

Energy Savings in Heterogeneous Networks with Self-Organizing Backhauling



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Abstract Heterogeneous network (HetNet) deployment of a large number of low-power small base stations (SBS) is expected to meet up coverage and capacity challenges arising from the global upsurge of mobile data traffic volumes, driven mostly by increase of data-intensive devices, such as smartphones and tablets. However, effective backhaul implementation for the SBS still remains the main bottleneck, as the ever-increasing SBS density will lead to a more complex backhauling and, as such, increased risk of raising capital, and operational and network energy costs. In this paper, the conventional microwave backhauls are compared with self-backhauling for typical dense and sparse environments. A heterogeneous network backhaul-energy model is proposed and used to investigate the energy efficiency of the two systems. The impacts of network traffic load and small cells density on power consumption for both backhaul systems were investigated. Furthermore, we present a break-even power point and load threshold level for safe operating regions toward achieving optimum utilization of self-backhauling in a way for higher energy-efficient and sustainable networks compared to traditional homogeneous macro network deployments.

Keywords Base station powering · Self-backhauling · Small cells · Energy saving · Heterogeneous networks

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1 Introduction

The demand for wireless data services, coupled with the global upsurge in mobile connected devices, has created a capacity challenge for the next-generation networks. The number of global mobile connected devices is increasing and has exceeded the world population. This is expected to reach 24 billion in 2019 as predicted by Cisco Visual Networking Index [1]. This has pushed the world's Information Communication Technology (ICT) systems' power consumption to grow by 8% in 2013 from 2% as it was in 2007 [2]. A large share of this growth is due to the power consumption of mobile networks. Globally, mobile network operators (MNOs) have been challenged by this increase of mobile data traffic which is mostly driven by the adoption of data-intensive devices, such as smartphones, leading to continuous network capacity and coverage enhancements so as to meet users' quality of experience thereby to remain competitive and sustain the market share. Network densification using small base stations (SBS) is highly anticipated to meeting up this constraint [3]. This is achieved by replacing the high-powered macro base stations (MBS) with numerous SBS. This approach was found to be efficient in meeting up the network capacity constraints. However, increasing the number of base station (BS) sites would, in turn, increase the energy consumption of the network, rendering the approach to be unsustainable. Typically, in developed countries with stable power supplies, the energy consumption costs for the MNOs contribute to 15% relative to the total network operation expenses [4]. This could exceed 50% in countries, mostly in Africa where there are power generation deficits. In most of these countries, the energy supply is far below the demand; this forced the MNOs to be operating mainly off-grid sites thereby relying on alternative power sources such as the diesel generators and recently solar and battery inverters. Moreover, the on-grid sites still experienced irregular power supply.

Most implementations of the energy-saving strategies are mainly in the radio access network (RAN) and cooling. Some of these include: remote radio units (RRU), radio standby mode, passive cooling, advanced climate control for air conditioners, higher efficiency rectifiers, and DC power system ECO mode [5], little or no effort has been devoted to backhauling. The strategy of scaling network capacity through heterogeneous network (HetNet) deployment of a large number of low-power small base stations (SBS) to complement existing macro base stations (MBS) umbrella coverage (see Fig. 2) is an approach that also has the potential to minimize overall network energy consumption [6]. However, while energy-efficient operation is possible in the small cell radio access, there is always a need for powering in the high-capacity backhaul connection between SBS and the mobile core network.

Currently, SBS backhauling is mostly implemented using point-to-point (PtP) or point-to-multipoint (PtMP) microwave radio links, due to unavailability of cabling and prohibitive cost of using a wired backhaul link toward each SBS [7]. The need for powering of the SBS backhaul links would, in turn, increases risk of raise in capital and operational costs associated with the energy consumption of the SBS sites beyond what could be supported with low-cost renewable energy solutions. Some efforts in

[8–10] were made to investigate the effect of backhaul power consumption and it was established that this cannot be neglected as it affects the total power of a HetNet. The increased SBS deployment density would, in turn, require more backhauling and almost certainly accompanied by increased overall energy consumption mostly attributed to the SBS backhauling. In addition, complexities of the backhaul network could be a big issue since the SBSs would be placed both indoors and outdoors and, considering the usual height of the SBSs that could be in the range 3-6 m above the ground level, the presence of building structures and urban clutter could, therefore, make line-of-sight (LOS) configuration for PtP very challenging. The time required for setting up the network, as well as manpower and network management systems could also be challenging. Self-organizing backhaul networks [11] or self-backhauling is a general concept where the MBS provides backhauling to SBSs via the existing macro RAN. This automation would mitigate backhaul connectivity and management bottlenecks associated with existing backhaul system such as the PtP. Furthermore, it would help in faster deployment and network rollout with minimal human intervention.

This paper, therefore, proposes an energy-efficient backhaul solution for next-generation wireless systems. The conventional microwave backhauls are compared with self-backhauling for typical dense and sparse environments. The paper also presents a break-even power point and the load threshold level for safe operation regions toward achieving optimum utilization of self-backhaul deployment and green backhauling for the deployment of HetNets in a way that is more energy-efficient and sustainable compared to traditional homogeneous macro network deployments.

2 Base Station Types in HETNET and Power System Consideration

2.1 Base Station Types in HetNet

HetNet architecture consists of various base station types, each having different coverage and operating functionalities. In a typical LTE-Advanced multitier HetNet rollout, the network may consist of macro, micro, pico, and femto base stations, remote radio heads (RRHs), and as well as relay stations. Each of these base stations, aside the macro BS, is commonly referred to as low-power nodes (LPN). We generalize this concept as small base stations (SBS). Figure 1 shows typical deployment scenario of HetNet which consists of macro base station and small base stations.

I. Macro Base Station (MBS)

Macro base stations are deployed outdoors and are able to provide 2G, 3G, and 4G services in the range of kilometers. They are backhauled via fiber optics and/or microwave. A macro base station consists of three main segments: the transmission equipment (TE), cooling equipment, and auxiliary equipment (AE). The TE includes

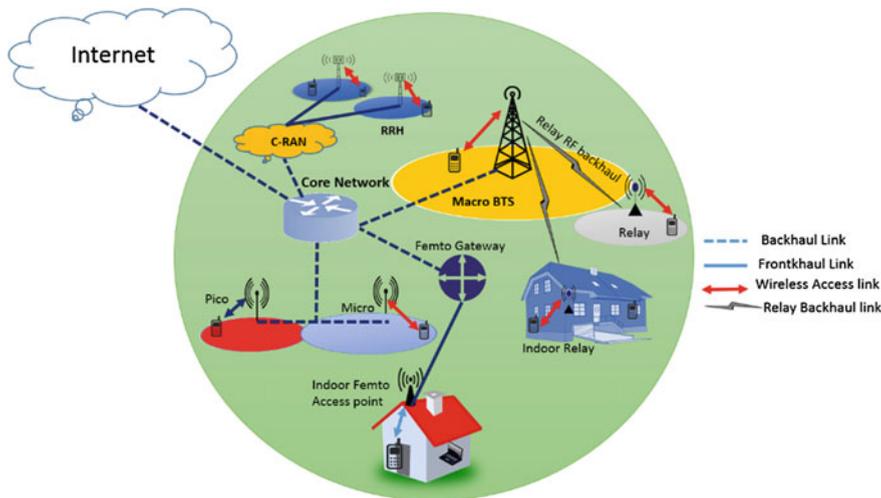


Fig. 1 Typical heterogeneous network deployment scenario

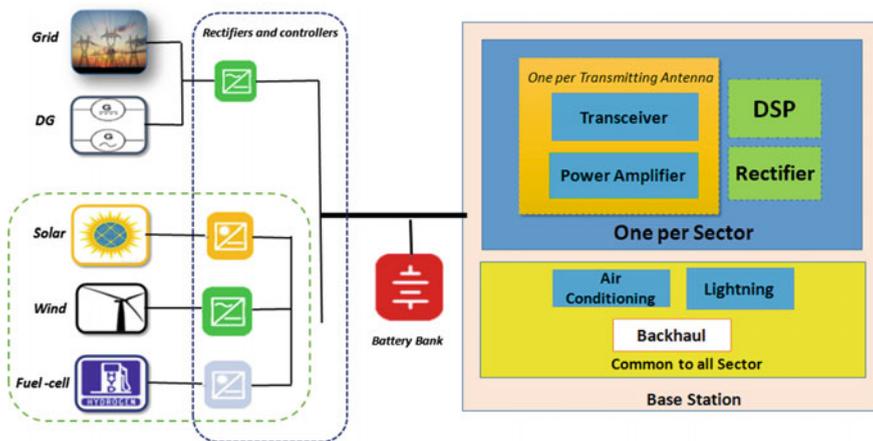


Fig. 2 Block diagram of base transceiver station (BTS) site and complete power system

