

Backhaul-aware energy efficient heterogeneous networks with dual connectivity

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Abstract In this paper, we consider backhaul-aware mechanisms for energy efficient operation of next generation heterogeneous wireless networks, with dense small cell deployments. We assume control and data plane separation based on the LTE-Advanced dual connectivity architecture. The mechanisms are evaluated using LTE-Advanced heterogeneous network scenarios, with varying levels of network densities, user traffic and cell load conditions. For comparison, conventional traffic offloading schemes based on small cell proximity and load are also evaluated. The performance results indicate significant energy saving (ES) gains for the backhaul-aware mechanism, depending on the backhaul technology used. Evaluations were also done on the impacts of user mobility, and for indoor and outdoor deployments of small cells. Trade-offs between user throughput and energy efficiency are evaluated, and using the considered mechanism, ES gains of up to 20 % is observed, without significant loss in throughput.

Keywords Energy efficiency · Heterogeneous networks · Green wireless networks · LTE-advanced · Dual connectivity · Inter-eNB carrier aggregation

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1 Introduction

Fourth generation (4G) networks such as Third Generation Partnership Project (3GPP) Long Term Evolution (LTE)-Advanced with key technology enhancements such as improved local area access, multi-antenna enhancements, machine type and device-to-device communication are still being standardized, developed, and deployed across the world [1]. With the increase in user throughput requirements and related challenges such as energy efficiency, low cost hardware deployments for small cells using cloud infrastructure, related architecture evolutions, etc., there is also an increased focus from industry, as well as academia, towards the evolution of current radio access technologies towards fifth generation (5G) wireless communication systems. One of the key focus areas of such an evolution would be the cost-efficient deployment of networks with better user experience and data rates. New architectures which enable such cost and energy efficient deployments of networks would be one of the main focus area of this work.

Cloud-based radio access network deployments which enable network densification and centralized processing of information, using low cost remote radio heads or small cells, could reduce the deployment costs of such networks [2]. Currently, 3GPP is working on small cell enhancements, with both ideal and non-ideal backhaul technologies, which could be considered as a key enabler for such an architecture evolution [3,4]. One such enhancement is the Dual connectivity feature, which enables operators to design the network by providing wide area control and data plane coverage using Master eNodeBs (MeNBs), and densify the network using for e.g. low cost cloud-based radio access networks, small cells or secondary eNodeBs (SeNBs), which provides data plane throughput enhancements. Data plane coverage using MeNBs are essential for improving mobility performance

and connectivity throughout the network, while reducing the occurrence of radio link failure. Such an architecture with separate control and user plane, called the phantom cell concept, has been evaluated in [5], and performance results indicate significant gains in terms of user throughput and mobility.

While such deployments could enable overall cost efficiency as well as reduction in initial capital expenditure (CAPEX), energy efficient operation of networks can provide significant reductions in operational expenditure (OPEX) as well. Green or energy efficient wireless networks have recently received significant attention from academia as well as industry. The work done in [6] evaluates the power consumption profiles of LTE eNBs, based on which active and sleep mode power consumption models are defined, which are used in this work as well. The use of coordinated multipoint for macro cell deactivation without transmit power adjustment from compensating neighboring cells is presented in [7]. A similar problem of macro cell switch off is studied in [8], from a game theoretic perspective, in a multi-operator environment.

A detailed evaluation of the energy efficiency of network infrastructure is done in [9]. The work considers the need for having a holistic approach towards energy efficiency evaluations, as well as to improve energy productivity of network infrastructure, services, and applications. The energy efficiency of base stations and network deployments, and impacts related to site configuration and network dimensioning is studied in [10], based on radio access networks in Finland. Based on the evaluations done, it is shown that significant energy saving gains can be obtained by having region-specific network deployment strategies. The work done in [11] evaluates energy efficient sleep strategies for mobile devices, mainly from a WiMAX system perspective. A power saving mechanism called the adaptive dual-threshold scheme is proposed which takes real-time traffic, as well as quality of service (QoS) requirements into account, and is shown to provide significant energy saving (ES) gains.

Energy efficiency using discontinuous transmissions (DTX) at the eNB is studied in [12–14], from both macro and small cell perspective. The evaluations were done mainly from a macro cellular perspective in [12, 13], and small cell perspective in [14], with significant gains shown using various cell DTX techniques. Different sleep mode techniques for ES were also evaluated in [15], using different traffic models, and significant ES were shown using the proposed techniques. The work done in [16] evaluates small cell activation technique in heterogeneous networks, with a load based offloading criteria, without taking the backhaul power consumption into account. ES enhancements for a dual connectivity environment using a database for location estimation, cell selection, and activation is presented in [17]. Most of the current work in this field focuses mainly on the radio access

network power consumption, with limited attention to the impact of the backhaul link on the overall network energy efficiency.

The work in [18] considers the impact of ‘ideal’ fiber optical backhaul links on the network power consumption. In [19], the authors evaluate the energy consumption using different backhaul types in a heterogeneous network with macro and femto cells as well. The evaluations are mainly done using full load assumptions, with varying levels of small cell density, in order to evaluate their impact on overall power consumption. The impact of backhaul power consumption on the overall network energy efficiency is studied in [20]. Techniques based on context-aware energy efficient user association are also proposed, which are shown to provide energy efficiency without compromising spectral efficiency. The mobile backhaul initiative of broadband forum is currently studying and defining techniques for energy efficient backhaul architectures to be integrated with the radio access networks [21, 22], taking into account different types of backhaul links. Currently, 3GPP is also working on developing ES enhancements for LTE-Advanced heterogeneous networks [23], where small eNBs are assumed to enter ES state under certain conditions, while macro cells provide compensation in terms of coverage and capacity.

The current works available in literature mainly focuses on efficient cell activation based on load, or on the overall network power consumption due to node densification and backhaul links. In this work, we consider a backhaul aware small cell activation and data offloading mechanism based on dual connectivity architecture. Here, backhaul awareness means that the macro eNB is aware of the small cell backhaul link power consumption (e.g. by means of configuration), such that ES decisions can be made, taking into account the overall system power consumption. The proposed mechanism performs offloading of traffic to small cells in ES state only when the offloading action minimizes the overall energy consumption of the network, or if it provides improvement in service quality for the users. We show that this mechanism leads to significant reduction in power consumption depending on network load and user densities, while maintaining good service quality in terms of bandwidth for the users.

Recently, heterogeneous network mobility and related challenges has been an important topic of interest, with challenges related to inter-frequency discovery of small cells considered in [24]. Currently, the main focus of mobility within heterogeneous networks has been on maximizing the offloading opportunities in a reliable manner [25]. In this work, we also consider the inter-frequency deployment of small cells for capacity enhancements, and the impact of mobility on the backhaul aware energy efficiency criteria. The optimal network deployment densities for different constraints, to minimize deployment costs, using random deployment of small cells is studied in [26]. Here, we consider both indoor and

outdoor deployment of small cells for evaluations, with different deployment and user densities, evaluating the system mainly from energy efficiency perspective.

The rest of the paper is structured as follows: Section 2 gives an overview of the system model used. Section 3 discusses the evaluated mechanism. Section 4 presents the simulation assumptions and system level parameters used, along with detailed performance results. Section 5 provides a summary of the paper.

2 System model

We consider a system with heterogeneous deployment of network elements, with Macro or MeNB and Pico (small) or SeNB, as shown in Fig. 1. A Master eNB indicates a Macro eNB which is deployed within a dual connectivity framework. An MeNB can have multiple SeNBs within its coverage footprint, but a SeNB is assumed to have the X2 interface with only a single MeNB, and the eNBs are assumed to be synchronized.

Following the assumptions in [1, 3, 4], SeNBs are deployed in a dedicated carrier (F2) as compared to MeNBs (F1), in order to support dual connectivity. The dual connectivity architecture considered in this work is based on agreed assumptions from [4]. It enables the split of control and user plane traffic, where the MeNB provides wide area coverage, as well as robust and reliable control plane signaling to the UEs. The SeNBs will provide user plane capacity enhancements at hotspot locations. Such an architecture enables the operators to deploy networks with coverage provided using MeNBs, and capacity through network densification using SeNBs, without the need for additional network plane entities.

Dual connectivity can be considered as a key enabler for the separation between the control and user plane entities of the network. The control plane of the MeNB uses the control plane interface with EPC entities such as the Mobility Management Entity (via S1-MME interface). User plane data can be provided by the MeNB, as well as by the SeNB via the

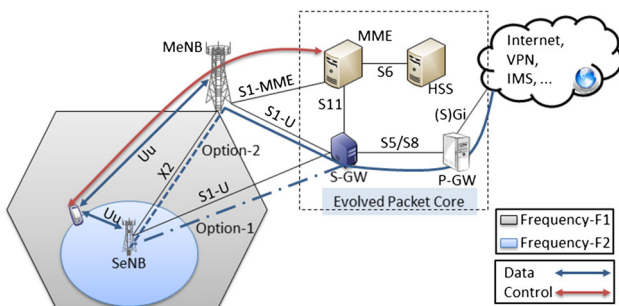


Fig. 1 Dual connectivity architecture [27]

S1-U to the Serving- and subsequently Packet data network-GateWay (S-GW and P-GW) nodes. Currently, two options are considered for offloading user traffic to SeNBs - informing the S-GW to redirect the offloaded traffic to the SeNB (Option-1), or using the logical interface between MeNB and SeNB called X2 for data forwarding from MeNB (Option-2). The options gives network operators the flexibility to adapt their network architecture depending on the backhaul link quality between the MeNB, SeNB and the traffic aggregation node. Option-1 requires less coordination between the eNBs using a non-ideal X2, but still requires an ideal u-plane interface, S1-U, with the EPC. This is required for traffic with high QoS requirements (low packet delay, packet loss rate, etc.), which could still be offloaded to the SeNB. Option-2 involves tight coordination between MeNB and SeNB for radio resource management, scheduling, etc., with an ideal X2 interface with low delay. Due to these factors, we assume a ideal fiber optic backhaul considered in [18] to be used by MeNBs in the system. For SeNBs, we consider different types of ideal, as well as non-ideal backhuls having different power consumption profiles.

