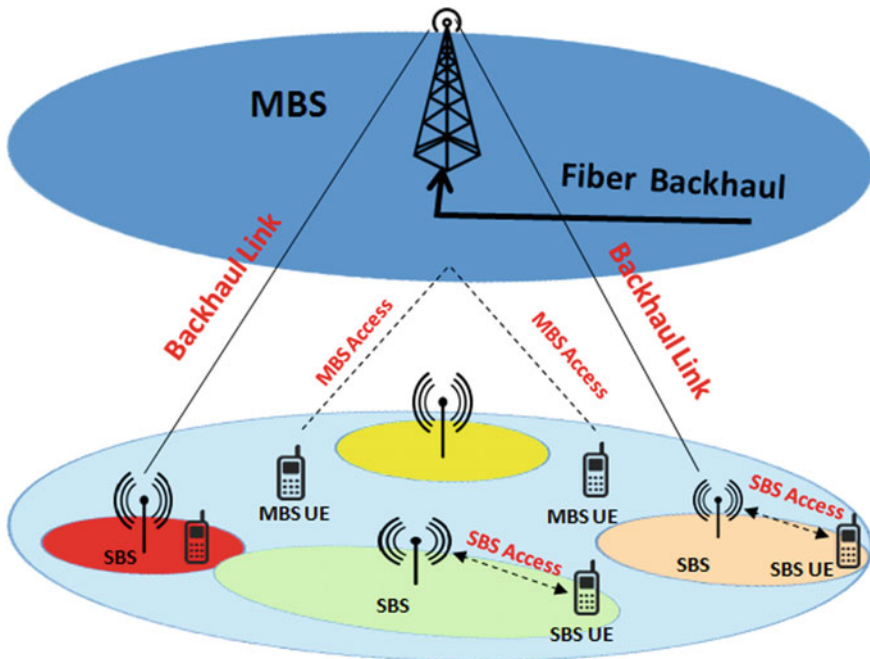
Fig. 4 Architecture of self-backhauling network
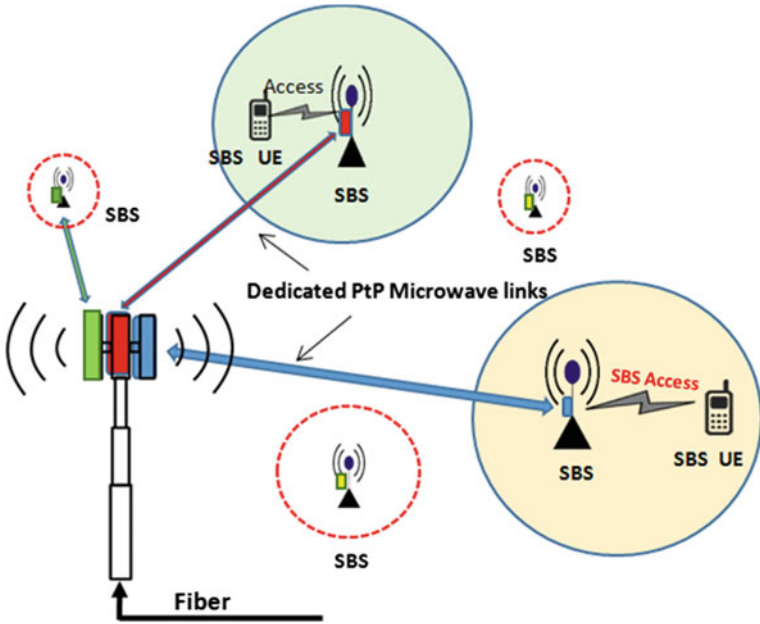
Fig. 5 Architecture of microwave and millimeter wave backhaul
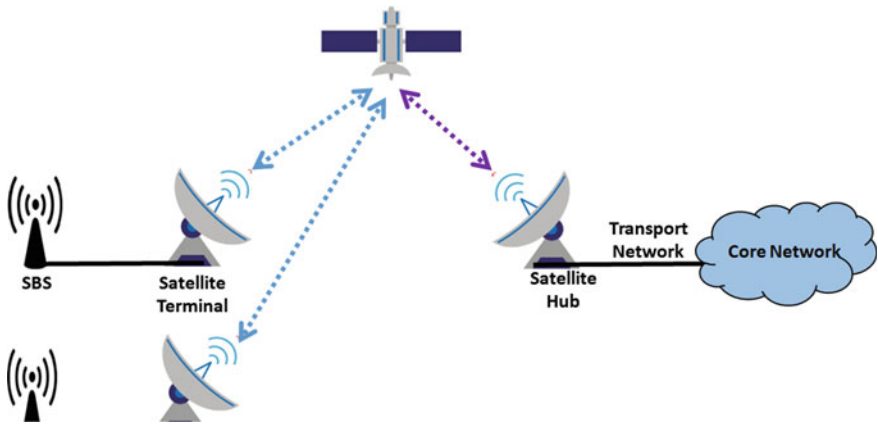
Fig. 6 Satellite backhaul architecture
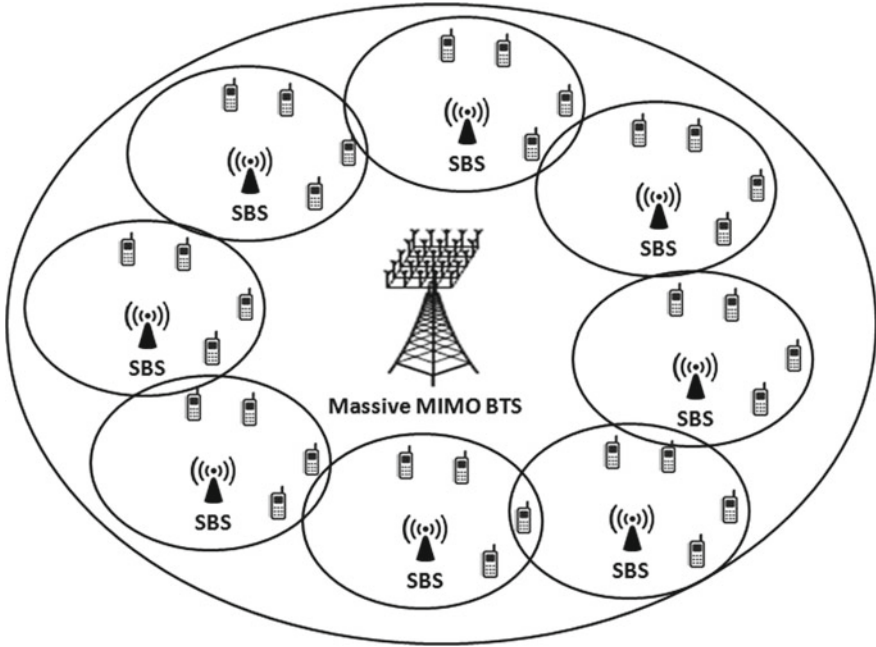
Fig. 7 Architecture of M-MIMO HetNet