the power amplifiers (PA), transceivers (TRX), digital signal processing (DSP), and rectifiers, and these are deployed per sector or cell at a given BS site as shown in Fig. 2.

Therefore, the overall power consumption budget of the BS site is per sector consumption multiplied by the number of sectors and the number of TXR per sector in the case of MIMO antenna systems. The cooling systems, lightning, security alarms, and backhauls are all common to all sectors and are deployed to serve the whole BS site. Among these components, the PA and air conditioners (ACs) are the

most power-consuming components with AC consuming about 50–60% of the total power consumed by the BS site (see for instance, measurement conducted in [12]).

II. Small Base Stations (SBS)

Compared to MBS, a micro BS consumes less power since it does not need power hungry cooling solution. Moreover, the power consumption of the PA, which is a function of the radiated power is also reduced significantly due to smaller coverage footprint of the micro BS. The power consumption of pico and femto BSs is even a smaller fraction of the MBS power consumption (see Table 1), as only TRX, PA, microprocessor, and FPGA are present to make up the functioning BS. Moreover, omnidirectional (single sector) antenna configuration is being used. Pico BS could be deployed outdoor or indoor, while Femto BS is completely meant for indoor deployments in the residential or business premises. Relay nodes (RNs) are used to improve coverage at cell edge of the existing network. It is defined in LTE-A relay standard [13]. This could be deployed in indoor or outdoor locations and could exhibit similar features of the femto cells. RNs are backhauled using the macro RAN. Remote radio heads (RRHs) are high powered, low weights nodes with the capability of reducing cost, improving efficiency and performance when deploying new base stations. RRHs can operate in multimode where different standards such as GSM, HSPA, LTE, and WiMAX could be operated [14]. They can be used to extend the coverage of BTS/NodeB/eNodeB in rural locations and tunnels. Table 1 provides the power consumption and coverage range for different base station types.

2.2 Power System Consideration of BS Sites

The geographical location, deployment sites (e.g., urban, suburban, or rural rollout), and climatic condition are some factors that may influence the power requirements for a BS site. In tropical dry climates (e.g., Nigeria), two ACs with minimum power capacity of 2500 W each may be needed to maintain the indoor temperature of the BS shelter, usually, below 25 °C [18]. This is to avoid excessive heat dissipation from the TE; this means additional cooling for the SBS which was originally omitted from

Table 1 Base station types in HetNet [12, 15–17]

Base state type	Coverage	Radiated power (W)		Power consumption (W)	Commonly used backhaul type
		Indoor	Outdoor		
Macro	<35 km	–	5–40	1000–5000	Fiber/Microwave
Micro	<2 km	–	0.5–2	100–300	Microwave
Pico	<200 m	0.1	0.25–2	9–15	Microwave/Fiber/DSL
Femto	10–15 m	<0.1	–	6–14	Fiber/DSL
RRH	<2 km	–	5–20	550–760	Fiber
Relay	<2 km	<1	0.25–7	10–120	via DeNB

the new green design architecture (Refer to [9 and 16] for EARTH project). However, deployments in polar climate may not require any cooling as the climate is characterized by average temperatures below 10 °C throughout the year, with temperatures typically ranging from −47 °C in February to −11 °C in August [19]. Base stations TEs in these locations could therefore be cooled by natural air convection. It is on this note that the BS power requirement varies with geographical locations due to differences in climatic conditions. In addition, temporal variability of the traffic density associated with the location-dependent population distribution is another factor as the BS consumes more power during the peak hours [15, 17, 20].

Provision of sustainable energy source to the BS sites, while minimizing the network energy cost which constitutes about 60% of the total network OPEX, has been a major bottleneck in most emerging markets. The requirement of achieving 99.95% availability necessitates the MNO to provide power 24×7 throughout the year, thus the need for reliable power supply. However, developing countries are faced with limited grid power infrastructure, limited grid coverage, and erratic power supply. The unreliability of the grid power and grid reach (coverage) forces the MNOs to rely on diesel generators to power up their BS sites. In some situations, diesel generators (DGs) are used as both primary and backup power sources depending on the grid and power supply situation. For example, in Europe and North America, one diesel generator is used for emergency backup, while two generators are used in developing countries for primary and backup [21]. For off-grid sites, DGs act as the primary source only as efforts have been made recently to cut down on the carbon footprint, thus making the MNOs to look inward to renewable energy sources such as wind and solar. In Fig. 2, we provide different power sources options to a BS site.

3 Small Cells Deployment and Backhauling Options

Network densification through the use of small cells has been identified as the key enabler for the success of next-generation wireless systems [6]. The market growth for small cells have been very encouraging, from less than 2 million units in 2011 to about 4 million units in 2015, and this is expected to grow up to 10 million in 2018 according to Small Cell Forum [22]. From the technical and economic points of view, deployment of small cells would enable the mobile operators to ease significant amount of traffic from the macro base stations and this would, subsequently, reduce the network overhead and increase the network capacity without necessarily, adding new macro sites which are inherently costlier. Small cells could boost spectral efficiency per unit area through spatial reuse of the spectrum, thereby improving both network coverage and capacity. Furthermore, deployment of small cells would drastically reduce the network energy expenditures, both capital (CAPEX) and operation (OPEX). Figure 3 provides an illustration of network densification. However, this paradigm shift from the use of conventional macro cells only to small cells have been seen to improve the network performance but also introduces challenges. For instance, effective backhaul implementation still remains the main challenge as the

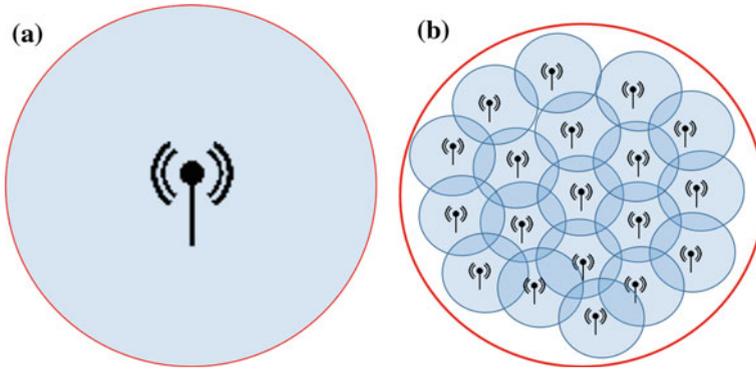


Fig. 3 Network densification (ND) **a** single-tier cellular network. **b** ND with small cells

ever-increasing number of small cells or SBS to meet up the need to support more services may lead to a more complex backhaul and, as such, increase risk of rising operational costs.

