A Survey of Energy Efficiency Optimization in Heterogeneous Cellular Networks

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Abstract

The research on optimization of cellular network's energy efficiency (EE) towards environmental and economic sustainability has attracted increasing attention recently. In this survey, we discuss the opportunities, trends and challenges of this challenging topic. Two major contributions are presented namely 1) survey of proposed energy efficiency metrics; 2) survey of proposed energy efficient solutions. We provide a broad overview of the state of-the-art energy efficient methods covering base station (BS) hardware design, network planning and deployment, and network management and operation stages. In order to further understand how EE is assessed and improved through the heterogeneous network (HetNet), BS's energy-awareness and several typical HetNet deployment scenarios such as macrocell-microcell and macrocell-picocell are presented. The analysis of different HetNet deployment scenarios gives insights towards a successful deployment of energy efficient cellular networks.

Keywords: Energy efficiency, HetNet, sleep mode, load adaptive

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1. Introduction

The rapid and tremendous growth of information and communication technology (ICT) sector world-wide has a major contribution to the total global energy consumption. According to [1], the ICT sector alone is responsible for up to 10% of the world energy consumption in 2010. Within this sector, about 0.5% of the world energy is consumed by mobile radio networks alone [1]. With increasing demand for broadband services, the network is naturally becoming denser and therefore any increase in energy prices will post a significant cost challenge to the network operator. Therefore, it is important to assess the network energy efficiency (EE) from the operator's point of view [2]–[4].

Energy awareness in telecommunication networks is the perception and identification of all energy resources and characteristics gathered from all network elements (NE) in order to proceed to certain power adjustments and maximize networks' EE and lifetime. It is a collective term which can be used to specify how much energy a NE uses, what the NE actually uses the energy for, where the energy comes from, the effects of using it on the depletion of resources, economic and environmental aspects, and what a NE can do to minimize its energy consumption and its undesirable effects. The considerations on EE have recently gained attention not only on reducing energy consumption, but also due to environmental aspects such as lowering CO_2. There are primarily two ways to improve EE in a mobile network namely 1) by reducing the power consumption of the base station (BS) either by using more power efficient hardware or by using more advanced software to adapt power consumption to the traffic situation as well as to balance between energy consumption and performance [5]. 2) by applying intelligent network deployment strategies such as using a higher density of small base stations (BSs). The usage of small BSs results in lower power consumption as these nodes are located closer to mobile users [6]. Hence, network deployments based on smaller cells such as micro, pico or even femtocells are perceived to be a viable way to reduce the total power consumption of a cellular network. However, as indicated by some research works, the design of such heterogeneous network (HetNet) needs to be carried out with more caution as spreading a high density of small cells will overburden and decrease the EE of the central BS. In addition, the embodied energy consumed by all processes associated with the production of equipment may actually dominate and result in an increase in total energy consumption [7]. As such, this paper presents an extensive review on the state of the art of current green cellular networks and more particularly to the energy-awareness issues in HetNet.

A classification of the state-of-the-art approaches towards green cellular network solutions is shown in **Fig. 1**. As shown, we focus on four important aspects: 1) identifying green metrics, 2) bringing technical changes in BSs hardware design, 3) network planning and 4) network operation. In Section 2, we review the proposed energy efficiency metrics. Section 3 addresses the EE assessment and improvement. In this section, we also describe the EE improvement potentials in all the stages of network lifecycle including hardware design, network planning and deployment, and network management and operation. Based on some typical HetNet deployment scenarios, we present reviews on energy-awareness in heterogeneous cellular network based on these classifications in Section 4. Finally, Section 5 provides some concluding remarks.