$$P^{\text{MBS}}(f_a) = n_{\text{sector}} \times \left(f_a \times \left(n_{\text{TX}} X \left(P_{\text{PA}} + \frac{P_{\text{TRX}}}{P_{\text{RF}}} \right) + P_{\text{DSP}} \right) + P_{\text{rec}} \right) + \sum_{i=1}^{n} P_i^{\text{link}} + P_{\text{cool}} \quad (1)$$

6.2   Power Consumption in SBS

The power consumption of the SBS P^{SBS} (in watts) is given in Eq. (2) [3]:

$$P^{\text{SBS}}(f_b) = P_{\text{rec}} + f_b \times (P_{\text{PA}} + P_{\text{DSP}} + P_{\text{rec}}) + P_{\text{cool}} \quad (2)$$

6.3   Self-backhauling

The power consumption for the self-backhaul is given in Eq. (3) [3]:

$$P_{\text{selfB}}(f_a) = \sum_{j=Q}^{r=1} N_j P_j^{\text{MBS}} f_a \quad (3)$$

6.4 M-MIMO Backhauling

The power consumption of M-MIMO MBS can be modeled adopting a linear BS power consumption model as shown in Eq. (4).

$$P^{\text{MB}}(f_{\text{a}}) = f_{\text{a}} \times (1/n_{\text{PA}} \times P_{\text{t}} + M \times P_{\text{c}}) + P_{\text{DSP}} + P_{\text{rec}} + P_{\text{cool}} \qquad (4)$$