It is therefore very essential for the network operators when designing backhaul solution to consider scalability, maintainability, fast and efficient installation, and cost [7]. In this section, we provide various backhaul options for SBS deployments and some challenges that may be encountered during rollout.

3.1 *Wired Backhaul Options for Small Cells*

Wired backhaul solutions have been deployed and proved promising for years for cellular mobile base stations. There are so many options available for small cells such as:

i. **Direct Fiber Optics**

Fiber optics could provide direct end-to-end, point-to-point high speed, and unlimited backhaul capacity with minimal latency. Gigabit passive optical network (GPON), which is based on PtMP technology that incorporates passive filters, could link multiple small cells' nodes. This is particularly attractive in dense urban rollout [10]. Direct fiber backhaul infrastructure for new small cell sites could be cost prohibitive and may take years to roll out, aside difficulties that might arise laying the fiber cables to each closet location of the small cells. Terrain and clutter features along the backhaul-access path could hinder deployments; bypassing such features could increase both CAPEX and manpower costs.

ii. **Digital Subscriber Line (xDSL)**

xDSL is a general term for the broadband access technologies based on digital subscriber line (DSL) technology. It uses the existing copper wires and due to its lower

cost compared with fiber, it could be used for small cell backhaul. Cost of deployment may relatively be the same as in the case for fiber, but the speed provided will be very limited. The backhaul capacity of xDSL depends on the technology type and the distance from the exchange. Typical urban rollout is usually 300–400 m from the cabinet [23]. Very-high-bit-rate digital subscriber line 2 (VDSL 2) is based on ITU G.993.2 standard and can provide peak data rates above 100 Mbps [23]. However, this may require careful planning to ensure that the distance between the VDSL2 and the digital subscriber line access multiplexer (DSLAM) does not exceed the maximum 300 m required by the VDSL2.

iii. Hybrid Backhaul Solutions

Hybrid approach could also be used where the fiber from the exchange will terminate at the cabinet (i.e., fiber to the cable (FTTC)) and thereafter, VDSL 2 cable will take the capacity to the locations where the small cells are deployed. In the case of fiber to the node (FTTN), each small cell is connected to a VDSL 2 modem that is connected to a DSLAM which is connected to a fiber switch using 1 Gbps point-to-point optical link [23]. This type of solution is usually available for dense urban areas and can provide capacity to urban small cells.

iv. Cloud Radio Access Network (Cloud-RAN)

Cloud-RAN (C-RAN) is one candidate technology aimed at solving the challenges related to densification and increased base station cooperation. In C-RAN architecture, remote radio units (RRU) of different cells are connected to the cloud server via a high-speed front-haul link, such as a fiber network [24]. Recent deployment trials by China Mobile [24] provide 30 and 53% CAPEX and OPEX reduction, respectively. Ericsson-LG also showed the possibility of replacing 28 3G NodeBs with 195 RRUs which reduced the total network power consumption by 2/3; from user's experience, the call drop ratio reduced by 70% with increase in throughput gain of 100%. However, the latency requirements for the base band unit (BBU) impose an upper bound for BBU processing time and the front-haul transport latency. Real-time requirement for operating system, clock synchronization, and capacity requirement for the front-hauls could be challenging [24]. Despite this, the network would in practice eliminate the need for local backhaul since end user data traffic will be delivered to and from the centralized location. Still, it will require high-speed fiber front-haul connections to the small cells and therefore, may not be cost-effective for massive small cell deployments particularly in the developing economies.

3.2 Wireless Backhaul Options

The deployment of small cells in outdoor urban and rural areas or inside building where cabling infrastructure is not available makes the adoption of wired backhaul very challenging. It is also important to note that the increasing traffic demands would

require the installation of wired backhubs, supposedly fiber, in all new small cell sites locations; this approach may therefore not be cost-effective. Wireless backhauling could therefore provide cost-effective means of connecting these cells.

i. Microwave Radio links

Microwave links still remain the most dominant backhaul solution in the mobile industry. It provides an alternative to complement the fiber optics which is inherently costly and almost practically impossible to deploy in some designated locations. With the advent of millimeter waves, i.e., 60 GHz V-band and 70/90 GHz E-band, end-to-end high-capacity backhaul could be achieved. Microwave radio links could operate in line of sight (LOS) or non-line of sight (NLOS) depending on the operating frequency, and these could be in PtP or PtMP topology depending on the choice of deployment and capacity requirements. The LOS typically requires the use of parabolic dishes which could be unsuitable for many small cells since the outdoor small cells are typically 3–6 m above the ground level and direct LOS is not always the case in urban deployments. Moreover, at extremely high frequencies, there is a risk of increased rain attenuation, oxygen absorption, and, possibly, antenna alignment complications. These problems could hinder the performance of the network. From technical design perspectives, the realization of suitable integrated circuits in those bands could be challenging due to nonlinear distortion of power amplifiers, IQ imbalance, and the need for highly directional antennas [25]. The need for more backhubs as the cells become dense would, in turn, consume more energy and also increase the complexity in designing the network.

ii. Satellite Backhaul

This type of solution is preferred in remote areas where fiber, copper, or microwave solutions are uneconomical to deploy. Satellites have universal availability and could provide data rate up to 350 Mbit/s with the size of the dish and power amplifier constraints. A typical capacity that a satellite can provide to small cells will be in the range 1 M–10 Mbps [22]. The most commonly used satellite band is Ku-band which has operating frequency of 10–12 GHz and is slightly affected by rain. The lower-frequency bands (i.e., C-band: 4–6 GHz) is practically unaffected by weather conditions. However, the 20–30 GHz Ka-band, which is predominantly used, is heavily affected by weather and fading [23]. In addition, delay and jitter are constraints to deployment of satellite backhaul. For example, typical expected average jitter is between 5 and 50 ms [22], while the round trip signal propagation delay could be 240–260 ms depending on the small cell location, hub site and, also the satellite. Moreover, packetization and processing delay is typically 35–50 ms, which would increase the total delay to 275–310 ms far, beyond the acceptable thresholds [22]. The adoption of satellite for small cell backhauling has not been widely reported, but there is a huge market potential for the system.

iii. Free Space Optics

Free space optics (FSO) [26] is given attention due its associated lower cost as no underlaying fiber cabling is needed. In addition, very high-capacity data rates could be achieved with minimal interference. However, atmospheric disturbance, such as absorption and scattering, could hinder the signal propagation. Most importantly, eye safety regulations for the use of laser beams, designing backhaul systems in dense environments while meeting up with the international safety regulations, and specifications defined by international standard could be very challenging.

iv. TV White Space

Unused portion of the electromagnetic spectrum within the TV bands is referred to as TV white space (TVWS). Secondary operation on TVWS is still under process although some countries, such as USA, UK, Japan, Finland, and Singapore, have already developed a regulatory framework for its use [23]. Substantial research studies and piloting have been conducted globally; there are also success stories from Africa [27]. Due to its favorable propagation characteristics, TVWS has been found to be very attractive for small cell deployment [28]. The availability of TVWS varies with location and the transmit power of the primary users (i.e., TV broadcast stations); these could limit the number of available TV channels to be used in dense environments. Although considerable capacity up to 18 Mb/s with 600 MHz band could be achieved in NLOS, radio design, and secondary user coexistence to comply with the regulator standard on interference could still pose some challenges.