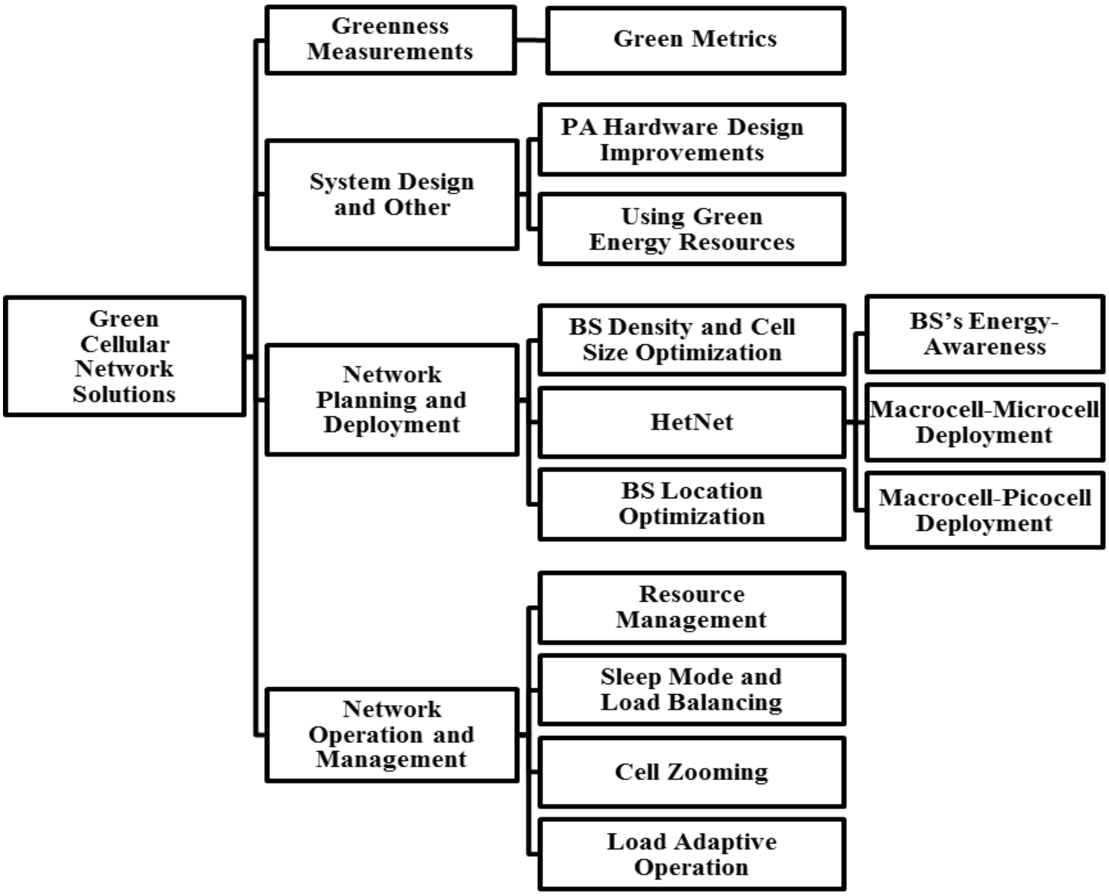

Fig. 1. Classification of Approaches towards Green Cellular Network Solutions

2. Related Work to green metrics

How do we measure and define the degree of "greenness" in a telecommunication network is the first research question. Although carbon footprint or CO_2 emissions is naturally considered a measure of "greenness", the share of carbon emissions for telecommunication networks is low (less than 1%). For the telecommunication networks, characteristics of "green" wireless technology should also include economic benefits (lower energy costs) and practical usage. Therefore, the energy saving seems to be a more appropriate choice for measuring "greenness". Thus, the notion of "greenness" in telecommunication systems can be more meaningful with a comprehensive evaluation that includes both energy savings and network performance of a practical system. Both energy savings and network performance subsequently form the basis of EE metrics. These metrics enable network designers to directly compare and assess the power consumption and the EE of various components in the network as well as the overall power consumption of the network. In addition, these metrics also help researchers to set long term goals on improving the EE [8]. However, there is a need to define appropriate EE metrics that capture the power budget of the whole network. Depending on the purpose of the system, EE can be defined in different perspectives such as a ratio of effective output energy to total input energy. EE metrics are classified into two categories: absolute metrics, which indicate the actual energy consumed, and relative metrics which show how EE is improved. Several metrics are used in the existing literatures for measuring the efficiency of a communication link. The most commonly used metric is bit per joule E_e, which is defined as the ratio of total network data rate to the total network power consumption, where the unit is bits/Joule [9]

$$E_e = \frac{R}{Pc} \tag{1}$$

where R denotes the average date rate provided by the BS with consumed power Pc. E_e can also be represented in bit/s/watt. Although this metric is simple and intuitive, it does not capture network specific aspects such as coverage and user fairness. Also higher layer aspects such as quality of service (QoS) are neglected. Hence, the metric of (1) should be complemented by other metrics [10]. To account for the data rate as well the communication distance, a modified metric of bit meter per joule can be used. Essentially this metric defines how efficient a bit of data can be transported over a distance in terms of per unit of energy consumed. For a cellular coverage, this metric is modified by [11] to bits per joule per unit of coverage area. Mahadevan et al. [12] introduce the energy proportionality index (EPI), that measures the dynamic nature of the equipment's energy consumptionand which can be divided into two types of energy consumption namely static and dynamic. Static energy consumption is the energy required for maintaining equipment, independent from processing traffic. Dynamic energy consumption is the energy required for processing traffic [12]. The standardized energy metrics however are usually the variants of the following two basic definitions namely the Energy Consumption Ratio (ECR) and the Telecommunications Energy Efficiency Ratio (TEER) [13]–[15]. The ECR is defined as the ratio of the peak power (in Watts) to the peak data throughput as follows:

$$ECR = \frac{E}{M} = \frac{PT}{M} = \frac{P}{R} \tag{2}$$

where E is the energy required to deliver M bits over time T, and $R = M/T$ is the data rate in bits/s. This energy metric indicates the amount of energy consumed in Joules for transporting one bit of information. The ECR metric is evaluated either for the whole radio access network (RAN) or for one cell or cell sector assuming a given RF average transmission power and a given average throughput in each cell [15]. A system with a lower ECR is more efficient in its energy use than a system with a higher ECR, as each bit requires less power for transmission [7]. The TEER metric is more general than the ECR metric and it can be written as TEER= useful work/power. The units of the TEER metric depends on the specific quantity considered the useful work. The standards usually do not specify explicitly the definitions of the power used in the ECR and TEER metrics, e.g., whether the power accounts for the RF power only [15]. Parker et al. [16] proposes an absolute EE metric (measured in dB) which is given by

$$dB\varepsilon = 10\log_{10}\left(\frac{power / Bit\ Rate}{K\,Te\,\ln 2}\right) \tag{3}$$

where K is the Boltzmann constant and Te is the absolute temperature of medium. The authors argue that this metric can be applied across the board as a metric for various types of ICT components [16]. Furthermore, the green radio (GR) project has defined the energy consumption gain (ECG) metric as a ratio of the ECR metrics of the two systems under consideration, for example, a baseline reference system and a system with a more energy efficient network architecture. Consequently, the ECG metric quantifies the energy consumption improvement relative to common reference system. It is worth mentioning that the ECG is often unfair and can be misleading when it is used to compare systems with different characteristics. To solve this problem, more complex metrics are used in the literature. In particular, amongst the network level metrics, we can distinguish those metrics that are presented as Energy Consumption Index (ECI) and those that are described as Energy Efficiency Index (EEI) [17]. ECI metrics are computed as the ratio of the consumed energy and a given Key Performance Indicator (KPI), whereas EEI metrics are defined the other way around.

$$\left.\begin{aligned} ECI &= \frac{E}{KPI} \\ EEI &= \frac{KPI}{E} \end{aligned}\right\} \Rightarrow ECI = EEI^{-1} \tag{4}$$

In some scenarios, the energy reduction gain (ERG) (expressed in percent) is preferable. The ERG metric is derived from the ECG metric as [15]

$$ERG = (1 - \frac{1}{ECG}) \times 100 \ \ [\%] \tag{5}$$

The classical optimization criterion for wireless network is the area spectral efficiency, which is measured in (bit/s/Hz/m^2) [18]. By referring to the area spectral efficiency, Richter et al. [19] propose the concept of the area power consumption for cellular networks. The metric for the area power consumption ρ is defined as

$$\rho = \frac{Pc}{A} \tag{6}$$

where A is the coverage area. The area power consumption figure cannot be the exclusive metric describing EE since it does not take into account the provided additional network capacity and higher system spectral efficiency. Nevertheless, this metric makes it possible to evaluate different network topologies with similar performance figures with regards to EE [20]. In order to assess the EE of the network relative to its size, authors of [9] introduce the notion of Area EE (AEE) which is defined as the bit/Joule/unit area supported by a cell. AEE for a certain station can be expressed as

$$AEE = \frac{E_e}{A} \tag{7}$$

where E_e and A denote the EE in bit /Joule and the area covered by a certain station with the unit of km^2 respectively [9]. In order to quantify the EE improvement, a metric called EE improvement gain (EE_{gain}) is used to find the EE improvement of a network with adaptive power consumption over network with static power consumption. **Table 1** summarizes the typical metrics used to measure EE with a brief description on their cons and pros. However so far, the conventional EE metrics only capture a small fraction of the overall power budget of the network, and may therefore lead to incomplete and potentially misleading conclusions.

Table 1. EE Metrics and Abbreviations

Metric	Definition	Unit	Pros	Cons
E_e	The ratio of total network data rate over the energy consuption	bit/s/watt	It is proportional with the power consumption and data rate	It is not consider the coverage area
EPI	It measures the dynamic nature of the equipment's energy consumptionand	Percent	It quantifies the proportionality between consumed energy and traffic load on a network	It is not relevant for coverage limited network
ECR	It is defined as the ratio of the peak transmission power to the peak data throughput	Joule/bit	It enables optimization at different operating points	Complicated calculation
$dB\varepsilon$	Absolute metric that can be applied across the board for various types of ICT components	dB	It provides universal comparability irrespective to specific technology	It is not relevant for coverage limited network
ECG	The ratio of the ECR metrics of two different systems consideration,	Percent	Simple calculation	Useful only to compare elements with same characteristics
ERG	It is derived from the ECG metric to illustrate energy saving gains	Percent	Useful to compare networks with different sizes	It is not relevant for coverage limited network
APC	It is used to assess power consumption of the network relative to its size	Watt/km^2	It allows to compare networks of different cell sizes	It is not relevant for capacity limited network
AEE	It is defined as the overall data rate per total consumed power per unit area	bit /Joule/ km^2	It reflects coverage area aspects;	Useful only to compare networks with same coverage area
EE_{gain}	It evaluates the EE improvement gain in network with different scenarios	Percent	Useful to compare network with different scenarios	It is not relevant for coverage limited network

Further details about some energy metrics proposed by various standards bodies and then adopted worldwide by equipment manufacturers and network operators can be found in [21]. However, EE is not the only figure of merit used for designing wireless networks. Spectral efficiency (SE), deployment cost, network coverage, transmission rate and delay are also important. Details analysis on the fundamental tradeoffs of these metrics can be found in [22].