6.5 Microwave Backhauling

Given SBS $\left(C_j^{\text{SBS}}\right)$ be the aggregate backhaul capacity of the microwave links at the SBS at the site j and N_k^{SBS} the total number of microwave at SBS, then the power consumption of the microwave at the central point is given as [3]:

$$P_{\text{SBS,t}}^{\text{bh}} = P_{\text{SBS}}^{\text{agg}}\left(C_j^{\text{SBS}}\right) + P_{\text{switch}}^{\text{SBS}}\left(N_k^{\text{SBS}}, \; C_j^{\text{SBS}}\right) \qquad (5)$$

$$P_{\text{c},t}^{bh} = P_{\text{c}}^{\text{agg}}(C^{\text{c}}) + P_{\text{switch}}^{\text{c}}\left(N_k^{\text{c}}, C^{\text{c}}\right) \qquad (6)$$

If C_{th} is assumed to be 500 Mbps, therefore, generalize the total backhaul consumption for the microwave (i.e., P2P and P2MP) network topology as:

$$P_{\text{tot,t}}^{\text{bh}} = \begin{cases} P_{\text{c,t}}^{\text{bh}} + N_k P_{\text{SBS,t}}^{\text{bh}} & t \in \text{P2MP} \\ \left(P_{\text{c,t}}^{\text{bh}} + P_{\text{SBS,t}}^{\text{bh}}\right)N_k & t \in \text{P2P} \end{cases} \qquad (7)$$

6.6 Satellite Backhaul Power Model

The power consumption of a heterogeneous satellite VSAT network including the backhaul part can be written as:

$$P_{\text{tot}}^{\text{sat}} = \sum_{i=1}^{N} M_i P_i + P_{\text{hub}}^{\text{sat}} + P_{\text{switch}} + P_{\text{sbs}}^{\text{sat}} \qquad (8)$$

$$P_{\text{bh}}^{\text{sat}} = P_{\text{hub}}^{\text{sat}} + \sum_{j=1}^{M_{\text{bs}}} P_j^{\text{sbs}} \qquad (9)$$

6.7 C-RAN Backhauling

Regarding the total power consumption in C-RAN where power consumed by RRHs as well as that by the BBU pool is concerned. It can be expressed as follows:

$$P_{\text{total}} = \sum_{i\text{EN}} P_{\text{R}} + P_{\text{B}}, \tag{10}$$

As for the power consumption at RRH, P_{R} can be expressed as:

$$P_{\text{R}} = \frac{x_i . P_i}{\eta} + P_{\text{RF}}, \tag{11}$$

Thus, P_{B} can be expressed as follows:

$$P_{\text{B}} = m.\left(P_0 + \Delta_{\text{p}} \cdot P_{\text{max}} \cdot y\right), \tag{12}$$

where m denotes the number of active BBUs, P_0, and P_{max} are the power consumption of BBU in idle mode and in full usage mode, respectively. Besides, Δp is the slope of the equivalent linear power model which depends on the specific server adopted, and y denotes the average utilization of each active BBU. Furthermore, the number of active BBUs and the average utilization of each active BBU are related to the load of each RRH. Based on this fact, parameters m and y can be expressed as follow:

$$m = \left[\frac{\sum_{i\text{EN}} k.x_i}{X_{\text{cap}}}\right] \quad y = \frac{\sum_{i\text{EN}} k \cdot x_i}{m \cdot X_{\text{cap}}} \tag{13}$$

where k is a relevant coefficient, X_{cap} denotes the baseband processing capacity of one BBU in the BBU pool. In addition, load balancing is considered in calculating the average utilization of each active BBU. Also, P_{B} can be further expressed as follows:

$$P_{\text{B}} = \left[\frac{\sum_{i\text{EN}} k \cdot x_i}{X_{\text{cap}}}\right] P_0 + \frac{\Delta_p . P_{\text{max}}}{X_{\text{cap}}} \sum_{i\text{EN}} k \cdot x_i \tag{14}$$

In summary, the total power consumption in C-RAN, where both wireless transmission power and baseband processing power are concerned, can be written as follows:

$$p_{\text{total}} = m \cdot P_0 + \sum_{i\text{EN}}(a \cdot p_i \cdot x_i + b \cdot x_i + P_{\text{RF}}) \tag{15}$$

where $a = 1 = \eta, b = \Delta p \cdot P_{\text{max}} \cdot k/X_{\text{cap}}$.