2.1 Energy consumption model

In this paper, we consider and optimize the power consumption due to the radio access network including the eNBs, as well as the backhaul link towards the core network. Following [6], the total power P_C [W] consumed by a cell including backhaul power is given by:

$$P_C = \begin{cases} N_A(P_0 + \Delta_p \rho P_m) + P_{bh_a}, & \text{active mode} \\ N_A P_s + P_{bh_s}, & \text{sleep mode,} \end{cases} \quad (1)$$

with

$$\rho = \frac{N_U}{N_T}, \quad (2)$$

where N_A is the number of antennas, P_0 is the power consumption at zero RF output power, Δ_p is the slope of the load dependent power consumption, P_m [W] is the maximum RMS transmit power of the base station, and P_s the power consumption [W] when the BS is in sleep mode. P_{bh_a} and P_{bh_s} are the active and sleep mode power consumption of the backhaul link. The load factor ρ is the ratio of number of resources being used N_U , and the total available resources N_T .

The energy consumption of the ideal MeNB backhaul link is based on [18]. The active backhaul link power consumption for macro cell, $P_{bh_{a-id}}$ [W] is [18]:

$$P_{bh_{a-id}} = b_{bh} + \frac{(1 - \tau) P_{switch}^{max}}{n_{ports} C_{switch}^{max}} A_{gswitch} + \frac{\tau P_{switch}^{max}}{n_{ports}}, \quad (3)$$

where b_{bh} is the power consumed by backhaul transceiver and uplink interface, P_{switch}^{max} is the maximum power consumption of the backhaul switch, Ag_{switch} is the aggregate traffic traveling through the switch, C_{switch}^{max} is the maximum capacity of the switch, n_{ports} the number of ports, and τ is the percentage of switch power consumed, independent of the network traffic.

The MeNB is always assumed to be active, providing basic coverage throughout the network, and hence, the backhaul link is assumed to be always active as well. The linear power consumption model considered for base stations is similar to the ones presented in [12, 16]. While the MeNBs are always active, the SeNB cells and its backhaul link can be active, or in sleep or ES mode, following Eq. (1). Such considerations are in line with the assumptions made for LTE-Advanced heterogeneous networks in [23]. Here, the X2 interface is used for ES cells to inform the MeNB before entering ES state, and MeNBs for activating the ES cells based on certain activation conditions. The cell activation request, and response messages [28] could be used for this.

For SeNBs we assume both wired (Wrd) and wireless backhaul with characteristics as shown in Table 1, based on the study conducted by network operators [29]. We broadly classify the different possible backhauls as fiber-optic, Wrd (using DSL/cable) and wireless backhaul. Different active and sleep mode energy consumption models for these backhaul types based on values available in literature are presented as well.

2.1.1 Fiber access

For fiber access (FA) backhaul for SeNBs, we consider the power consumption model for Gigabit Passive Optical Network (GPON) presented in [30]. For evaluations, we use the power saving model obtained using power shedding techniques, which provides load-independent active and sleep mode power values, $P_{bh_{a-FA}}$ and $P_{bh_{s-FA}}$, respectively. Similar power consumption assumptions have been made for optical fiber backhaul for wireless networks in [31, 32] as well. As indicated in Table 1, the FA could be considered as

Table 1 Different categories of Backhaul [29]

Backhaul technology	One-way latency	Throughput	Backhaul type
Fiber access-1	10–30ms	10 M–10 Gbps	Non-ideal
Fiber access-2	5–10ms	100–1000 Mbps	Non-ideal
Fiber access-3	2–5 ms	50 M–10 Gbps	Non-ideal
Fiber access-4	<2.5 μ s	\leq 10 Gbps	Ideal
DSL access	15–60ms	10–100Mbps	Non-ideal
Cable	25–35ms	10–100Mbps	Non-ideal
Wireless	5–35 ms	10–100Mbps	Non-ideal

ideal or non-ideal mainly based on the experienced latency or delay in the backhaul link.

2.1.2 Ideal fiber access backhaul (Symmetric MeNB–SeNB)

In this scenario, we assume SeNB and MeNB to have symmetric ideal fiber-optic backhaul with active mode power consumption as given by Eq. (3). The sleep mode power consumption is assumed to be $P_{bh_{s-id}} = \beta P_{bh_{a-id}}$, with $Ag_{switch} = 0$. Here, $\beta \in [0, 1]$ represents the possible sleep mode power consumption factor for the backhaul link elements involved, when there is no traffic flowing through them. The value indicates that the backhaul link nodes for cells in ES mode are either completely switched off, consume a portion of the power consumed while fully active, or are fully active.

2.1.3 Wired backhaul (Cable and DSL)

Here we consider a slightly modified fiber-to-the-node using VDSL2 architecture model presented in [19], with the assumption that the small cell architecture is integrated with the MeNB fiber optic one. Thus the power model, excluding that of the fiber switch for each small cell is given by:

$$P_{bh_{a-wrd}} = P_{modem} + \frac{P_{DSLAM} + 2P_{SFP}}{n_{ports}^D}. \quad (4)$$

Similar to the ideal symmetric backhaul (SB) case, we assume the sleep mode power consumption to be $P_{bh_{a-wrd}} = \beta P_{bh_{s-wrd}}$, in order to evaluate its impact on energy efficient system operation.

2.1.4 Wireless backhaul

The wireless backhaul power consumption used in this work is based on the model presented in [33] for device ‘‘G’’, which is similar to a wireless local area network (WLAN) access point. The model used for the wireless backhaul power consumption $P_{bh_{s-wB}}$ [W] can be expressed as follows:

$$P_{bh_{a-wb}} = I_{wb} + \Delta_{wb} \rho_{wb} M_{wb}, \quad (5)$$

where I_{wb} is the measured idle power, Δ_{wb} is the load dependent slope of the backhaul power consumption, M_{wb} is the measured max. power and ρ_{wb} is the load of the wireless backhaul access point. The sleep or idle mode power consumption is taken to be $P_{bh_{a-wb}} = I_{wb}$, when the load in the backhaul link $\rho_{wb} = 0$. We did not consider microwave backhaul due to the relatively high power consumption [19], compared to the SeNB power values. This factor makes it challenging to be used along with dense low-power small

cell deployments, unless new architecture and power models are investigated.

2.2 Bandwidth and energy efficiency model

For calculating the throughput capacity on the serving link, the potential target cell, as well as backhaul link load, we consider the effective bandwidth model developed in [34]. The capacity of the link S [b/s/Hz] is:

$$S = \min \left\{ B_{\text{eff}} \cdot \log_2 \left(1 + \frac{\gamma}{\gamma_{\text{eff}}} \right), S_{\text{eff}} \right\}, \quad (6)$$

where B_{eff} is the bandwidth efficiency which indicates the reduction in bandwidth utilization due to practical filter implementation, adjacent channel leakage ratio, etc., γ is the signal-to-interference-noise ratio (SINR), γ_{eff} the SINR efficiency, and S_{eff} the maximum spectral efficiency of the system [34].

Furthermore, for a system having $N_T = N_{\text{RB}}$ RBs each with size RB_s [Hz], a user data rate of R [bps] will use N_U RBs, given by [16]

$$N_U = \frac{R}{S \cdot RB_s}. \quad (7)$$

We consider then the energy efficiency of the network, ψ [bps/W] as a key metric, given by [18]:

$$\psi = \frac{C_{\text{net}}}{P_{\text{net}}}, \quad (8)$$

where for a system having K cells, the network power consumption, $P_{\text{net}} = \sum_{k=1}^K P_{C_k}$ [W] and network capacity, $C_{\text{net}} = \sum_{k=1}^K C_{\text{cell}_k}$ [bps]. The capacity of cell k , $C_{\text{cell}_k} = \sum_{i=1}^{N_{UE}} R_i$, depends on the real-time sum throughput rates, R_i , between the radio access network (RAN) and the core network. Here, for P_{bh_a} due to cell k , $Ag_{switch} = C_{\text{cell}_k}$, since for the considered downlink centric system, that would be the amount of traffic traversing through the backhaul switch.

In this work, we assume a system with dynamic load conditions, with the backhaul link entering sleep mode, when its corresponding SeNB cell is in ES state. For a system such as LTE, the load of the system would depend on the physical resource block (PRB) utilization in each cell, as compared to the total available PRBs. The real-time exchange of such resource utilization information is possible over the X2 interface using the currently defined standards [28]. There are various techniques currently being proposed in [23] for determining UE proximity with an ES cell, for accurate switching on of ES cells. The SINR and load estimation mechanisms used are assumed to be similar to the one considered in [16]. The backhaul link nodes for cells in ES state, while entering sleep mode are assumed to enter active state when it receives

data traffic. Thus, when the MeNB sends the cell activation request [28] for activating the SeNB, the messages arrive with a delay required for activating the backhaul nodes, which is not considered in this work.