v. Long-Range Wi-Fi

Wi-Fi was primarily designed for local area networks and it uses the 2.4 and 5 GHz ISM radio bands to provide telecommunication services such as VoIP. This technology is based on 802.11 standards and has recently been proved to provide cost-effective communication for long-distance applications. Very long-distance PtP Wi-Fi network was proposed wherein 279 and 133 km links were successfully connected in Venezuela and in northern Italy, respectively [29]. The long-range capabilities of Wi-Fi networks could be leveraged to provide backhaul services to small cell sites, particularly given the constraints where fiber POP is unlikely to be deployable due to the small cell locations and microwave point-to-point (PtP) links that could exacerbate both the OPEX and CAPEX costs. Sites acquisition, backhaul installation, and maintenance will drastically reduce and no license fee for the spectrum is required since it operates in the ISM band. However, long-range Wi-Fi backhaul would require LOS. It is also vulnerable to interference since it operates in an unlicensed band, though enhanced technologies such as the adaptive directional antennas coupled with smart meshing and predictive channel management [30] could drastically minimize the interference. However, in typical dense urban deployments where hundreds of cells could be deployed within a close proximity, the backhaul interference will be very high and unsustainable. Moreover, the predictive channel management may not attain maximum throughput due to the available frequency pool within the 2.4 and

5 GHz ISM bands. Therefore, interference avoidance by simply frequency hopping may still not yield sufficient gain.

vi. **Self-Backhauling of Small Cells**

Self-backhauling is a general concept where a macro base station (MBS) provides backhaul to a small base station (SBS) via the existing macro RAN. This has already been introduced by mobile standardization bodies, such as in the Third Generation Partnership Project (3GPP) in the form of the relaying concept standardized for 3GPP Release 10 LTE-Advanced networks [13]. The relay base stations are low-power nodes that enhance achievable performance of macro UEs in areas of poor coverage, such as the cell edge. In 3GPP standard, the relay node backhaul is connected to a “donor” macro cell. The LTE or LTE-Advanced (Release 8/9 or 10) UEs are then connected to a macro cell via the relay access network within a relay BS coverage area. Self-backhauling generalizes this approach by considering other radio access technologies (not only LTE or LTE-Advanced) in both the SBS backhaul and SBS radio access. As a result of this flexibility in radio technology selection, self-backhauling is able to be implemented with little or no impact on the existing standards. For instance, Qualcomm proposed a so-called Velcro relays self-backhauling approach, whereby macro LTE provides backhauling for evolved 3G BS (e.g., HSPA+) to efficiently exploit the spare LTE resources in places with low LTE UE penetration [31]. Recent deployment case studies in Addis Abba show the feasibility of self-backhauling [32]. When compared with other backhaul systems, self-backhauling could help in reducing the cost of deployment as a result of minimal on-site installation efforts from the operators. This could drastically also reduce the cost of maintenance; moreover, network management and control entities such as the radio resource management and security management are been shared. The RAN mainly is operating on lower frequencies usually below the 6-GHz bands. This would further simplify the installation cost, time, and efforts since the string LOS requirements that could demand careful installation is no longer needed, thereby making the deployment faster and flexible for dense urban environments. The need for building another infrastructure as in the case of fixed-wireless backhauling is also not needed since self-backhauling reuses the macro site infrastructures.

Backhaul capacity could be an issue in self-backhauling, since the base station serves multiple small cells, and access and backhaul links shared the total pool of the available resources. This might cause capacity bottleneck. Also, with the large number of SBS, signaling load and excessive handover could manifest. However, there have been active research efforts trying to mitigate these problems. In [33], significant spectral efficiency and throughput gains was achieved for the SBS backhaul through the use of selected CoMP technique under realizable feedback overhead, even under feedback bit error. In [34], LTE-based backhaul concept (self-backhauling) for heterogeneous networks was simulated using microwave frequencies for two virtual cities (European and USA) and sufficient capacity was obtained.

4 System Concept

The system concept introduced in this paper, as illustrated in Fig. 4, consists of a conventional fixed microwave backhauling and the self-backhauling. The first scenario is a fixed-wireless backhauling which is achieved with PtP or PtMP radio links. In most cases, this requires LOS clearance between the radio links backhaul (wireless hub) and the SBS due to operation in higher-frequency bands (Fig. 4a). The LOS requirement for fixed-wireless backhauling links can be relaxed through use of alternative multihop topologies (e.g., mesh) to route the fixed-wireless links around shadowing objects (e.g., buildings, mountains, etc.). In the second scenario, we assume the SBS to be distributed within the MBS coverage area. The MBS users (MBS UE) and SBS users (SBS UE) are randomly distributed within the MBS and SBS coverage areas, respectively, while the SBSs 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 as shown in Fig. 4b. For fairness, in the two scenarios, we assumed that all the SBS transmits on the same power level, and therefore under normal condition, their power consumption, sizes of their coverage footprint are expected to be same. Moreover, the number of SBSs and the aggregated backhaul capacity for both scenarios are also assumed to be the same. The SBSs are connected to the MBS and RRL with star topology. It is a natural connection configuration since star topology is more power efficient than ring and mesh [9].

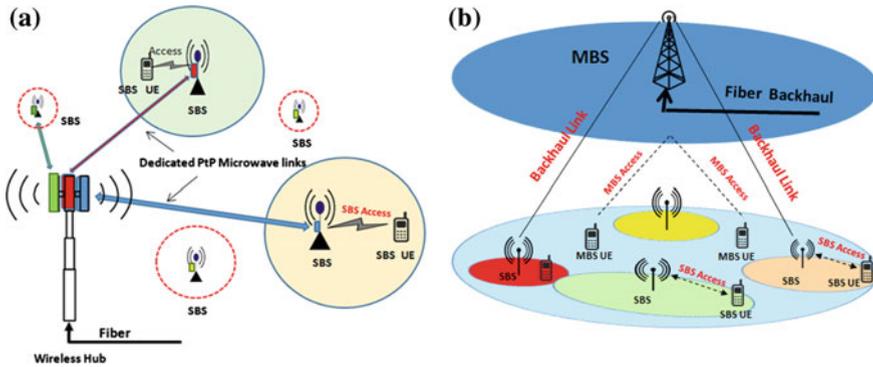


Fig. 4 Backhauling SBS using **a** fixed-wireless microwave backhauling and **b** self-backhauling

5 Backhaul-Energy Model

Using the HetNet architecture presented in Fig. 4, the power consumption of each HetNet scenario is the sum of the power consumption of the SBS and the backhauling. Let $P_{c,t}^{\text{bh}}$ and $P_{\text{SBS},t}^{\text{bh}}$ represent the power consumption of the microwave unit(s) at the wireless hub and SBS, respectively. The total power consumption of microwave radio link (RRL) $P_{\text{tot},t}^{\text{bh}}$ can be written as:

$$P_{\text{tot},t}^{\text{bh}} = P_{c,t}^{\text{bh}} + P_{\text{SBS},t}^{\text{bh}} \quad (1)$$

Let SBS (C_j^{SBS}) be the aggregated backhaul capacity of the RRL at the SBS at site j and N_k^{SBS} the total number of RRLs at SBS, then the power consumption of the RRL at the central point is derived as:

$$P_{\text{SBS},t}^{\text{bh}} = P_{\text{SBS}}^{\text{agg}}(C_j^{\text{SBS}}) + P_{\text{switch}}^{\text{SBS}}(N_k^{\text{SBS}}, C_j^{\text{SBS}}) \quad (2)$$

$$P_{c,t}^{\text{bh}} = P_c^{\text{agg}}(C^c) + P_{\text{switch}}^c(N_k^c, C^c) \quad (3)$$