6.8 *Fiber Optic Backhauling*

For the fiber-based case, the total power consumption of a heterogeneous mobile radio network including the mobile backhaul can be written as:

$$P_{\text{tot}}^{\text{FIB}} = \sum_{i=1}^{m} N_i P_i + P_{\text{bh}}^{\text{FIB}} \tag{16}$$

where according to the parameters defined below:

$$P_i = a_i P_{\text{tx}} + b_i + c_i \tag{17}$$

$$P_{\text{bh}} = \left[\frac{1}{\max_{\text{dl}}} \left(\sum_{i=1}^{m} N_i \right) \right] p_s + \left(\sum_{i=1}^{m} N_i \right) P_{\text{dl}} + N_{\text{ul}} P_{\text{ul}}$$

7 Simulation Parameters and Energy Efficiency Metrics

The energy consumption metric is used to quantify the energy consumption of HetNets in order to characterized and measure our findings. This is to compare the various HetNets system under investigation and to evaluate their efficiency and identify where backhaul solution can be deployed while highlighting the trade-off for such deployment. Our metrics were defined energy consumption per some entities which include coverage area (w/m^2), capacity (w/bits), and per load factor. The two major energy standard metrics are the energy consumption ratio (ECR) and the telecommunications energy efficiency ratio (TEER).

The ECR metric is defined as the ratio of the peak power (measured in Watts) to the peak data throughput rate in bits per second and thus can be described as energy consumed per bit of information transported express in joules per bit. This can be mathematically express as:

$$\text{ECR} = \frac{\text{POWER}}{\text{DATA RATE}} = \frac{\text{Watt}}{\text{Bps}} = \frac{\text{joul}}{\text{bit}} \tag{18}$$

The TEER metric is a generic metric which is defined the ratio of useful work done to the total power consumed; hence, we defined our TEER as coverage area per consumed power which is mathematically expressed as:

$$\text{TEER} = \frac{\text{POWER}}{\text{COVERAGE}} = \frac{\text{Watt}}{\text{Area}} = \frac{\text{joul}}{\text{m}^2} \tag{19}$$

8 Results and Discussion

The power consumption of different backhaul systems is given by Eqs. (10)–(19). In this analysis, a HetNet system with 7 SBS was considered. Specific implementation of the energy-efficient microwave links was also considered based on realistic power consumption. This typically ranges from 25 to 50 W. We also considered the load-varying power consumption of the microwave units. In Fig. 8, the power consumption profiles (i) M-MIMO, (ii) self-backhauling, (iii) P2P wireless backhaul, (iv) P2MP wireless backhaul, (v) satellite backhauling, (vi) CRAN, and (vii) fiber are shown. The HetNet system comprises of seven (7) small base stations (SBS). The power consumption of the SBS was kept low (<200 W) as possible, even though, the load-dependent components only contributed 39.5 W of the total power consumption, while the non-load dependent amounted to 160 W and this is about 80% of the total power which is mainly attributed to cooling. The MIMO backhaul system consumes the highest power of 3.6341 kW at maximum load. In this analysis, we used 48 transmitting antennas ($M = 48$). This power budget is rather conservative as 48 transmitting antennas were used since no specific figure is set that constitutes M-MIMO setup. However, Huawei, ZTE, and Facebook used as many as 96–128 antennas to demonstrate M-MIMO systems. Therefore, the power requirement would be high. For the self-backhauling, the transmitter power levels for the MBS is assumed to be 20 W and the power consumption of the DSP, transceiver, rectifier, and backhaul, respectively, are 29.5, 13, 180, and 35 W [3]. Then, the load-dependent power consumption for a 3-sector LTE system with 10 MHz bandwidth and 2×2 MIMO system for the MBS gave the highest value at peak load as 2.7693 kW.
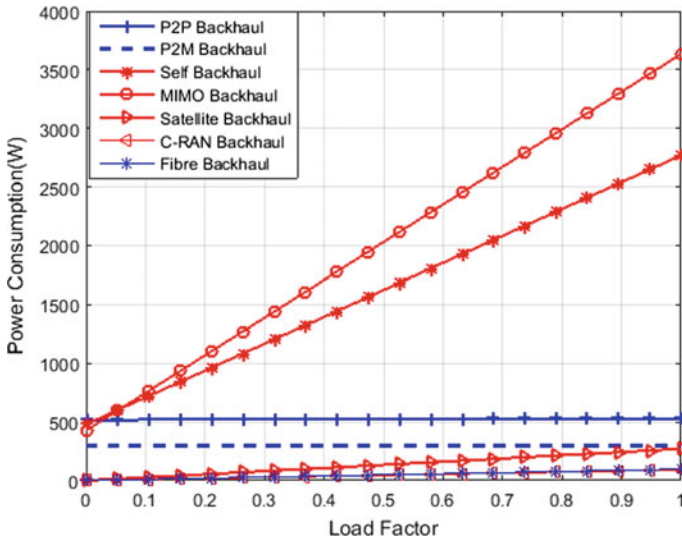