We evaluate the potential energy efficient operation of the system, remaining agnostic regarding how the accurate ES or SeNB cell for activation is determined by the MeNB. The proximity estimation could also be done using radio fingerprint mechanism considered for small cell discovery in [24], which was shown to provide accurate estimations of UE to an inter-frequency small cell, without actually detecting the cell. In the context of SeNBs, a cell essentially means a SeNB node, whereas in the MeNB case, each eNB is split into multiple cells.

3 Backhaul-aware energy efficient network operation scheme

We consider the offloading of user plane traffic to SeNBs in an energy efficient manner, in a dual connectivity environment. The data traffic offloaded from MeNBs to SeNBs in ES state are considered in terms of energy offloaded, as well as taking into account the improvement of UE quality of experience due to the potential increase in traffic rates. The energy offloaded here implies the potential energy consumption reduction of the MeNB due to load of the offloaded traffic. By taking the energy offloaded as well as the service quality, the aim is to provide a mechanism for operating an energy efficient network with good service quality for the users. Energy efficiency can be maximized by operating only those SeNBs which minimizes the network power consumption, and by optimizing the load of all the eNBs. User service quality is considered to be a combination of user data rates, as well as the traffic type and related characteristics. By combining these two factors which could sometimes be conflicting, network operators can have the flexibility to have trade-offs between energy efficiency and higher network capacity, depending on the traffic characteristics of the user.

The energy efficiency criteria is backhaul aware, since the potential reduction in energy consumption due to backhaul load reduction at MeNB, as well as the potential increase in energy consumption due to activating the SeNB backhaul link is also taken into account by the scheme. The backhaul-aware energy efficiency criteria is given by:

$$\rho_{MS} > \frac{\left(N_{A_s} (P_{0_s} + \Delta_{p_s} \rho_{SM} P_{m_s} - P_{s_s}) + P_{bh_{a_s}} - P_{bh_{s_s}} - P_{bh_{a_m-off}} \right)}{N_{A_m} \Delta_{p_m} P_{m_m}}, \quad (9)$$

where N_{A_m} , Δ_{p_m} , P_{m_m} are power consumption values from Eq. (1) for the MeNB, and N_{A_s} , Δ_{p_s} , P_{m_s} are those of the SeNB. ρ_{MS} is the aggregate load of the users offloaded from

MeNB to SeNB, and ρ_{SM} the estimated load due to the offloaded users at the SeNB. $P_{bh_{as}}$ and $P_{bh_{s_s}}$ are the active and sleep mode backhaul power consumption of the SeNB backhaul links. Here, $P_{bh_{am-off}}$ is the load dependent part of the MeNB backhaul power consumption in Eq. (3), given by:

$$P_{bh_{am-off}} = \frac{(1 - \tau) P_{switch}^{max}}{n_{ports} C_{switch}^{max}} \sum_{n=1}^{N_{off}} R_n, \quad (10)$$

where N_{off} is the number of offloaded users, and R_n is the traffic rate of each user. Here, ρ_{MS} and ρ_{SM} are dependent on the sum rates of the offloaded users, $\sum_{n=1}^{N_{off}} R_n$, whose values can be calculated using Eq. (2).

Before activating a SeNB in ES state, the MeNB will take the energy efficiency criteria given by Eq. (9) into account, as well as the characteristics of traffic that could be offloaded. The traffic characteristics could be identified using deep packet inspection of the incoming packets, or consider the QoS class information of the traffic bearer [16], or using an explicit indication to the MeNB whether or not to apply energy saving mechanisms. QoS class information indicates the type of resource, its priority, as well as the packet delay budget and error loss characteristics to the eNB. From this, the eNB can derive the priority of the traffic as defined in the core network. Currently, for user plane congestion mitigation, 3GPP is also studying the advantages of defining packet marking for intra-bearer traffic flow prioritization [35]. The packet marking would enable operators to define different priority information to traffic flows within the same bearer, using which eNBs can schedule packets accordingly. We assume that, the MeNB uses such assistance information while offloading traffic in a dual connectivity environment as well. The inverse of the criteria in Eq. (9) can be used to deactivate SeNBs during low load conditions, taking into account the potential traffic load and power consumption increase caused to the MeNB. The scheme can be considered as an extension of the work presented in [27], taking the backhaul sleep power consumption assumptions into account.

3.1 Load estimation

From Eqs. (9) and (10), we can observe that the only unknown factor required for taking accurate cell activation and deactivation decision is the potential load caused to the target cell. The accuracy of this would have impacts on the network energy efficiency, while activating and deactivating the SeNBs. In this work, we assume the use of “minimization of drive test” (MDT) feature related data processing analytic tools to be integrated with the radio access network, as shown in Fig. 2. The detailed architecture and location tagged information reporting mechanisms used for MDT is

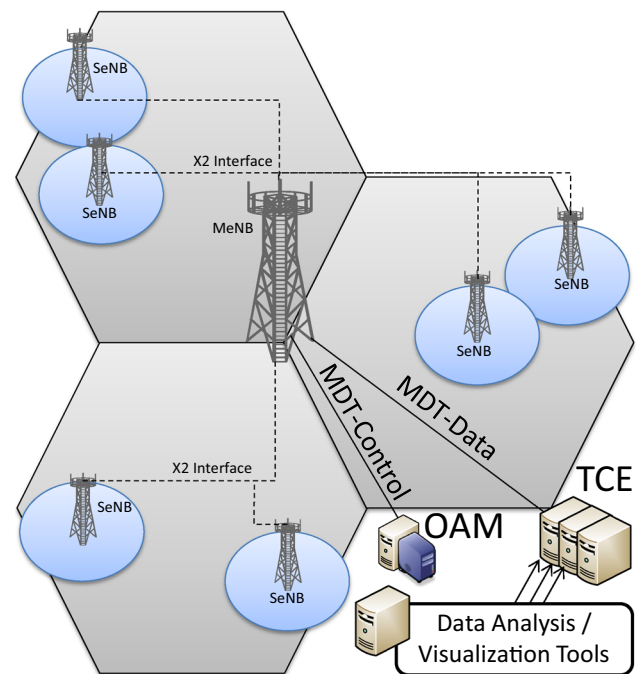


Fig. 2 MDT integrated along with radio access network

presented in [36]. Similar data collection mechanisms for handover decisions using a central network resource management entity is considered in [37]. Since the UE receives and reports control plane information to the MeNB, the UE is assumed to report the location tagged detailed measurements to the MeNB, along with the load information from SeNB using X2 signaling. The MeNB is assumed to combine these information and report to the trace collection entity (TCE), which is a database of all the UE reported information from the RAN.

Using such a database, the operator is able to reconstruct the radio environment of the network, and extract valuable information such as the SINR experienced by each UE at different physical locations. Such information is assumed to be fed back to the MeNB, which then uses it for load estimation and related ES actions. The control information for MDT is received from the OAM entity to the MeNB, and the interface for data is connected to the TCE database. Since the complete information for load estimation is assumed to be present at the MeNB, while taking switch OFF decisions, SeNB first exchanges its load and traffic information with the MeNB, using a cell deactivation request. MeNB then decides whether the cell deactivation request would lead to ES or change in UE service quality, before making the decision. Similar database for energy efficient dual connectivity environment is considered in [17], where the database is used to select the best SeNB cell in ES mode for offloading. Even though the paper considers the MeNB to take the cell activation and deactivation decisions, the mechanism is essentially agnostic in terms of which network entity could be used in

a real network. The decision could be taken by control plane entities such as a software defined, self-organizing network controller, or the OAM entity as well, based on the mechanisms described in the paper. While the decision could be taken by any control plane entity, the activation/deactivation messages are always sent by the MeNB to which the SeNB has an X2 interface.

3.2 Heterogeneous network mobility

Currently, heterogeneous network mobility considers short time-of-stay metric, indicating the minimum small cell connected time above which a small cell handover is considered to be beneficial, mainly from signaling load impact perspective. From an energy efficiency perspective, Eq. (9) holds if there are no delays associated with activating and deactivating SeNBs. Thus, if the offloading duration is the same as cell activation duration T_c , the factor of time to be taken into account for calculating energy, need not be considered. But, if there is an additional delay T_d , during which small cell and the backhaul link is active with zero load, this would mean that there is an additional energy consumption factor E_d that needs to be taken into account. The value of this energy due to cell activation/deactivation delay, E_d [J] is given by:

$$E_d = T_d (N_{A_s} (P_{0_s} - P_{s_s}) + P_{bh_{a_s}} - P_{bh_{s_s}}). \quad (11)$$

Let P_{MS} be the MeNB transmit power reduction due to the traffic offloaded to SeNB, and P_{SM} be the additional power consumed at SeNB due to the offloaded traffic from MeNB including the backhaul link power consumption, both of which can be derived from Eq. (9). From Eqs. (9) and (11), we can calculate the minimum small cell connected time for energy efficient operation, $T_{c(min)}$ [s], as:

$$T_{c(min)} > \frac{T_d (N_{A_s} (P_{0_s} - P_{s_s}) + P_{bh_{a_s}} - P_{bh_{s_s}})}{P_{MS} - P_{SM}}. \quad (12)$$

Thus, in an environment with user mobility, the network can be energy efficient as long as the small cell connected time $T_c > T_{c(min)}$. This value can also be considered as the short time-of-stay parameter, below which connecting to a SeNB is no longer assumed to be beneficial. Assuming uniform distribution of small cell connected times, for a cell having radius R , the mean connected distance, $d_{mean} = 4R/\pi$ [38]. For each UE traversing through such a small cell with speed v , it is no longer beneficial to connect to the small cell if $T_{c(min)} < d_{mean}/v$.