A threshold capacity C_{th} is defined to classify two traffic conditions: low and high demands. With this assumption, the aggregated power consumption limits for the central hub $P_c^{\text{agg}}(C^c)$ and SBS $P_{\text{SBS}}^{\text{agg}}(C_j^{\text{SBS}})$ are derived as follows:

$$P_{\text{SBS}}^{\text{agg}}(C_j^{\text{SBS}}) = \begin{cases} P_{\text{low}}, & \text{if } C_j^{\text{SBS}} \leq C_{\text{th}} \\ P_{\text{high}}, & \text{otherwise} \end{cases} \quad (4)$$

$$P_{\text{switch}}^{\text{SBS}}(N_k^{\text{SBS}}, C_j^{\text{SBS}}) = \begin{cases} 0, & \text{if } N_k^{\text{SBS}} = 1 \\ P_{\text{switch},t} \times \left[\frac{C_j^{\text{SBS}}}{C_{\text{Max-Switch},t}} \right], & \text{otherwise} \end{cases} \quad (5)$$

And

$$P_c^{\text{agg}}(C^c) = \begin{cases} P_{\text{low}}, & \text{if } C^c \leq C_{\text{th}} \\ P_{\text{high}}, & \text{otherwise} \end{cases} \quad (6)$$

$$P_{\text{switch}}^c(N_k^c, C^c) = \begin{cases} 0, & \text{if } N_k^c = 1 \\ P_{\text{switch},t} \times \left[\frac{C^c}{C_{\text{Max-Switch},t}} \right], & \text{otherwise} \end{cases} \quad (7)$$

In [9], C_{th} was assumed to be 500 Mbps. We, therefore, generalize the total backhaul power consumption for the RRL (i.e., PtP and PtMP) network topology as:

$$P_{\text{tot},t}^{\text{bh}} = \begin{cases} P_{c,t}^{\text{bh}} + N_k P_{\text{SBS},t}^{\text{bh}} & t \in \text{PtMP} \\ (P_{c,t}^{\text{bh}} + P_{\text{SBS},t}^{\text{bh}}) N_k & t \in \text{PtP} \end{cases} \quad (8)$$

where P_{low} and P_{high} are the power consumption of the microwave antennas associated with the low and high traffic conditions, respectively. $P_{\text{switch}}^{\text{SBS}}$ and P_{switch}^c represent the power consumption of the switches used at SBS and central hub, respectively. C_j^{SBS} and C_j^c are the total backhaul capacity at the SBS and hub site, while N_k^{SBS} and N_k^c are the respective number of microwave links at the SBS and hub site, respectively. $C_{\text{Max-Switch},t}$ is the maximum capacity of the switch of type t . $P_{\text{switch},t}$ is the fixed power consumed by switch of type t irrespective of the load, and ψ_{bh} is the backhaul type (PtP or PtMP).

We introduce an indicator variable $\chi_{k,t}^j$, the site selector, which indicates whether the backhaul device t located in j is PtP or PtMP type. The total backhaul power consumption could be written as:

$$P_{\text{tot},t}^{\text{bh}} = \sum_{t \in \psi_{\text{bh}}} \sum_{k \in K_t} P_{\text{tot},t}^{\text{bh}}(N_k) \chi_{k,t}^j \quad (9)$$

where k represents the set of backhaul devices of type t , and

$$\chi_{k,t}^j = \begin{cases} 1, & \text{if type } t \text{ used in location } j \\ 0, & \text{otherwise} \end{cases} \quad (10)$$

Therefore, the power consumption of the HetNet for the SBS backhauled with RRL and also self-backhauled are derived in Eqs. (11) and (12).

$$P_{\text{RRL}}(f_b) = \sum_{i \in M_t} N_i P_i^{\text{SBS}}(f_b) + \sum_{t \in \psi_{\text{bh}}} \sum_{k \in K_t} P_{\text{tot},t}^{\text{bh}}(N_k) \chi_{k,t}^j \quad (11)$$

$$P_{\text{Self}}(f_a, f_b) = \sum_{j \in Q_t} N_j P_j^{\text{MBS}}(f_a) + \sum_{v \in S_t} N_v P_v^{\text{SBS}}(f_b) \quad (12)$$

where f_a , f_b , and f are load factors for MBS, SBS, and HetNet, respectively, and the HetNet load factor, f , is given by:

$$f = f_a + f_b \text{ and } f_a + f_b \leq 1 \quad (13)$$

Using Eqs. (11) and (12), the power savings for the self-backhauling compared with point-to-point (PtP) or point-to-multipoint (PtMP) fixed-wireless backhaul is expressed as:

$$P_S = \lambda_p \left[\sum_{i \in M_t} N_i P_i^{\text{SBS}}(f_b) + \sum_{t \in \psi_{\text{bh}}} \sum_{k \in K_t} P_{\text{tot},t}^{\text{bh}}(N_k) \chi_{k,t}^j - \left\{ \sum_{j \in Q_t} N_j P_j^{\text{MBS}}(f_a) + \sum_{v \in S_t} N_v P_v^{\text{SBS}}(f_b) \right\} \right] \quad (14)$$

The power savings can be represented by an indicator function $1_{D(P_S)}$,

$$1_{D(P_S)} = \begin{cases} \text{Gain, if } P_S \geq 0 \\ \text{Loss, otherwise} \end{cases} \quad (15)$$

where M and S represent set of SBS types t used in the networks. N_i and N_v represent the total number of SBS of specific type. Q represents the set of MBS type t used as self-backhaul. N_j represents the total number of MBS of specific type t . P_j^{MBS} , P_i^{SBS} , and P_v^{SBS} are the power consumption of MBS and SBS of types t , respectively. f , f_a , and f_b are the instantaneous load on the HetNet, MBS and SBS, respectively, λ_p is the self-backhaul factor representing the percentage of number of sites equipped to have self-backhauling capabilities and p is the number of mobile operator's MBS sites.

6 Results and Discussions

In this work, simple and validated power consumption models presented in [15–17, 35] for macro and micro base stations were adopted. These were used to analyze the power consumption of a typical three-sector macro base station, PtP, and PtMP microwave backhauls. The BS equipment power consumption without cooling and, other auxiliary equipments is between 1 and 2 kW and, that of two ACs as used in most tropical and dry climate regions ranges between 2 and 4 kW [36].

6.1 Typical Power Consumption of Macro BS and Microwave Backhaul Hub Sites

Figure 5 shows the load-dependant power consumption of the MBS with and without backhaul; the peak power is 4.3 kW at maximum traffic load condition. We also present the power consumption of the backhaul system. The backhauling power varies from less than 50 W for fiber backhaul to about 500 W for long-range PtMP microwave links. The most widely used backhaul system in emerging markets is PtP backhaul link which consumes 100–200 W [36]. In this analysis, we use 100 and 500 W for PtP and PtMP backhauls, respectively, while and the load-dependent component is neglected. The results show that for microwave backhaul with 50 PtP backhaul links (i.e., $N_k^c = 50$), the peak power is 5 kW and this increases to 10.025 W when 25% of the backhauls are PtMP. This is power consumption at the hub site only and did not include that of the SBS links (N_k^{SBS}). When SBS links are included, the overall backhaul power requirement for the PtP backhaul system will be 10 kW and that of PtMP will depend on the mapping of PtMP to SBS backhauls.