Fig. 8 Power consumption profile of different backhaul systems

The power consumption of the microwave P2P backhaul for both at the hub site and SBS location are 528.6 and 216.44 W, respectively. The backhaul power was computed for the P2MP HetNet at both hub site and SBS as 302.0571 and 216.4400 W, respectively. In this analysis, a microwave unit that supports up to seven small cells was considered. Furthermore, the power consumption of the switch at the hub site and SBS were observed to be 53 and 37 W, respectively. As shown in Fig. 8, the load-dependent component of the power is negligible. The P2MP system consumed less power as few backhaul units are needed to support many cells. In this situation, one microwave unit was used to backhaul seven SBS. On the other hand, the satellite, fiber, and C-RAN are at the lower part of the curve with fiber optics backhaul consuming the least. Moreover, the load-dependent component of the power is negligible, and little effects were observed. Almost no load impact was observed for C-RAN and fiber as both backhaul system operates similarly. The total power consumed by the satellite hub site (backhaul) and SBS are 271.0571 and 216.4400 W, respectively. Component power of 25, 30, 96.8083, and 90.1920 W were consumed by the transponder, VSAT hub, fiber, and C-RAN backhaul, respectively.

Figures 9 and 10 depict the capacity efficiencies of all the backhaul systems under consideration. The capacity efficiency shows how much power is consumed to receive, process, and transmit a bit of information. This is computed by normalizing the power consumption for each backhaul system relative to the backhaul capacity. In this analysis, we used a fixed and uniform capacity of 500 Mbps. Figure 9 shows that fiber is the most efficient as it consumed less power to deliver the expected capacity, followed by the CRAN, satellite, P2MP in that order. Figure 10 shows how this power demand varies with capacity requirements. Similarly, peak power consumption for each backhaul was used, although this is expected to significantly higher than the values used. For a simple illustration, we maintained these peak values. Also, Fig. 10 shows that the capacity efficiency decreases with an increase in data rates, fiber, and C-RAN yielding best results as only about 10 W is required to process and transmit a bit of information at 10 Gbps for fiber, whereas, about 364 W is needed for massive MIMO and 278 W for self-backhauls.