Since the energy efficiency criteria essentially optimizes offloading to reduce the network power consumption, there is always a cost involved in terms of service quality. For evaluating this cost due to the energy efficiency criteria on the user throughput, we consider a dynamic offloading rate factor

$\delta_{off} \in [0, 1]$, to indicate the cases where small cells are activated even when the energy efficiency criteria is not satisfied, but the offloading action would result in an improvement in the user experience.

4 Simulation results

4.1 Simulation assumptions

We consider a heterogeneous network scenario consisting of seven MeNBs having three cells each, altogether forming 21 cells. Within each MeNB cell, SeNBs or pico cells are dropped at random locations with minimum pico-to-pico distance of 30 m and macro-to-pico distance of 60 m, in order to have spatial separation between the cells. For the static user scenario, simulations were run as a series of snapshots with parameters such as shadow fading, user location, etc. remaining static during the snapshot. For the mobile user scenario, users move around the simulation world in random straight directions until the end of the simulation scenario is reached, after which a new random direction within the scenario is selected. The speed of the user remains the same in each simulation run. The simulation duration for this scenario was taken to be 4,000 s, during which each user can move from one end of the simulation world to the other at least twice.

For ES evaluations, users were dropped uniformly at random across the scenario, with number of UEs, N_{UE} varying between 1 and 100. For evaluating the potential throughput gains using dual connectivity, with full-buffer traffic conditions, users were dropped randomly within the coverage area of SeNBs. Uncorrelated slow fading was used for simulations, detailed parameters of which are as shown in Table 2. The path loss models, antenna pattern, etc., used for evaluation follows 3GPP case 1 model defined in [40]. The path-loss is given by:

$$L_M = 128.1 + 37.6 \log_{10}(R) \quad (13)$$

$$L_P = 140.7 + 36.7 \log_{10}(R), \quad (14)$$

where L_M corresponds to distance dependent path-loss from macro BS to the UE and L_P corresponds to the path loss from pico cell to the UE. Here R [km] is the distance between the transmitter and receiver.

Ideal load estimation was assumed during simulations, for calculating the offloading criteria. As a reference scheme, we have used the location or small cell proximity based cell activation (Loc. or Location Based) scheme. According to this scheme, MeNB activates a SeNB in sleep mode as soon as an active mode UE engaged in data transfer enters the proximity of the SeNB. Such a scheme essentially does not take into account the traffic characteristics, nor additional power

Table 2 System level simulation parameters

Basic radio configuration parameters [39]		
Macro cell ISD	500 m	
Shadowing standard deviation	Macro (Pico) cell	8 (10) dB
Spectrum allocation	10 MHz Channels	
	Macro and pico in separate carriers	
Macro (Pico) Max Tx power [dBm]	46 (30)	
Antenna gain [dB]	Macro (Pico)	15 (5)
Cell range expansion offset	12 dB	
Transmit power related parameters [6]		
N_A (per cell)	Macro (Pico)	2 (2)
P_0 [W]	Macro (Pico)	130.0 (6.8)
Δ_p	Macro (Pico)	4.7 (4.0)
P_m [W]	Macro (Pico)	20.0 (0.5)
P_s [W]	Macro (Pico)	75.0 (4.3)
Other simulation parameters		
Spectral efficiency, S_{eff}	4.0	
No. of RBs, N_{RB}	50	
PRB size, RB_s	180 kHz	
Bandwidth efficiency, B_{eff}	0.65	
SINR efficiency, γ_{eff}	0.95	
No. of Picos, N_P	[1–10] per cell	
User placement	Random, $N_{\text{UE}} = [1–100]$ UEs/cell	
Min. Pico-to-Pico distance	30 m	
Min. Macro-to-Pico distance	60 m	
Penetration loss	20 dB	
Static traffic	R [kbps]	128
Dynamic traffic	$R_{\text{max}}(R_{\text{min}})$ [kbps]	512 (128)

consumption information. The location based scheme can be considered as a special case of the energy efficient scheme considered in the paper, with $\delta_{\text{off}} = 0$. The cell is deactivated as soon as all the UEs within the coverage area leaves the cell. A load based (Load Based) cell activation scheme is also considered as a reference scheme, where the MeNB considers only the load caused due to the active UE while taking the cell activation decision. Such a scheme essentially takes the UE traffic characteristics into account, ignoring the backhaul link power consumption, and can be considered similar to the scheme used in [16]. This can be considered as a special case in Eq. (9), where the backhaul power related values are assumed to be zero. The proposed scheme is denoted as ‘Load+Backhaul’ or ‘Load+BH’ in the evaluations. The ES gains are shown for the case where $\delta_{\text{off}} = 1$, and the gains would vary between Loc. based and Load+BH based schemes depending on the value of δ_{off} used by the MeNB while enabling dual connectivity with SeNB for the user.

Detailed power consumption values for the radio access network nodes are shown in Table 2. The power values

obtained by substituting these values in Eq. (1) for active and sleep mode SeNBs are as shown in Fig. 3. From the figure we can observe that SB consumes the highest amount of active mode power, with sleep mode power varying depending on the value of β . FA and Wrd backhaul have similar levels of active mode power consumption, with FA enabling significant sleep mode power savings, as compared to Wrd access, again depending on the values of β . Among the different backhaul types, wireless (WL) consumes the least amount of active mode power, but it also consumes the same amount of idle mode power as compared to Wrd, $\beta = 0.5$ backhaul link type. The power consumption values used are as shown in Table 3. For making energy efficient offloading decisions, we assume that the backhaul power consumption parameters are pre-configured at the MeNB using the OAM entity. In this work, 10MHz bandwidth has been considered mainly due to the system level assumptions and models in [4,6]. The mechanism and related gains should be applicable for other system bandwidths as well, with eNBs having linear and load-dependent power consumption models.

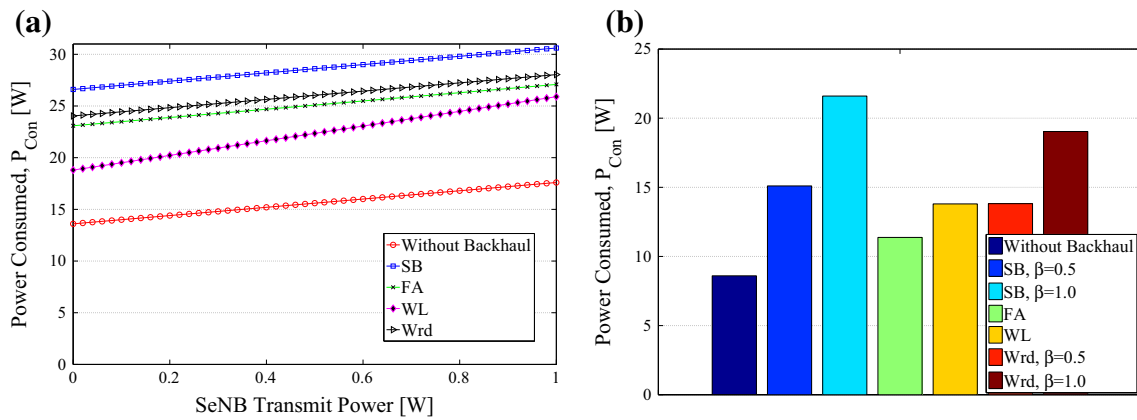


Fig. 3 SeNB Transmit Power versus actual power consumption with and without considering backhaul power consumption. **a** Active mode power consumption. **b** Sleep mode power consumption

Table 3 Backhaul related parameters [18, 19, 30, 33]

Parameter	Value
$b_{bh} (P_{switch}^{max})$ [W]	3 (300)
$\tau (N_{ports})$	0.8 (24)
C_{switch}^{max} [Gbps]	10
P_{bh_s-FA} [W]	9.77
P_{bh_a-FA} [W]	2.77
$I_{wb} (M_{wb})$ [W]	5.2 (8.3)
P_{modem} [W]	5.0
P_{SFP} [W]	1
n_{ports}^D	16
P_{DSLAM}	85

Accurate SINR estimation of both SeNB and MeNB was assumed during simulations. MeNBs and SeNBs were assumed to be synchronized, and full load assumptions were made for neighboring nodes while estimating the SINR of each UE. This is based on the assumption that, for uniform distribution of users, with each cell having symmetric load, similar resource block allocations could be made, enabling more realistic interference estimation using this technique. The load caused to a cell for various SINR values and traffic rates are as shown in Fig. 4, based on Eqs. (2), (6) and (7). The values used in the equations are shown in Table 2 as well. In the mobile and static user scenarios, the cell selection for activation and offloading conditions remain the same. Cell deactivation is done by the MeNB once the energy efficient criteria is no longer met by the SeNB.