3. EE Assessment and Improvement Stages

There is a great interest from academia and industry to improve the EE in all the stages of network lifecycle including hardware design, network planning and deployment, and network management and operation. Large scale research projects on green communications have sprung up worldwide, notably NeTwork TecHnologies (EARTH) [23], Green Radio [24] and GreenTouch [25]. The following sections discuss the EE assessment and improvement in all these stages in more details.

3.1 Hardware Design

The EE of a typical BS can be improved by minimizing its power consumption. Power consumption reduction in BS can be achieved by adopting more energy efficient power amplifiers (PA) [26], [27] and [28]. Analyses show that the power consumption of BSs of GSM 900 is greater than the GSM 1800 and UMTS access technologies while the UMTS BS has the lowest power consumption. This is a direct result of hardware improvements built into the newer GSM 1800 and UMTS BSs [29]. In order to improve hardware design of a BS for power consumption, the EE of PA has been investigated in many literatures [30] [31] and [32]. A PA dominates the power consumption of a BS and its EE depends on the frequency band, modulation and operating environment. Some works such as [33] and [34] focus on the hardware involved in the activation/deactivation mechanisms, and propose algorithms with the ability of putting small cells in a low-power sleep mode when traffic load is low.

The EE of a PA is calculated based on the ratio between the AC power input and the generated RF output power. Depending on the system used (e.g., UMTS, GSM, CDMA) and the equipment's condition, PA efficiency can be between 5 to 20 percent [35]. However, higher efficiency PAs have been reported in [35] and [36] with efficiency reaching over 50 percent. Additional efficiency can be achieved by shifting to switch-mode PAs rather than traditional RF amplifiers. Switch-mode PAs generate very little power as heat, resulting in a highly efficient power supply. The total component efficiency of such devices can reach around 70 percent [37]. The drawback of the modern schemes such as WCDMA/HSPA and LTE is that, they require highly linear PAs that needs to be trade off with low power efficiency in order to attain the quality of transmitted radio signals [34]. However, the PA efficiency of LTE BS is better than GSM and UMTS [38]. The overall component-efficiency of these energy efficient devices is expected to be around 70% [35]. One more significant setback in increasing power efficiency with PAs is that they perform better at maximum output power in order to maintain the required signal quality. Using different linearization techniques and various design techniques with different kind of DSP methods that improve the PA performance have also been suggested in [39] and [31]. However, during the low traffic load conditions, a lot of energy is routinely wasted. Therefore, design of flexible PA architectures that would allow a better adaptation of the amplifier to the required output power needs to be addressed [35].

3.2 Network Planning

Network planning is a primary task that locates and configures transmission facilities at a minimal cost. It plays a key role to reduce the total power consumption of cellular networks. The main object of network planning is to guarantee coverage and traffic capacity while minimizing the number of BSs. Since the network is still required to provide a high QoS, EE is now considered as another key metric of the network performance [26], [40]. Another important objective of network planning is to study the relationships between deployment cost, service guarantee, and the EE under different deployment strategies and cell sizes [22] [41]. Network planning has to take into account the spatial-temporal load profile throughout the network. An efficient network design must not only take into account the energy management, but also jointly considers both deployment and operational costs [42]. A green planning for energy-efficient wireless network design is presented in [43] [44] [45]. Optimizations of the BS size, location and density have been investigated in [13], [40], [41], [46]–[52], where the tradeoff between EE and deployment cost is also discussed. It is shown that an optimal number of BSs or cell size with minimal power consumption exists. By exploring energy efficient network planning, the authors of [53] show that cooperating transmission can effectively minimize the number of deployed BSs while maintaining a low transmission power. EE enhancements of cellular networks can be also achieved during the network planning and operation stages [54], [55]. Some research works mainly focus on the practical deployment algorithms or techniques [56], [57]. [54] looks into the improvement of EE of cellular networks while keeping QoS at a satisfactory level. The authors argue that the EE of cellular networks can be improved by reducing the number of active BSs required per area through multicell cooperation. In [58] and [59], an energy-efficient transmission scheme based on BSs' cooperation that explores the coordinated multi-point (CoMP) transmission is proposed for improving the EE of the downlink.