Figure 11 presents the coverage effectiveness for each backhaul system. This is defined as the amount of power consumed per unit square area for each backhaul system. It indicates how much area is covered when 1 W power is consumed. We obtained the coverage effectiveness of self-backhaul and massive MIMO backhaul to be in a range of 0.0016–0.0025 and 0.0015–0.0028, respectively. At medium and high network load, self-backhaul consumes less power than the M-MIMO backhaul because the lower the W/m^2 the better the efficiency. But at extremely low network traffic, less than 10%, the massive MIMO backhaul is more efficient. We obtained the coverage effectiveness of point-to-point, point-to-multipoint microwave, and satellite backhauls to be in a range of 0.3898–0.04996 W/m^2, 0.4503–0.5619, and 0.3808–0.4911, respectively. Fiber and C-RAN backhauls consume negligible power to cover the area.
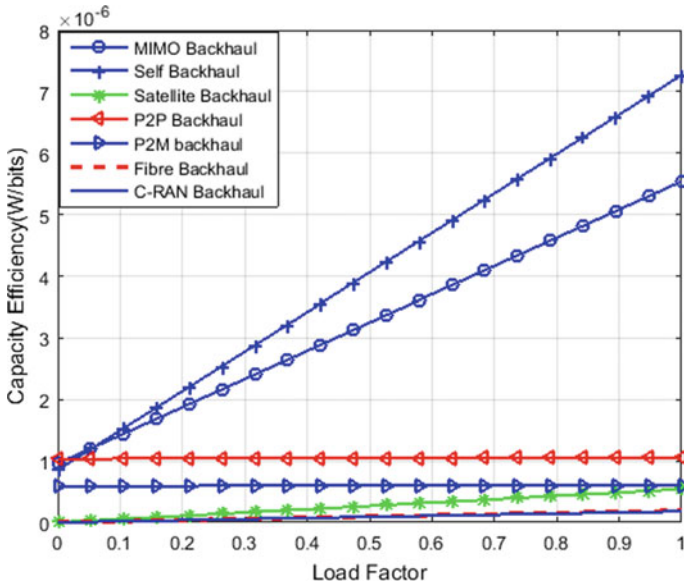
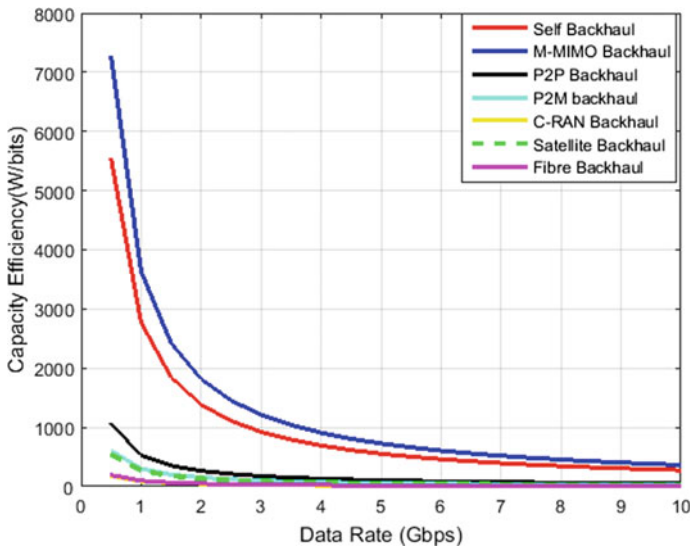**Fig. 9** Capacity efficiency of different backhaul systems

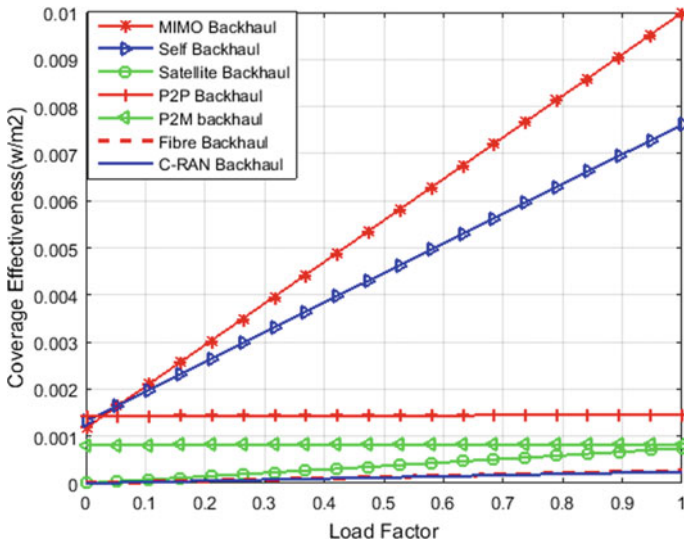**Fig. 10** Capacity efficiency of different data rates

Fig. 11 Coverage effectiveness of different backhaul systems

9   Conclusion

HetNet densification, by the means of deploying a large number of SBS, has been identified as a key enabling strategy in meeting up the unprecedented mobile data demands in next-generation cellular systems. Provision of effective backhaul system for a large number of SBS without a high risk of increasing the CAPEX, OPEX, and network energy costs still remains the main bottleneck.