Two types of traffic has been assumed for simulations: static and dynamic. Static traffic with $R = 128$ kbps, is essentially constant bit rate traffic, for which eNB reserves resources for the UE. This could be assumed as web traffic, voice or other low data rate traffic for which resource reservation is done for ensuring QoS or due to contrac-

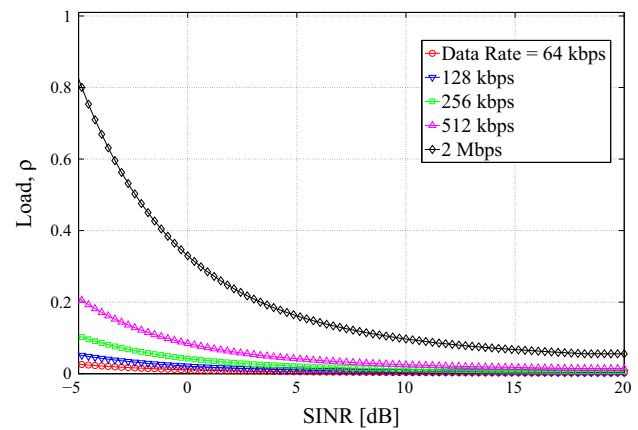


Fig. 4 Load, ρ versus SINR, γ [dB]

tual agreements with the user. For dynamic traffic case, we assume $R_{min} = 128$, and $R_{max} = 512$ kbps for simulating a more challenging environment where scheduler allocates resources for users using both resource reservations, and dynamic resource allocations in a round robin manner. Both indoor and outdoor scenarios have been considered for evaluations. For the indoor case, the wall attenuation or penetration loss value used, are as shown in the Table 2, with UE considered to be indoor when it is in the 50 m proximity of a SeNB. The SeNBs are randomly deployed for this scenario as well, with indoor path loss assumptions following [40]. The network power consumption for the mobility scenario is calculated by dividing the average total energy consumption during the simulated time period, with the simulation run-time. The heterogeneous network and mobility related assumptions used are mostly in line with the ones used in [39]. For scenarios with varying UEs, the no. of picos deployed per cell, $N_P = 10$, and with varying picos, no. of UEs dropped per cell, $N_{UE} = 50$, unless otherwise mentioned.

4.2 Simulation results and analysis

The user throughput statistics for a non-uniform user distribution with complete network densification, where all UEs are within the coverage of a SeNB is as shown in Fig. 5. Here, the SeNBs are randomly chosen while dropping a UE, and results are shown for low and high user density scenarios. For both cases, we can observe significant gains in terms of 5th percentile and mean user throughput, due to inter-eNB carrier aggregation between MeNB and SeNB for the dual connectivity case. The results are shown here to indicate the potential throughput gains that can be achieved with limited bandwidth, using dual connectivity. The steps observed in the distribution is mainly due to the varying user densities at each SeNB, leading to significant differences in user throughput values. For the low user density case, the steps would indicate the difference in user throughput while for e.g. having one UE or multiple UEs per SeNB. We can observe from the figure that for low user density, the maximum throughput that can be achieved by a UE with dual connectivity is significantly improved, as compared to the single connectivity case.

The ES gains for SB case for various user distribution, small cell density, as well as traffic rates are as shown in Fig. 6. From the figures, we can observe that the considered Load+BH backhaul scheme provides significant gains of more than 20% in terms of energy efficiency and power consumption reductions. The gains are dependent on the backhaul sleep power consumption value β , as well as the user traffic. From Fig. 6a we can observe that, for low user traffic, $R = 128$ kbps case, the gains are significant when $\beta = 0, 0.5$. But, the gains converge with the load based scheme when $\beta = 1.0$. This is due to the fact that, backhaul links never enter sleep mode, thus the load based scheme and the backhaul aware scheme provides similar ES. The results are similar for the $R_{max} = 512$ kbps scenario shown in Fig. 6b, with gains diminished due to higher load of the UEs leading to more offloading of traffic. For $\beta = 1.0$ case, the ES obtained by optimizing cell activation is diminished by the higher backhaul power consumption.

Similar trends can be observed in the energy efficiency curves shown in Fig. 6c. The energy efficiency gains are further diminished due to higher throughput gains that can be achieved due to higher offloading, leading to convergence between the different schemes. Energy efficiency with varying N_P , with fixed $N_{UE} = 50$ is as shown in Fig. 6d. For the dynamic traffic scenario, with $R_{max} = 512$ kbps, we can observe that energy efficiency increases first and decreases due to a perceived increase of capacity depending on the user density initially, but the gains further diminishing due to the increase in energy consumption due to the additional nodes present in the network. But even in this case, it is observed that the backhaul aware scheme provides higher

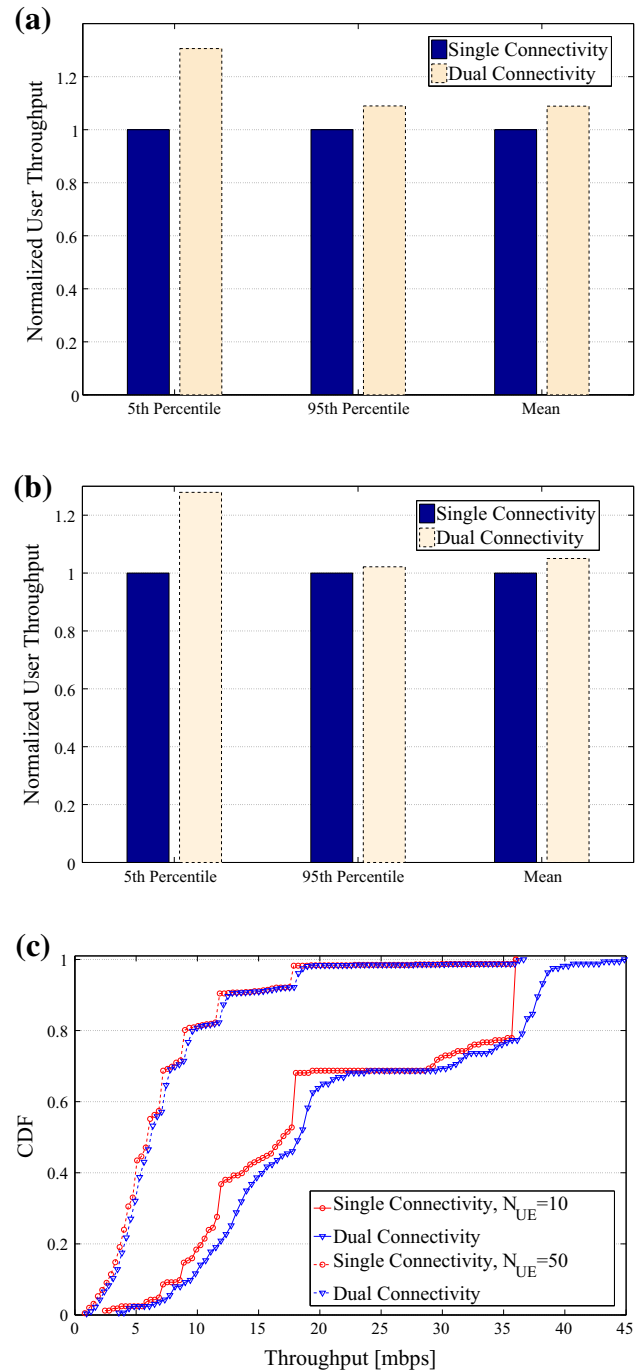


Fig. 5 Throughput distribution curves and normalized values with full buffer traffic, $N_P = 10$, **a** $N_{UE} = 10$, **b** $N_{UE} = 50$, **c** User Throughput CDF

energy efficiency. This is significant in a network, since the scheme provides higher energy efficiency with the perceived increase in network densification, without compromising the network capacity.

The ES gains for the FA backhaul scenario, is as shown in Fig. 7. The gains are similar to the one shown in the SB case (up to 20%), with gains converging for all the

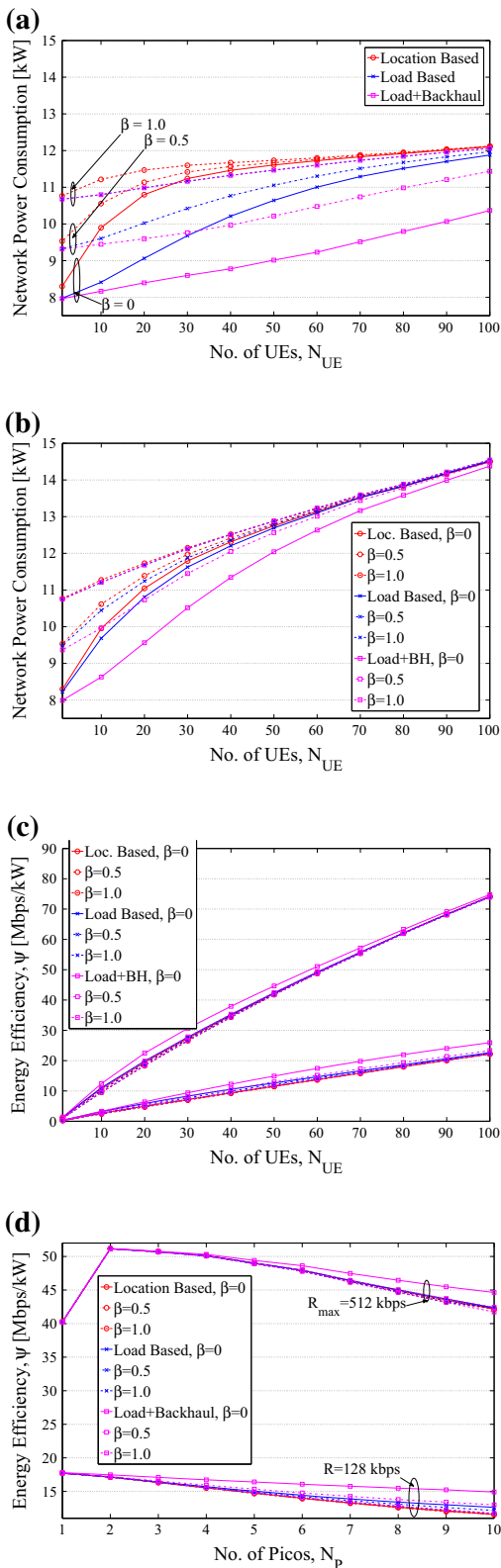


Fig. 6 Energy consumption and efficiency with symmetric backhaul, for various user distribution and traffic rates. **a** Static traffic, $R = 128$ kbps. **b** Dynamic traffic, $R_{max} = 512$ kbps. **c** Energy efficiency with varying N_{UE} . **d** Energy efficiency with varying N_P