An obvious approach of making the cellular networks more energy efficient is by decreasing the propagation distance between nodes, which then results in lower transmission power. Network topology optimization seems to be a good alternative to increase the system performance [60]. Therefore, HetNet deployments based on smaller cells such as micro, pico and femto BSs are very promising in this context [61]-[63] and is further discussed in Section 4. **Table 2** summarizes some of the issues, approaches and challenges related to EE in cellular networks.

Table 2. Summary of EE issues, approaches and challenges

Issues	Approaches and Trends	Challenges
Network capital expenditure	BS Density, cell size and location optimization, transmission schemes, scheduling algorithms.	Improve the network DE-EE trade-off relation
Network operational expenditure	Sleep mode, self-organizing techniques, Cell zooming techniques	Tracing spatial and temporal traffic load fluctuation, Energy scaling traffic load
Small Cell interference, energy scaling traffic load	Sleep mode, power control techniques	Macro-small cells coordination, Interference management
Coverage Holes	Power control techniques	Interference avoidance
Backhauling power Consumption	Backhauling strategies	Providing sufficient backhauling to offload traffic

3.3 Network Operation

The BSs of future cellular networks are expected to be powered by both on-grid energy and green energy. Green energy such as sustainable solar and wind energy are promising options to save on-grid energy consumed by BSs and reduce the CO_2 footprint. Optimal utilization of green energy can achieve a significant power savings and hence improving network EE [64]. Reducing power consumption has also economic impact on revenue, e.g., the wireless network operators are estimated to spend more than 10 billion dollars for electricity, a significant portion of the system's OPEX [65] [66]. However, modifying the network operation according to the varying traffic load represents a good opportunity to avoid unnecessary energy waste. One of the earliest insights into load adaptive operation techniques which dynamically adjust the network coverage size is presented in [67]. The authors proposed cell zooming for green networks in order to maintain coverage and reduce the number of active cells by changing the coverage pattern of cells based on traffic load. The cell zooming technique can adaptively adjust the cell size according to traffic load and thus has a potential to reduce the power consumption. Reference [68] demonstrates that a significant network power savings can be achieved by traffic management and workload consolidation techniques. It has been depicted how dynamic operation of cellular BSs, in which redundant low-traffic BSs are switched off, can provide significant energy savings advantages [65], [66], [69], [70]–[72]. Dynamic operational techniques can be divided into short-term load and long-term load adaptive techniques. Short term load adaptive techniques account for wireless channel fluctuation over the shorter duration while for long-term load adaptive techniques, it is sufficient to consider the average channel behavior by taking into average path loss. The main issue of power consumption in a radio BS is the energy scaling traffic load problem [3]. In addition, several other mechanisms such as sleep mode mechanisms are discussed in many literatures such as [13], [33], [47], [55], [65] [67], [73]-[76]. Energy savings can be achieved by switching off the BSs with low load; this can be performed after reassigning the users to various BSs in order to decide if a certain BS can be switched off or not [77]. When some cells are in sleep mode, the radio coverage can be guaranteed by the remaining active cells by filling in the gaps created. Cell zooming and sleep mode can save up over 80% of the overall energy consumption in cellular networks [76]. Moreover, load balancing mechanism is an important technique often used to offload the exclusive load traffic from high load cells to low load cells. The aim of load balancing is to distribute traffic loads among BS's to achieve better performance, whereas the goal in BS energy saving is to concentrate traffic to as few BS's as possible [78]. These techniques adjust the BS power consumption based on daily traffic load patterns that vary significantly between peak and quiet hours. For example, while 70% to 85% of total traffic is served by 19% to 25% of cells in peak hours, only 10% of cells contribute to the same traffic in the quiet hours. Such concepts of self-organizing networks (SON) [8], [11], [49], [79] have been introduced in 3GPP standard [80] to add network management and intelligence features so that the network is able to optimize, reconfigure and heal itself in order to reduce costs and improve network performance and flexibility [80].

Other techniques include joint wired/wireless green networking which is also attracting significant research attention [81]. As a case study in [82], the authors investigate single-carrier and multicarrier communication systems by applying both margin-adaptive and rate-adaptive pilot-assisted transmission to quantify the relevant energy savings opportunities. A holistic framework is developed in order to quantify the EE for the operation of cellular network [34], [83]. In [84], authors estimate the overall power consumption of a telecommunication network, given the power requirements of network equipment and the traffic from the users. They claim that future networks with enabled sleep modes and load adaptive operation will save a consistent amount of energy. Based on user context and network service, the work in [85] applies energy efficient decision algorithms on multi radio access technology networks in order to dynamically adapt the network capacity to the actual traffic load demands by reconfiguring distinct network elements. Moreover, the maximal EE can be achieved via resource allocation algorithms by adapting both overall transmit power and its allocation according to the channel states and the circuit energy consumption [86]. Bandwidth

Adaptation (BW), Capacity Adaptation (CAP), and Micro Discontinuous Transmission (micro DTX) are other energy saving approaches which are based on load adaptive techniques in LTE networks [87]. BW adaptation concept is based on adjusting the BW to the needed traffic load. CAP adaptation is accomplished by limiting the number of scheduled LTE resource blocks. At rather high resource utilization micro DTX can more flexibly utilize the void resources, where the fixed steps of BW and CAP adaptation limit the energy saving potential [87]. A discussion on the energy-aware management strategies for enabling green cellular network operations has been introduced in [88]. Summary of some methods related to EE assessment and improvement at all network levels is shown in **Table 3**.