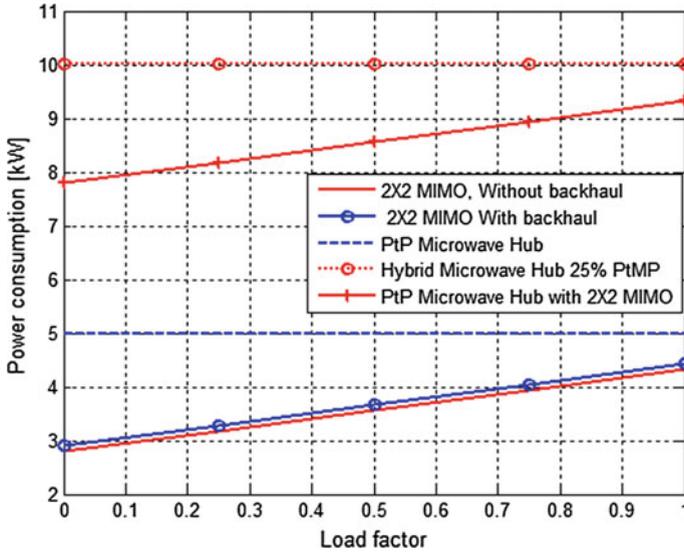
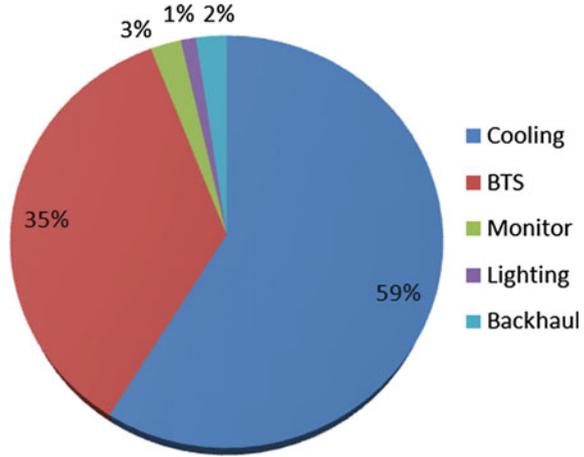


Fig. 5 Power consumption of macro BS and microwave backhaul hub

In Fig. 5, we have also illustrated the power consumption of a hub site with three-sector MBS. In Fig. 6, we show the distribution of power consumption of the BS site. The power consumption share of the BS equipment, cooling, backhauling, and auxiliary equipments are 35, 59, 2, and 4%, respectively. Recent energy-efficient BS equipment consumes less energy and the MBS site's power is between 1 and 1.5 kW [36] as opposed to the 4 kW for the current deployed networks. In the EARTH project, highly energy-efficient power amplifiers for the MBS, SBS, and feeder loss factor of 38.8, 28.5 and 0.5%, respectively, were used [16]. Passive cooling system of 170 W was used for the MBS and no active cooling for SBS [16]. In our analysis, we considered worst-case scenario that could occur in tropical areas, for instance, where 60 W of cooling would be required for the SBS. This is in accordance with the assumption presented in [15].

The transmitter power levels for the MBS and SBS can be assumed to be 20 and 2 W, respectively, and power consumption of the DSP, transceiver, rectifier, and backhaul, respectively, are 29.5, 13, 100, and 35 W [37]. Then, the load-dependent power consumption for three-sector LTE system with 10 MHz bandwidth and 2×2 MIMO system for the MBS and SBS gave the highest value at peak load as 1109 and 166.3 W, respectively. These values are few watts higher than the values obtained in the EARTH project [16] as active cooling, which could reduce the power for SBS to about 106 W, was not considered. However, these values are still within the range obtained from various publications for MBS and SBS [16, 37]. Deployment of the SBS has decreased the power consumption significantly from 4300 to 166 W, but the proportion of the backhaul power increased from 2 to 21% which is expected to increase further to 43% if the current 100 W PtP link is used at the SBS site.

Fig. 6 Distribution of power consumption of a BS site



6.2 Power Consumption of HetNet and the Break-Even Load

Using Eqs. (11) and (12), we analyzed a future HetNet power consumption by modeling the whole MBS and SBS power consumption. In this analysis, we consider a HetNet with 10 SBSs. We also considered specific implementation for the energy-efficient microwave links based on realistic power consumption typically, varying from 25 to 50 W [8]. However, in this analysis, we focused more on the average value of 35 W and assumed to be the maximum power consumption of each unit from the backhaul side (i.e., the wireless hub) and the SBSs locations. Even though, it is expected that the power consumption to be higher at the hub than the SBSs. For simplicity, we did not consider the load varying power consumption of the microwave units. In Fig. 7a, we show the power consumption of (i) MSB (macro) cell only without any SBSs deployment, (ii) PtP wireless backhaul only, (iii) SBSs backhauled with microwave links and finally, and (iv) SBSs backhauled with MBS (self-backhauling). Starting with the PtP wireless backhaul only, 25 W microwave units were deployed, since we have neglected the load varying power consumption part, it is easy to deduce that the total power consumption for the hub is 250 W (i.e., 10 PtP links serving 10 SBSs). For the MSB (macro only), the power consumption increases with an increase in traffic load with maximum peak achieved when the traffic load reached 100%. The power consumption at this load is around 1 kW. It should be noted that this is anticipated power consumption when highly efficient systems are used based on the system parameters such as air conditioning with a power rating of 170 W, provided in [37]. The current deployed MBS particularly the ones in temperate regions consumes high power as described I Sect. 6.1.

Furthermore, in Fig. 7a, we have analyzed the power consumption of the two systems backhauling 10 SBSs in the HetNet. For the microwave HetNet systems, the traffic load effect of the SBS manifested on the total power consumption as the power consumption increases with the traffic load which was earlier invariant when

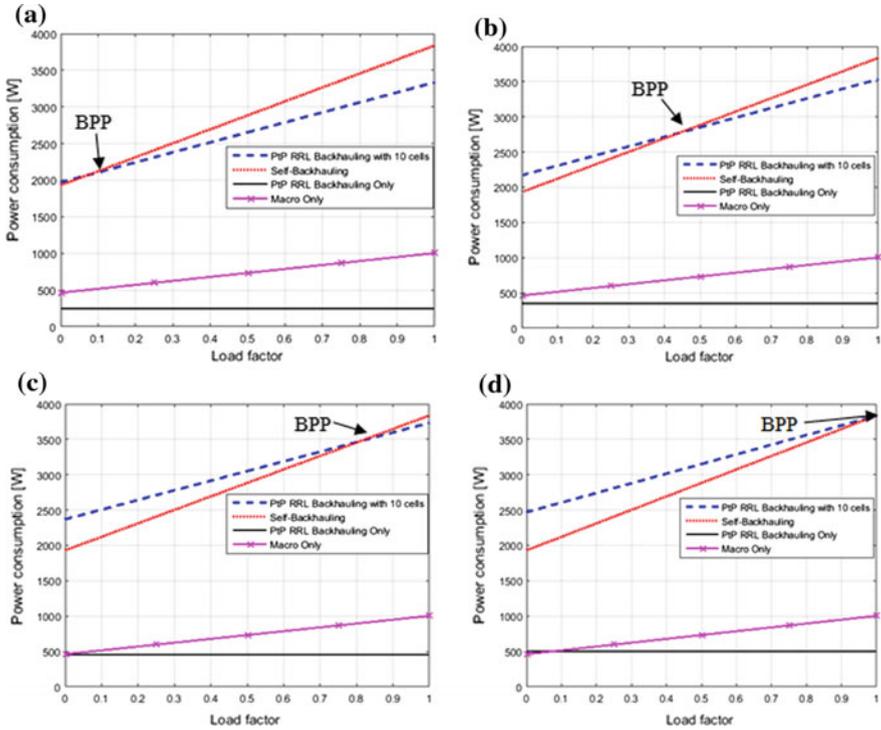


Fig. 7 Power consumption for fixed-wireless and self-backhaul networks with **a** 25 W RRL, **b** 35 W RRL, **c** 40 W RRL, and **d** 50 W RRL

backhaul links were deployed only. In this analysis, the power consumption of the traffic aggregating switch P_{switch}^c at the hub was not included. This was considered to be negligible when compared to the HetNet power demand. Based on this analysis, the numerical result as shown in Fig. 7a indicated that backhauling the 10 SBS with 25 W microwave units is more energy-efficient solution than the self-backhauling at all traffic loads. However, in Fig. 7b, when the 25 W radio units are being replaced with 35 W radio units, at lower traffic conditions (i.e., $f < 0.5$), the self-backhauling becomes a better solution. Even though, it's rare to have 100% loaded BS and sites with less than 50% load may not be popular. This type of configuration may be favoured in a site with low traffics typically in rural area deployments. It is worthy to mention that at some traffic load, there exists a point named *break-even power point (BPP)*, where one backhaul solution becomes more energy efficient than the other. In Fig. 7b, the point exist when the traffic load is about 45%, below this load, the self-backhaul solution is more preferable and above, otherwise. When high power radio units are used as backhaul (i.e., RRL = 40 W/50 W) in Fig. 7c and d, the BPP shift to almost 100% of the traffic load. This is an indication that the Self-B could be useful at low traffic condition or high traffics when the RRL power rating is above