This paper highlights various backhauling options for future SBS HetNet deployments. The pros and cons for each backhaul system technologies are compared with respect to popular performance metrics that are major drivers for future networks. Fiber optics and C-RAN still remain the most contending options as they are the most energy efficient and could provide unlimited data rates with minimal delay and latencies. The initial CAPEX and ease of deployment, however, may be the issue. Self-backhauling and M-MIMO consumed high power. The power demand varies with capacity requirements. The finding of this study will help the network service providers to make more informed decisions in achieving optimum, sustainable, and energy-efficient backhaul deployment for future heterogeneous networks.

References

1. Ghosh A et al (2012) Heterogeneous cellular networks: from theory to practice. IEEE Commun Mag 50(6)
2. Soh YS et al (2013) Energy efficient heterogeneous cellular networks. IEEE J Sel Areas Commun 31(5):840–850
3. Faruk N et al (2016) Energy savings through self-backhauling for future heterogeneous networks. Energy 115:711–721
4. Spagnuolo A et al (2015) Monitoring and optimization of energy consumption of base transceiver stations. Energy 81:286–293
5. Deruyck M et al (2011) Modelling and optimization of power consumption in wireless access networks. Comput Commun 34(17):2036–2046
6. Zhang Z et al (2015) Large-scale MIMO-based wireless backhaul in 5G networks. IEEE Wirel Commun 22(5):58–66
7. Jaber M et al (2016) 5G backhaul challenges and emerging research directions: a survey. IEEE Access 4:1743–1766
8. Tipmongkolsilp O, Zaghloul S, Jukan A (2011) The evolution of cellular backhaul technologies: current issues and future trends. IEEE Commun Surv Tutorials 13(1):97–113
9. Farias F et al (2016) Cost-and energy-efficient backhaul options for heterogeneous mobile network deployments. Photon Netw Commun 32(3):422–437
10. Muhammad AI, Mona J, Rahim T (2016) 5G Backhual and research direction: a survey. IEEE Access 1743–1766
11. Laxmi RK (2018) Fibre to the BTS—improving network flexibility & energy efficiency. FLA division study paper
12. Tombaz S, Monti P, Wang K, Vastberg A, Forzati M, Zander J (2011) Impact of backhauling power consumption on the deployment of heterogeneous mobile networks
13. GSMA (2014) Wireless backhaul spectrum policy recommendations & analysis. ABI Research Technology and Market Intelligence
14. Faruk N et al (2018) Green energy and technology. In: Advances on computational intelligence in Energy; the application of natural-inspired metahueristic Algorithm. Springer, Berlin
15. Alcatel-Lucent (2018) Small cells backhaul in strategic white paper
16. Oren D (2011) Satellite communication for efficient cellular backhaul
17. Evans BG (2014) The role of satellites in 5G. In: Advanced satellite multimedia systems conference and the 13th signal processing for space communications workshop (ASMS/SPSC), 7th 2014. IEEE
18. NetWorld's–SatCom W (2014) The role of satellites in 5G. White paper
19. Onireti O et al (2015) The role of satellites in 5G
20. Rusek F et al (2013) Scaling up MIMO: opportunities and challenges with very large arrays. IEEE Signal Process Mag 30(1):40–60
21. Larsson EG, Marzetta T, Rusek F (2013) Scaling up MIMO: opportunities and challenges with very large arrays. Sig Process Mag IEEE 30(1):40–60
22. Hoydis J, Ten Brink S, Debbah M (2013) Massive MIMO in the UL/DL of cellular networks: how many antennas do we need? IEEE J Sel Areas Commun 31(2):160–171
23. Li B, Zhu D, Liang P (2015) Small cell in-band wireless backhaul in massive MIMO systems: a cooperation of next-generation techniques. IEEE Trans Wire Commun 14(12):7057–7069
24. Hassan AHM et al (2015) Performance evaluation of qos in wimax network. arXiv preprint arXiv:1506.04902
25. Golshan R (2013) Fixed and mobile WiMAX overview