Table 3. Some methods related to EE assessment and improvement stages

Relevant to	Topic	Reference
Hardware design	PA improvements	[26]–[39]
Network planning and deployment	BSs cell size optimization	[13], [46], [47], [89], [90]
	BSs density optimization	[19], [52],[70], [91]
	BSs location optimization	[48], [57], [92], [93]
Network operation and management	Sleep modes	[33], [65], [70]–[72], [74], [75], [94]
	load balancing	[62], [94], [78]
	cell zooming	[26], [54], [67], [77]
	load adaptive operation	[66]-[72], [76]–[77]
	Self organization network	[8], [11], [49], [89], [95]-[96]

4. Reviews on energy-awareness in heterogeneous cellular network

The HetNet concept was proposed in LTE-Advanced framework to increase the spectral efficiency. In this approach, macro BSs are used to provide blanket coverage while small, low power BSs are introduced to eliminate the coverage holes as well as to increase the system capacity in hotspots. Furthermore, HetNet provides an opportunity for network providers to optimize overall costs, revenues and customer satisfaction [97]. HetNet is also found to be very energy efficient even though the target data rate requirement is high. This is due to the introduction of small cells that consume much less power [4]. A typical HetNet deployment is shown in **Fig. 2.** The macro BS is used to provide blanket coverage while small BSs such as

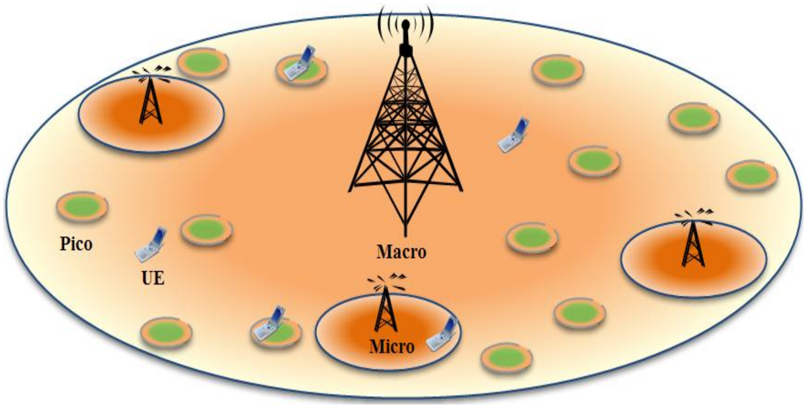

Fig. 2. HetNet Deployments [94]

micro, pico or femtocells provide high data-rate service to smaller areas with a high density of traffic. Micro/picocells cover the range of a few hundred meters, while femtocells are mostly used for indoor or home area [94]. In standards bodies such as the Institute of Electrical and Electronics Engineers (IEEE) and 3GPP, the concept of HetNet covers how different-sized cells can work together, how hand-off among them is achieved, how interference between them can be minimized, how spectrum and energy efficiencies can be optimized and so on [98]. However, from the EE perspective there are some issues and challenges in small cells and heterogeneous deployments such as:

- The capital expenditure increases with increasing number of sites. The sites come with infrastructure costs, backhaul transmission equipment site installation, and radio network controller equipment. Also for high-density deployments, the idle power of the BSs and backhaul is a significant factor [22] [27] [99].
- The deployment and maintenance of additional small cells cause heavy operational expenses (OPEXs) [6]. For example, deployment of femtocells may lead to a situation where numerous femtocells are turned on and spending energy even when traffic is nonexistent [27].
- One of the main challenges of HetNet is the severe inter-tier interference when different tiers of HetNet are deployed with the same frequency [69] [100].
- Small BSs such as femto BSs may create coverage holes or use spectrum that would otherwise be available for the macro layer [101]. Also the density of these BSs is limited to backhaul availability and wireless nodes will spend part of the transmission power on backhaul communication [102].

Improving EE by optimizing the layouts of microcells overlaying conventional macrocells have been widely investigated in [4], [6], [19], [27], [34], [40], [50], [73]-[75], [92], [103]-[111]. Due to the potential high node density in future HetNet, there is a demand for solutions that can reduce radio network planning and potentially allow both outdoor and indoor nodes to be deployed autonomously or with very little guidance. Deploying the small cells without location optimization can degrade network wide spectral efficiency, while automated deployment optimization techniques can provide a low-complexity solution to intelligent HetNet rollout. Moreover, the dense and random deployment of small cells and their uncoordinated operation raise important questions about the implication of EE in such multitier networks [65], [112]-[114]. The following subsections present a review on energy-awareness in HetNet based on different deployment scenarios.