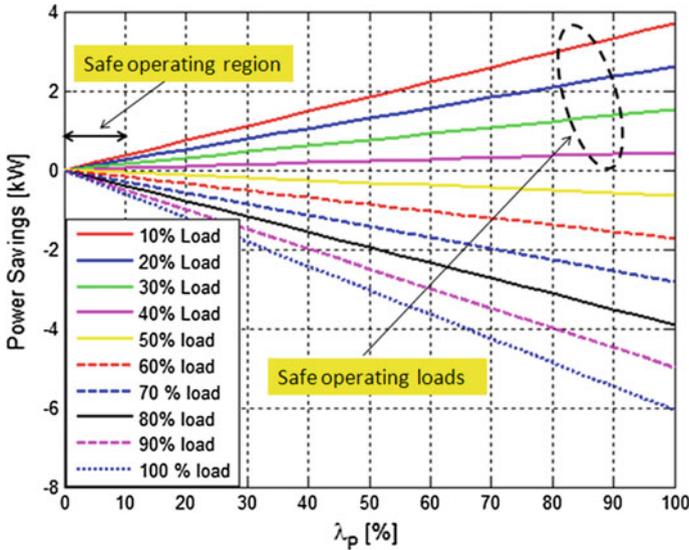


Fig. 8 Impact of load factor and self-backhaul factor on power saving. Network size, 1 MBS $p = 1$, 10 SBS, 35 W RRL

25 W. However, in view of the fact that the self-backhaul does not need radio link infrastructure as the case may be, but, it is clear that it is not an optimal solution at high load conditions, particularly when the radio links of 25 W and below are deployed. However, due to its simplicity and relatively, low loss of power efficiency still make it an attractive solution.

Figure 8 shows the impact of load factor and self-backhaul factor on power savings. The figure demonstrates how much power network operator would lose (or gain) if only self-backhauling solution is deployed. The percentage of the SBS that is self-backhauled is indicated by λ . The curves are presented as the difference from the network when all the SBS use RRL. The negative power saving is indicating that the network wastes power with respect to all RRL connections. We define the BPP as a point where the two backhaul options consume the same amount of power at a predefined traffic load and this is characterized in Fig. 9. When the curves reach 100% of load, it means self-backhaul solution would always be preferred for higher RRL power. For instance, we would always prefer self-backhaul if wireless links consume more than 17, 26, 35, and 55 W for 30, 20, 15, and 10 SBS per HetNet, respectively.

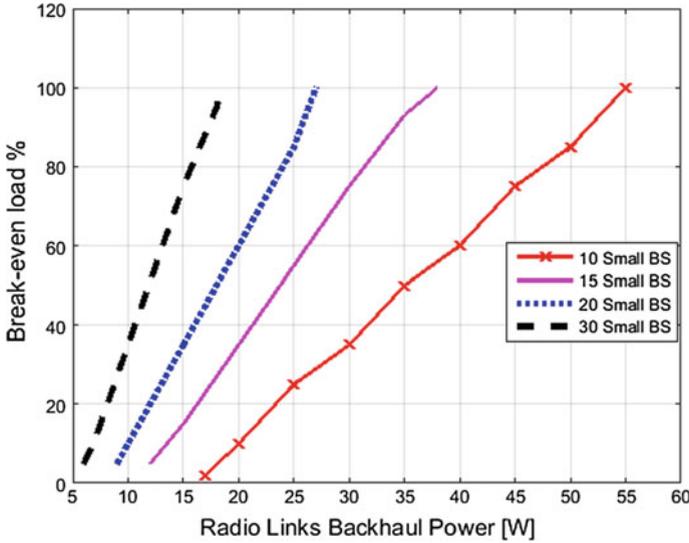


Fig. 9 Break-even load and power point as a function of SBS density [37]

6.3 Impact of Macro Base Station Load on Power Consumption

Power consumption largely depends on how traffic load is distributed on the network as illustrated in Fig. 7. The MBS serves as self-backhauling SBS but it also can serve UEs within its coverage area as illustrated in Fig. 4. In Fig. 10, the ratio of UE traffic served by MBS to UE traffic served by SBS is used as a parameter. The traffic loads for MBS and SBS are defined in Eq. (14) as f_a and f_b . We implement different load scenarios, whereby the MBS is fully loaded (i.e., 100%, $f_a = 1$), or partially loaded (i.e., 60%, $f_a = 0.6$) with the remaining 40% of the traffic loads routed to the SBS. The load-sharing effects on power consumption for the self-backhauled HetNet is observed. At low MBS: SBS load ratios of 40:60, even when the SBS is fully loaded with the remaining 60% (i.e., $f_b = 100\%$), the self-backhauled network is more energy efficient than the conventional RRL.

6.4 Energy Savings of Self-Backhauling

Assume a HetNet system consisting of 20 MBS, each of them containing 10 SBS some of which are connected over the microwave links, while the rest are self-backhauled. In Eq. (14), λ represents the percentage of SBS that are self-backhauled. The negative power saving (i.e., $P_S < 0$) indicates that the self-backhauled network

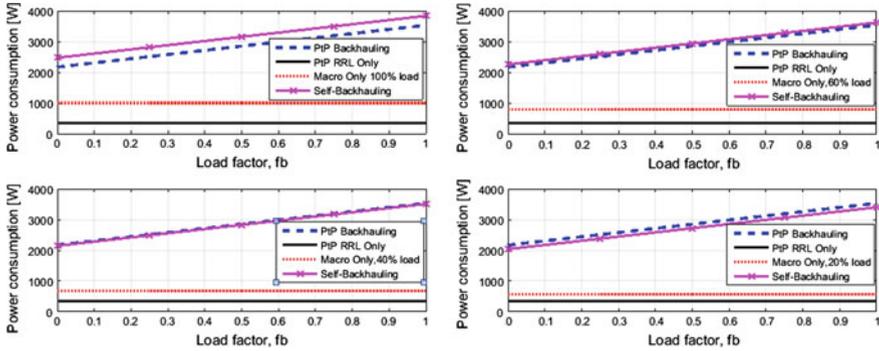


Fig. 10 Impact of macro base station load on power consumption

losses power with respect to microwave backhauled network and otherwise if $P_S \geq 0$ as indicated in Eq. (15). Figure 11 shows that when the network is fully loaded and RRL uses more than 50 W, then it is more preferable to use self-backhauling solutions. For lower loads, the self-backhauling is energy efficient and provides higher gains over the microwave backhauls. We also vary the percentage of SBS connected with self-backhauling, λ , and provide the curves for different traffic load. For lightly loaded network of 50%, the gain due to the use self-backhauling for all SBS (i.e., $\lambda = 100\%$) over 50 W RRL backhaul is about 5 k; this increases to 7.5 kW when the network load decreases to 30%.