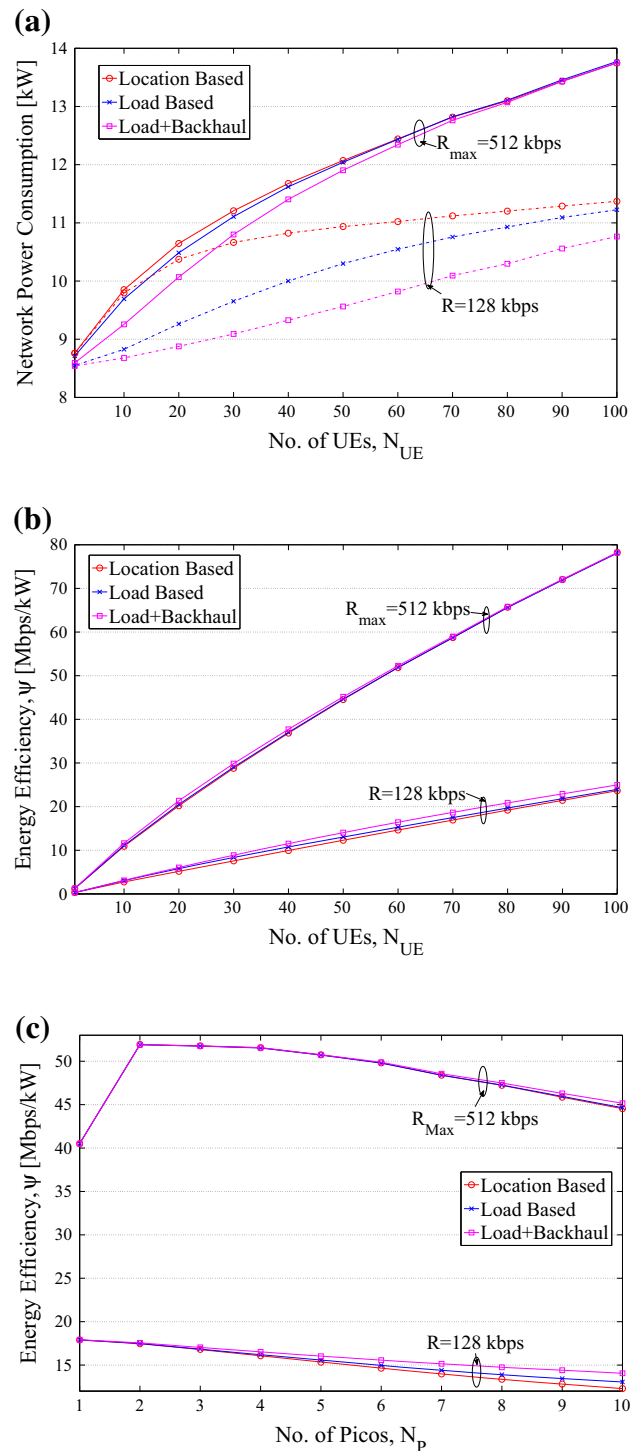


Fig. 7 Energy consumption and efficiency with fiber access backhaul, for various user distribution and traffic rates. **a** Power consumption. **b** Energy efficiency with varying N_{UE} . **c** Energy efficiency with varying N_P

evaluated schemes at high user density and traffic conditions. This is a desired behavior as well, since more cells should be activated at higher user density as well as traffic

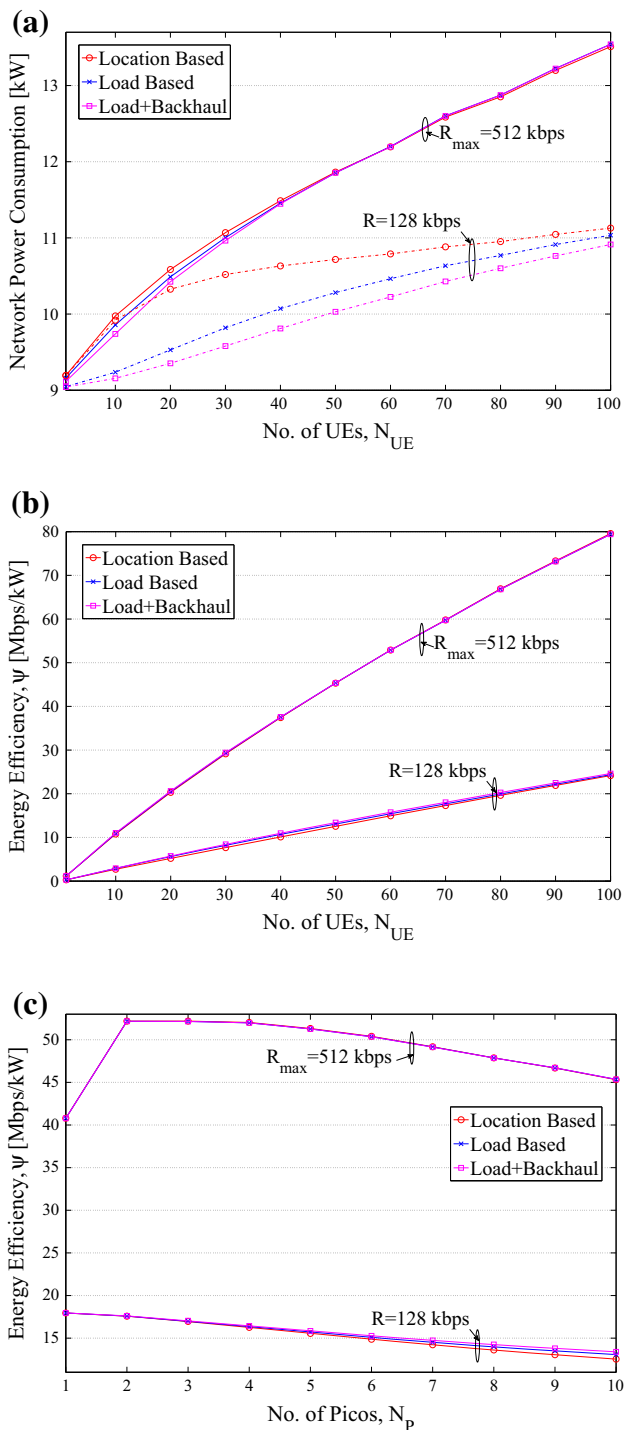


Fig. 8 Energy consumption and efficiency with wireless access backhaul, for various user distribution and traffic rates. **a** Power consumption. **b** Energy efficiency with varying N_{UE} . **c** Energy efficiency with varying N_p

conditions. The optimizations are essential for low density and traffic load, for e.g. during off-peak hours, so that network operators can reduce the OPEX of the network during that time. Energy efficiency gain trends are similar to

the earlier case as well, the difference essentially being the backhaul power consumption depending on the technology used.

The energy consumption results for wireless backhaul is as shown in Fig. 8. Here, due to the lower gains when the link is in idle mode reflects on the power consumption results, especially on the higher traffic load case. While there are slight gains (up to 10%), at low user densities, the gains diminish further at medium and high user densities, due to the lack of observable power savings from backhaul links entering power saving mode. The gains are low at $N_{UE} = 1$ case as well, due to low number of cells activated by the location and load based mechanisms.

The results for the Wrd backhaul link scenario are as shown in Fig. 9. The gains are similar to the symmetric backhaul scenario, and is dependent on the sleep mode backhaul link power consumption. We can observe that for $\beta = 0$ case, energy savings gains of more than 20% can be observed, and for $\beta = 0.5$, i.e., 50% backhaul power consumption during sleep mode there are significant ES gains (up to 10%) for the backhaul aware cell activation mechanism considered in this work, compared to the location and load based mechanisms. From the results presented so far, it can be observed that, significant energy savings are possible by using a backhaul aware cell activation mechanism. Since the cell activation and deactivation decisions are made by the MeNB, this gives network operators better control over the operational state of the network.