4.1 BS's Energy-Awareness

According to [24], about 57% of power consumption of a typical cellular network is consumed by the BS. The explosive demand for high data rate of mobile users has caused BSs to be the dominant total energy consumer within the cellular networks. It has been shown that the energy consumption for an LTE network has to increase about 60 times compared to a 2G network to offer the same level of coverage [115]. Due to this, most studies on EE in mobile cellular radio networks focused on the BS side. The BSs' EE has become a major consideration when designing cellular network. Next generation BSs go even as far as using more efficient power amplifiers and natural resources for cooling [66]. There are many parameters affecting the power consumption and coverage area of the network such as frequency band, shadowing, path loss and the receiver sensitivity. An investigation on the impact of these factors on EE has been presented in [46]. Authors of [116] presented the tradeoffs between gains in cell throughput and reception technologies and the increased energy consumption that they induced in cellular BSs. The EE in term of ECR of MIMO schemes applicable for 3GPP LTE is analyzed on different antenna configuration in [89] and [117]. Adaptive antenna techniques have a significant impact on the efficient use of the radiated power and they use lower power as compared to sectorized antenna by directing the beam toward the known positions of users [117]. The adoption of these techniques in future HetNet is expected to have significant improvements in the EE of network. The work in [83] elaborated on radio node level issues addressed by EARTH projects to identify concepts that will further improve the EE of wireless networks. Auer et al. [76] proposed an evaluation framework with some enhancement which applied to quantify the EE of the downlink of a 3GPP LTE. Their results revealed that in the current network design and operation, the power consumption is mostly independent of the traffic load. This clearly indicates a vast potential for energy savings by improving the EE of BSs at low load. Also, it is possible to establish more energy efficient, high data rate services by deploying more numerous but lower powered cells in a network [118]. Brevis et al. investigated techniques to optimize the number of BSs and their locations in order to minimize energy consumption with non-uniform user distributions across the coverage [48]. Study in [7] disagreed with other predictors that indicated a reduction in BS power and number would lead to significant energy savings and they justified that by the embodied energy that can contribute significantly towards the total energy consumption of the BS. Some analytical tools for optimizing the EE of a BS through power control based on elastic traffic in the downlink are shown in [90] and [119]. The energy saving potential of adaptive networks with respect to a reference network with constant power usage based on network traffic characteristics is studied in [120]. A framework in [121] proposed a BS energy saving that encompasses both dynamic BS operation and user association to find tradeoff between flow-level performance and energy consumption. The proposed energy-efficient user association and BS operation algorithms can dramatically reduce the total energy consumption by up to 70-80%, depending on the arrival rate of traffic and its spatial distribution as well as the density of BS deployment

4.2 Macrocell-Microcell Deployment

For a given average area spectral efficiency and uniform user distribution, a heterogeneous deployments using micro and macro BSs can achieve a moderate power saving in the network without any optimization on the specific location of the micro-cells [19]. In [6], a way to optimize the cell structure and breakdown of the network was given by the authors, which took into account the average micro sites per macro cell and the macro cell size itself, by altering the number of micro and macro sites to achieve similar system performance under full load conditions [6]. However, it has been proved that the homogeneous deployment using micro BSs only is not beneficial in terms of EE [40]. The work in [20] developed a power models for macro and micro BSs focusing on component level. The significant energy saving and traffic capacity gain could be obtained by deploying the micro BSs by carefully choosing other network design parameters. Dufkov’a et al. [122] quantify the energy consumptions of two alternative strategies to increase capacity in future LTE network deployments with deployment of redundant micro BSs by telecom operators at locations where traffic load was high and deployment of femto BSs by home users focusing on downlink traffic. They illustrated that these two strategies had similar energy consumption which was different from previous results where it stated that deployment of femto BSs was considerably more energy efficient [122]. In [103], the power model adapted to traffic load variation in micro BSs which were required for better EE in higher user densities. The study investigated the HetNet EE for uniformly distributed traffic and showed that reductions in energy consumption could be achieved by turning transceivers on and off, matching the variations in traffic demand [103].

In [123], the authors developed a capacity extension policy for a two-tier HetNet and determined which type of BSs should be added or switched off to achieve the optimal BS density. They determined the optimal macro/micro BS density that minimized the power consumption subject to a predefined QoS requirement given in terms of downlink data rate. Overall, in case of limited capacity demand, heterogeneous deployments with optimal numbers of additional micro BSs are better suited than homogeneous micro cell deployments [4], [10]. The combined use of micro cells and sleep mode deployment under medium to low traffic load conditions, improved the overall network EE by ERG up to 70-89% [74]. Tombaz et al. proposed strategies for different cell deployment and backhauling to reduce overall system cost by customizing the design of micro cells to suit traffic needs in order to ensure overall power saving from larger macro cells that use high powered BSs [99]. The EE of macro-micro deployments were compared with the user-deployed femto BSs, and it is stated that these strategies have similar power consumption for a given capacity enhancement requirement. However, a macro-micro deployment was proposed as a better solution for the operators due to their high convenience in terms of management and control [95], [96].