Therefore, with the current deployed 100 W PtP microwave backhauls, we provide energy-saving prospects for deploying self-backhauling in emerging markets. Our analysis is focused on Asia and Africa. As an illustration, Nigeria, Ghana, Kenya, Tanzania, Uganda, Bangladesh, Indonesia, Pakistan, and India are projected to have at least 37,651, 7052, 7029, 5801, 3874, 41,686, 88,425, 40,422, 400,000 MBS sites, respectively, in 2015 [38–40]. With 8.1% CAGR, except India where 3.1% is used, in the next five years, about 13,762 new MBS sites will be added in Nigeria and 2578 in Ghana. Assuming 1:10 ratio of MSB-SBS replacement, the network densification projection will be 137, 620 and 25,780 SBS, respectively.

If all the SBS are self-backhauled (i.e., $\lambda = 100\%$) the resulting energy saving in the year 2020 will be 383.35 MWh/day (i.e., about 16 MW power) and 71.82 MWh/day (3 MW). This is expected to be higher for countries like India with over 400,000 MBS sites and which is expected to grow to 511,000 by 2020 [41] amounting to savings of 4.07 GWh/day (170 MW) and 32 GWh/day (1336 MW) in 2035. Figure 12 shows the energy-saving forecast for the selected countries for the period of 20 years, from 2015 to 2035. Already, the energy production in most of the developing countries is far below the demand. For example, Nigeria has a per capita consumption of 115 kWh/year [39]. Also, India, Tanzania, and Bangladesh have 565, 68.55, and 234 kWh/year, respectively [42], these are very insignificant when compared with some developed countries like the USA’s 12,185 kWh/year, Finland’s 16,100.44 kWh/year, and Denmark’s 6026 kWh/year [43]. In Table 2,

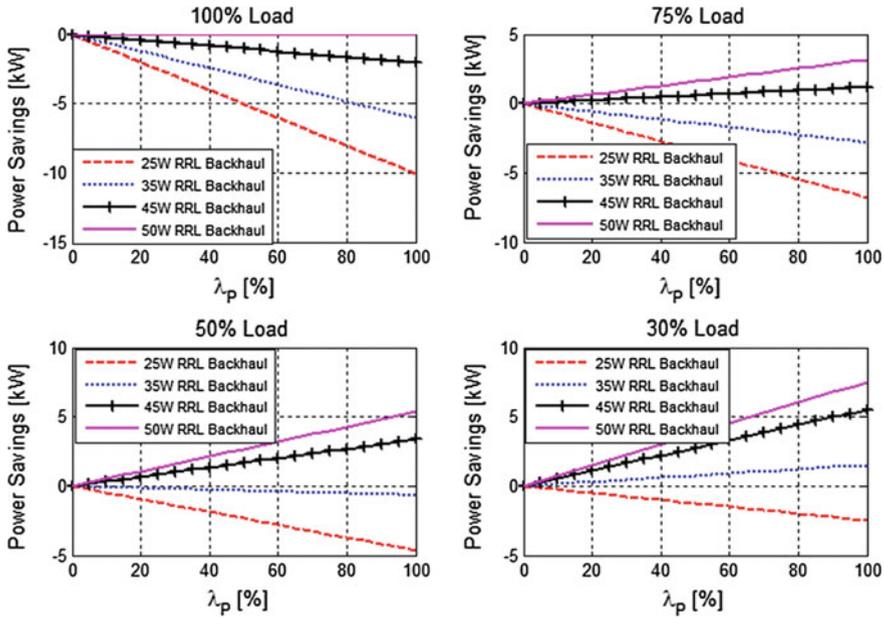


Fig. 11 Power savings for different RRL backhaul

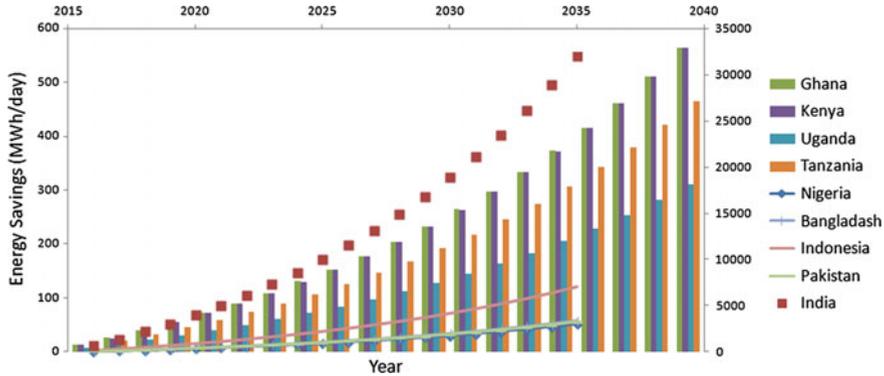


Fig. 12 Energy-saving forecast

we provide a summary of basic power indicators for some selected countries and prospective energy saving in 2035. Therefore, this energy-saving strategy would relieve the extra burden on the power network which will be more beneficial to the developing economies with a shortfall in energy production. While for the developed economies, it would yield a significant decrease in network energy costs.

Table 2 Electricity indicator indices and energy savings

Country	Population (Thousand)	GDP per capita	Power consumption per capita (Kwh)	Land mass (Km ²)	No. of BTS	Electricity production (GWh)	Energy savings (MWh/day)
Nigeria	182,201.96	2640.3	115.04	923,768	37,651	3.3	3018
Ghana	27,409.89	1369.7	206.19	239,460	7052	3.5	565
Kenya	46,050.30	1376.7	136.64	582,650	7029	1.8	564
Tanzania	53,470.42	879.0	68.55	945,087	5801	1.7	465
Uganda	39,032.38	705.3	61.03	236,040	3874	1.5	311
Bangladesh	160,995.64	1211.7	233.88	130,170	41,686	7.349	3341
Indonesia	257,563.82	3346.5	623	1,811,570	88,425	232,000	7087
Pakistan	188,924.87	1434.7	357.34	770,880	40,422	7487	3239
India	1,311,050.53	1598.3	565.21	2,973,190	400,000	1,368,000	32,059

7 Conclusions

Network densification using a large number of small cells (small base stations) has been identified as the key enabling strategy for meeting up coverage and capacity demands in next-generation cellular systems. Providing effective backhauling to the SBS locations have also been identified as the main bottleneck, as the ever-increasing SBS density will lead to a more complex backhauling and, as such, increase risk of raising capital, and operational and network energy costs. This paper highlighted various backhauling options for SBS deployments and some of the key challenges the mobile network operators may be encountered during rollout. The paper also provides power system requirements for various network configuration and their respective power options that would be sustainable. The use of self-organizing backhaul networks (i.e., self-backhauling) for SBS is highlighted and compared in terms of energy efficiency with existing microwave backhauling solutions. Numerical results of the comparison show that when the network is fully loaded and the microwave backhaul uses more than 50 W, then it is more preferable to use self-backhauling solutions. For lower loads, the self-backhauling is energy efficient and provides higher gains over the microwave backhauls. Furthermore, a break-even power point and load threshold level for safe operation regions are presented, and this will help toward achieving optimum utilization of self-backhaul deployment and green backhauling for the deployment of HetNets in a way that is more energy efficient and sustainable compared to traditional homogeneous macro network deployments. The prospect of the self-backhauling in terms of energy saving is presented by providing energy-saving forecast for some selected emerging economies for the period of 20 years, from 2015 to 2035. These energy savings would relieve the overburden on the power network which will be more beneficial to the

developing economies with shortfall in energy production. While for the developed economies, it would yield significant a decrease in network energy costs.

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