While we have considered a static scenario in terms of UE mobility so far, scenarios where UEs move around within the heterogeneous network with different speeds and cell deactivation delays, T_d , also contribute towards significant network energy consumption. When user density is low, the energy consumption values for $R = 128$ and $R_{max} = 512$ kbps cases are similar for the location based scheme, as shown in Fig. 10a. Here, we assume $\beta = 0$, in order to analyze the potential impacts due to mobility and switch off delays. This is due to the low load caused by the UEs and lower amount of cell activations. But, with mobility, it can be observed that the increase in power consumption due to cell deactivation delay is significant, especially for the loc. based, and load based schemes. For the backhaul aware scheme, since cell activations are optimized, it leads to significant ES of more than 10 and 8.5% compared to location and load based schemes, for $R = 128$ kbps, with the increase in energy consumption still limited with the increase in T_d . This is also due to the aggregate load considerations, leading to limited impact from $T_{c(min)}$, since essentially the offloading criteria consists of the aggregate $T_{c(min)}$ values of all users that can be potentially offloaded. From the figures, we can also observe that the impact of UE speed on overall network power consumption is limited.

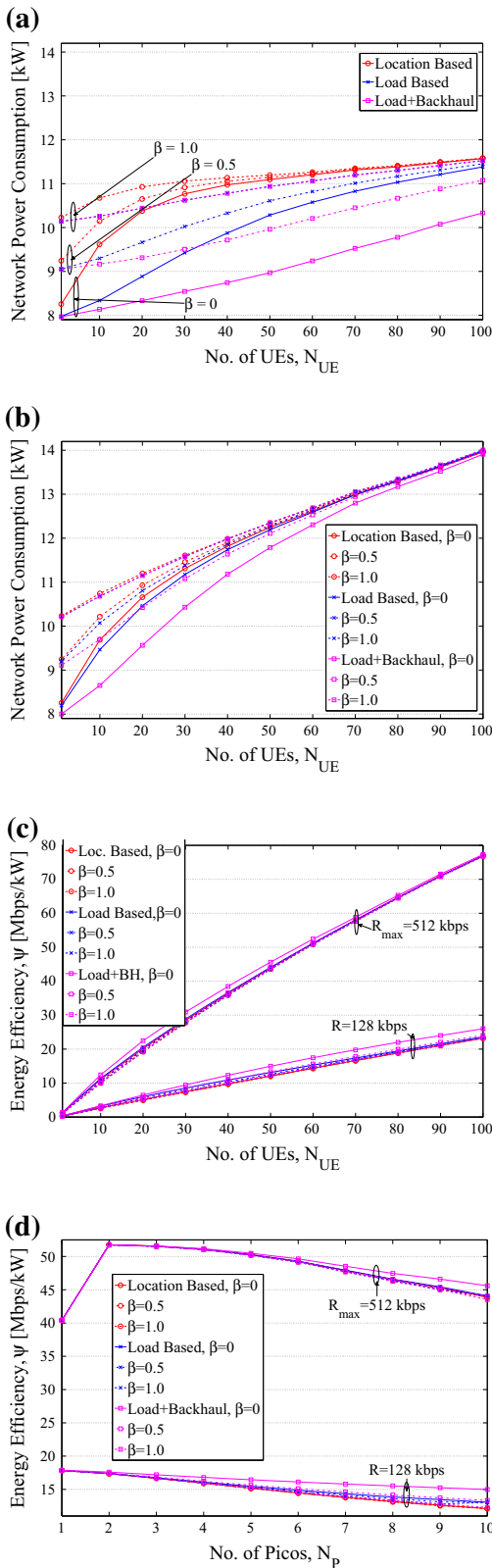


Fig. 9 Network energy consumption and efficiency with wired backhaul, for various user distribution and traffic rates. **a** Static traffic, $R = 128$ kbps. **b** Dynamic traffic, $R_{max} = 512$ kbps. **c** Energy efficiency with varying N_{UE} . **d** Energy efficiency with varying N_P

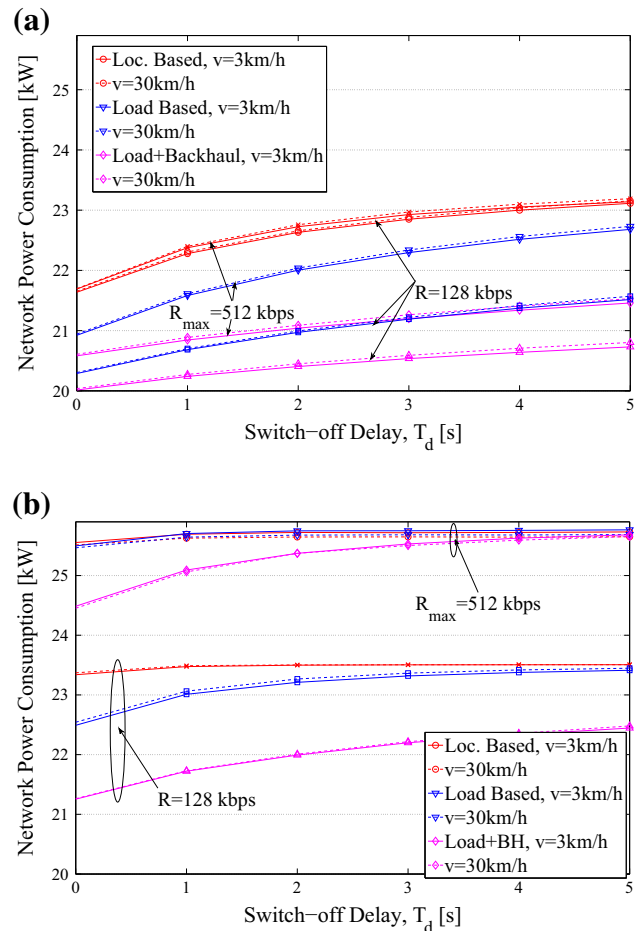


Fig. 10 Network energy consumption with symmetric backhaul, for various switch-off delays and UE speeds, $N_P = 10$. **a** $N_{UE} = 10$. **b** $N_{UE} = 50$

Figure 10b shows the power consumption values for various cell deactivation delays, with higher user density of $N_{UE} = 50$. From the figure, we can observe significant power consumption different between low and high user traffic rates. It can also be observed that the impact of T_d for location based scheme is limited, since the cells are always activated due to high probability of UEs to be present within its coverage footprint. Significant gains for the backhaul aware scenario can be observed here as well, with the gains diminishing for high traffic case, with higher values of T_d , since the probability of a cell being always active is high. But, for $R = 128$ kbps, due to the optimizations in cell activations, the impact of this delay can still be minimized, with ES gains of 5–10% compared to loc. based mechanism. The power consumption slope is less evident for $N_{UE} = 50$ case, due to the higher probability of UE being in the proximity of small cells, leading to more small cell activations even at lower values of T_d . But for $N_{UE} = 10$, the cell activation probability increases only when T_d increases, leading to an increase in power consumption as well.

The results presented so far have been considering outdoor deployment of SeNBs and UEs. The indoor deployment of small cells is also an important factor to be taken into account, while evaluating the backhaul aware mechanism. The power consumption and energy efficiency results for indoor deployment of SeNBs are as shown in Figs. 11 and 12 for symmetric and FA backhaul scenarios. While significant ES gains (with static traffic, up to 22% for the symmetric case with $\beta = 0$ and 15% for FA case), higher than the outdoor deployment case, can be observed here as well. The key consideration here is the increase in energy efficiency with the increase in network densification observed in Figs. 11d and 12c for this scenario. This happens due to the higher amount of small cell selections for activation due to the higher wall penetration loss for indoor UEs, which reduces the SINR for the MeNB link, thereby increasing the load caused to the MeNB, as compared to the significantly lower load towards the SeNB.

The user throughput distribution for backhaul aware cell activation, location and load based schemes with different user densities and dynamic traffic with $R_{max} = 512$ kbps is as shown in Fig. 13. As we can observe from the figure, the achievable user throughput significantly depends on the cell activation scheme used. For the backhaul aware scheme, we can also observe that there are evident tradeoffs in terms of throughput, depending on the value of δ_{off} selected by the MeNB. But, since this parameter is dependent on traffic characteristics, it also enables operators to have better control over the user experience. From the mean throughput values normalized to that of the loc. based scheme, shown in Fig. 13b, we can observe that, for low user density, even $\delta_{off} = 0$ enables significant ES using the backhaul aware mechanism, with less than 10% tradeoff in terms of user throughput. Using the backhaul aware mechanism, network operators can also configure the MeNBs to improve or deprioritize ES, depending on the importance of the traffic flowing towards the UE. This is currently not possible with traditional cell activations based on small cell proximity, as well as a pure load based offloading criteria.