4.3 Macrocell-Picocell Deployment

Picocells can be considered a good network densification option in terms of achieving a higher throughput at reasonable energy cost [124]. The deployment of multiple pico BSs associating with the macro BSs at the edge is able to provide more diversity gains. For example, in [93], macros BSs are modeled with a hexagonal grid, with exactly 6 pico BSs per macrocell in order to improve the diversity and EE. Claussen et al. have looked into the power savings of pico cells for residential end-user connectivity to macro cells that were commonly used to provide coverage to a region [35]. Saker et al. studied the EE and data traffic capacity of using pico cells in the context of LTE-A networks assuming that the energy consumption of such pico cells is not too high. Results indicated that networks where macro and pico BSs co-exist are more energy efficient as the demand for higher data rates grows [124].

Wang et al. demonstrated through system-level simulation of two-tier networks with macro and pico cells that both cell EE and area EE can be improved by deploying low power pico stations combined with reduction of macro transmission power [9]. The work [114] confirms that there exists an optimal pico-macro density ratio that maximizes the overall EE of a two tier network. Meanwhile, a new power consumption model for a mobile radio network considering backhaul for mobile radio network is proposed in [104] in three different HetNet deployments: macro BSs, macro and pico BSs, macro BSs and WLAN access points. Liu et al. proposed an energy saving strategy for LTE HetNet network with overlapping pico BSs, which uses the remaining resources of neighboring picocells and macrocell to accept the users of picocell to be switched off. Simulations showed that the proposed approach has better performance in improving the EE of the system [111]. HetNet with macrocells and picocells deployed in separate carrier frequencies are considered in [102]. The EE of their proposed solutions is evaluated by considering the energy spent by the. It has been observed that using intelligent schemes for pico cell discovery, significant UE power savings can be achieved with small loss in offloading – giving benefits both on system level and user experience.

Table 4 demonstrates some of the discussed methods that tried to improve the EE in different parts of the HetNet. The ultimate enhancement of EE in HetNet is likely to require an approach for small cells optimization. For instance, optimizing the inter site distance that achieve minimum area power consumption can further improve the EE of the whole networks. Besides, optimizing the number of small cells per macro BS as well as their size and location for different areas and environments may lead to more energy efficient network design.

Table 4. EE Improvement methods in different parts of the HetNet

Description	Hardware design	Planning	Operation
Macro	Efficient PA and natural resources	BSs density, cell size , location optimization	transmission technologies , power-down strategy, user association algorithm
Micro	-	Micro BSs density , cell size , location optimization	power-down strategy , energy-efficient user association algorithm
Pico	-	Pico BS density per macro and cell size optimization	power-down strategy
HetNet	-	Small BSs location, density and cell size optimization	power-down strategy , load balancing, cell zooming

5. Conclusion

This paper addresses the EE of cellular communication systems. We began our discussion with EE metrics or green metrics. Here, we presented a brief survey of existing efforts for the metrics' standardization and the challenges that place ahead. In particular, we discussed the potentials of reducing the power consumption of a typical BS by improving the BS hardware design such as the improvements in power amplifier technology that can be used to bring power savings in BSs. In addition, the EE from a network planning perspective is addressed in which we discuss how different types of network deployments based on smaller cells can be used to maximize the EE of a wireless network. We have also explored the EE improvements through the energy aware network planning by exploring the optimization on the BS size, location and density. It has been highlighted that cell size, location and density optimizations not only result in lower overall power consumption, but also better overall EE. The energy aware planning of the network can provide a low complexity solution to green HetNet rollout.

Regarding EE from a network operation perspective, the majority of the works investigate the most efficient ways to turn off cells/networks, while maintaining good quality of service. We put a special emphasis on sleep mode mechanism and load balancing techniques in order to bring attention to the benefits that can be attained by employing such techniques, and we highlighted new research avenues in making these techniques more energy efficient. Next, options and challenges for the dynamic operation in HetNet have been surveyed. The load adaptive operation can be identified as an effective therapeutic objective for reducing the network power consumption and hence improving the overall EE. Lastly, with the goal of understanding further the EE intricacies in HetNet, we have broadly divided the energy aware knowledge in HetNet into three scenarios: BS's energy-awareness, macrocell-microcell deployment and macrocell-picocell deployment. We looked into the current efforts on energy awareness with different deployments consist of macro, micro and picocells. By means of discussions, we highlighted different HetNet scenarios to provide essential understanding for successful deployment of green future HetNet.

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