From the evaluations done in this section, we can observe that ES gains can be obtained by considering a backhaul aware traffic offloading and cell activation mechanism, compared to conventional small cell proximity-based or purely traffic load based offloading. With the advent of dual connectivity technology for next generation heterogeneous networks, control plane MeNB nodes can optimize overall network power consumption, by controlling the traffic flow within the network, taking into account both radio access as well as backhaul link power consumption impacts. We can also observe that the considered backhaul aware mechanism performs well under mobility conditions, and with indoor or outdoor deployment of small cells. Power consumption

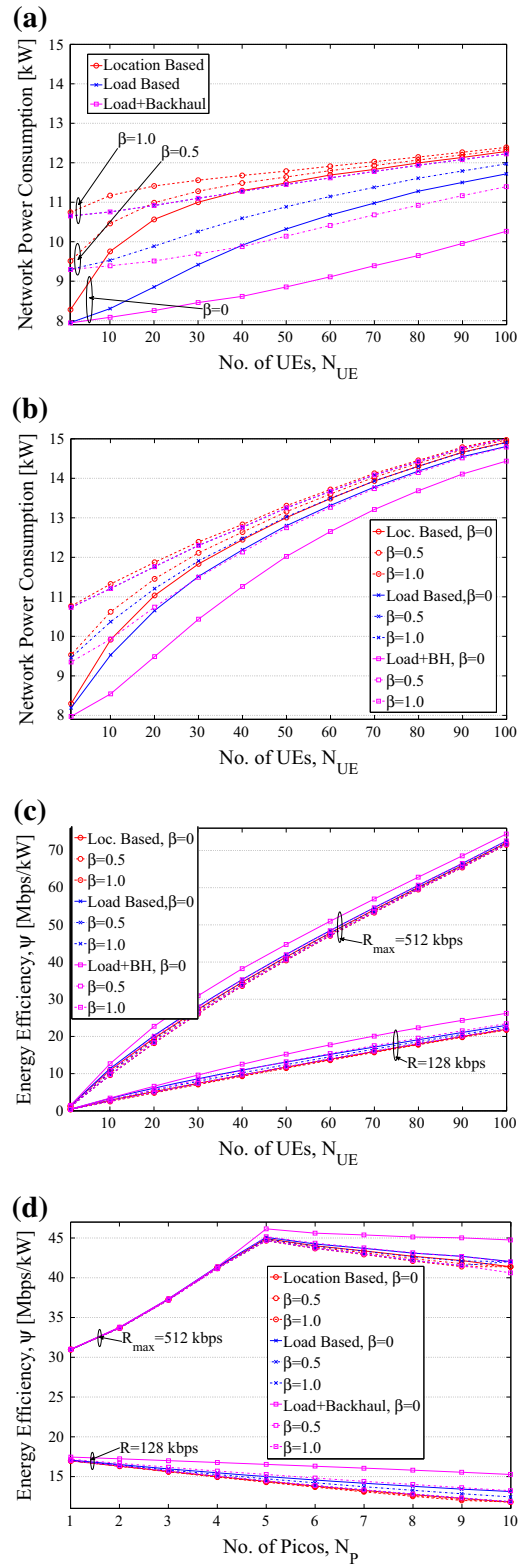


Fig. 11 Network energy consumption and energy efficiency with symmetric backhaul, for indoor users. **a** Static traffic, $R = 128$ kbps. **b** Dynamic traffic, $R_{max} = 512$ kbps. **c** Energy efficiency with varying N_{UE} . **d** Energy efficiency with varying N_P

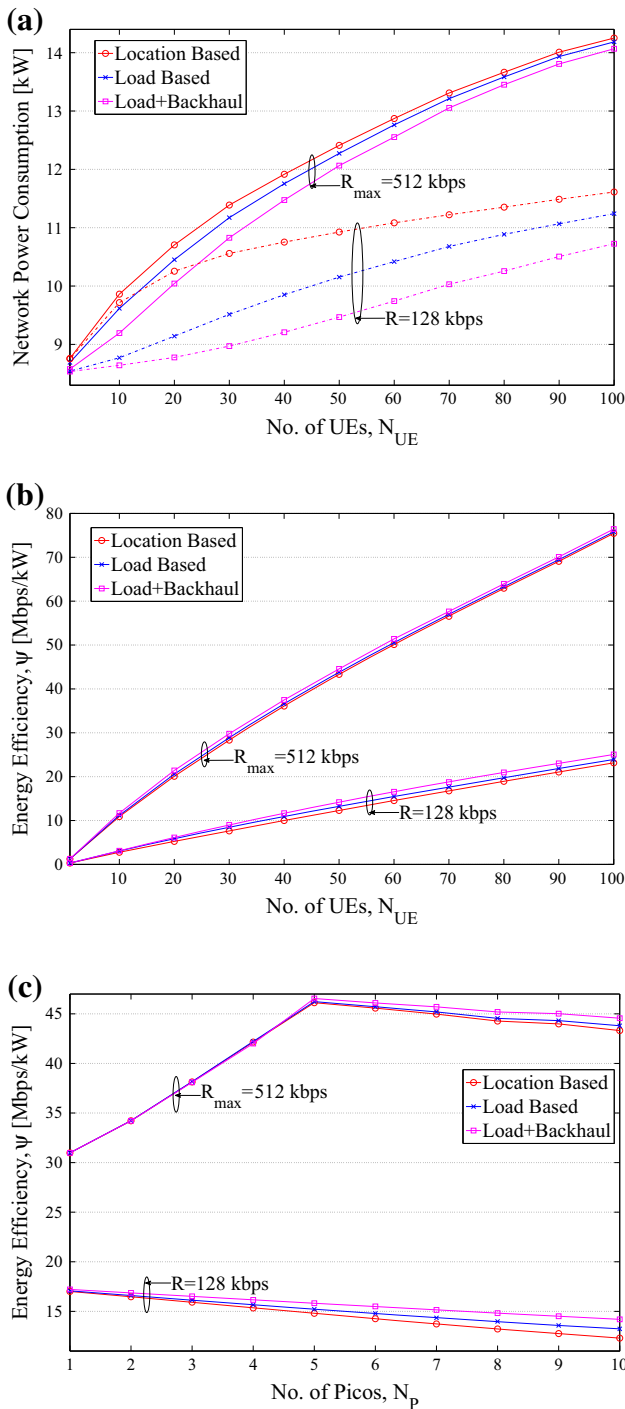


Fig. 12 Network energy consumption and energy efficiency with fiber access backhaul, for indoor users. **a** Power consumption, **b** energy efficiency with varying N_{UE} , **c** energy efficiency with varying N_P

reductions of up to 2.5 kW was observed for the SB case, under low traffic and user densities. Such gains could translate to significant energy savings (approximately 60 kWh per day), depending on the amount of time during which these optimizations can be applied. Similar gains were observed

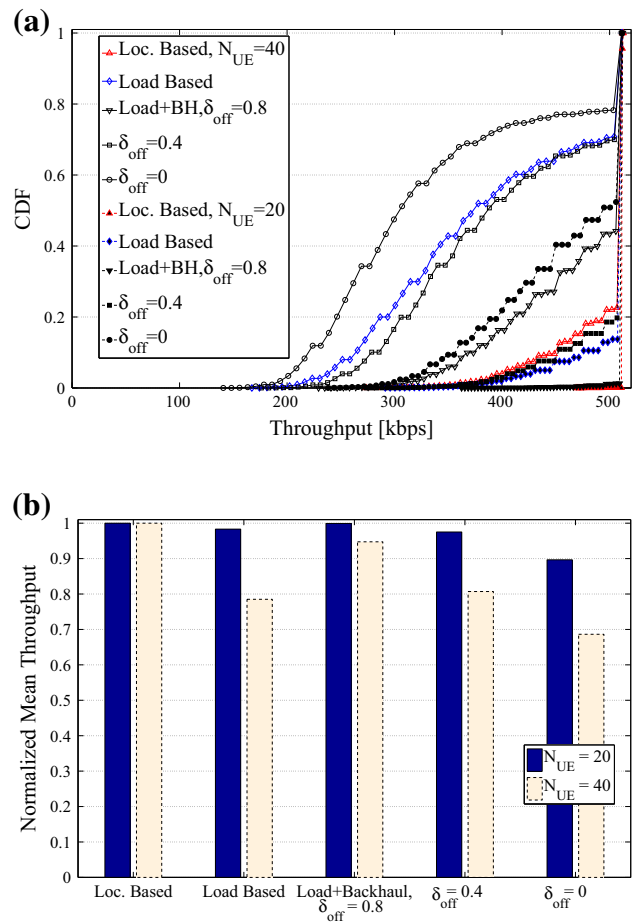


Fig. 13 Throughput distribution and normalized mean throughput values, $N_P = 5$. **a** Throughput Distribution, **b** normalized mean throughput

even with UE mobility and high switch of delay of $T_d = 5$ s, which could imply that the gains can be obtained for large periods of time during the off-peak hours, translating into significant ES gains and OPEX reductions for the network operator.

5 Conclusion

Due to perceived gains of dual connectivity technology in terms of throughput and mobility performance, the viability of the technology as a candidate for 5G evolution of radio access networks is evident. In this work, we have considered the power consumption models of different backhaul technologies, and evaluated an energy efficient and backhaul aware small cell activation mechanism with the use of dual connectivity. Based on the network power consumption and energy efficiency results, it can be concluded that the considered mechanism provides significant power savings for the network operator, with minimal implementation overhead,

enabling easy deployment of the energy efficient scheme. The implementation of the mechanism is evaluated based on the latest features available in an LTE-A heterogeneous networks. Heterogeneous network mobility scenarios, as well as indoor and outdoor deployment of small cells were evaluated to study the effectiveness of the mechanism under different conditions. Based on the evaluations done, the mechanism could be considered as an ideal candidate for enabling green radio access networks for next generation wireless systems. Future work on this topic could cover energy efficient small cell proximity estimation techniques, as well as the possible impacts on UE power consumption, due to additional measurements and signaling, in green wireless network deployments. The impact on QoS due to various backhaul types and related impacts on dual connectivity would also be an interesting area for further work.

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