Energy-Efficient Base-Stations Sleep-Mode Techniques in Green Cellular Networks: A Survey

Jingjin Wu, Yujing Zhang, Moshe Zukerman, *Fellow, IEEE*, and Edward Kai-Ning Yung, *Fellow, IEEE*

***Abstract*—Due to global climate change as well as economic concern of network operators, energy consumption of the infrastructure of cellular networks, or "Green Cellular Networking," has become a popular research topic. While energy saving can be achieved by adopting renewable energy resources or improving design of certain hardware (e.g., power amplifier) to make it more energy-efficient, the cost of purchasing, replacing, and installing new equipment (including manpower, transportation, disruption to normal operation, as well as associated energy and direct cost) is often prohibitive. By comparison, approaches that work on the operating protocols of the system do not require changes to current network architecture, making them far less costly and easier for testing and implementation. In this survey, we first present facts and figures that highlight the importance of green mobile networking and then review existing green cellular networking research with particular focus on techniques that incorporate the concept of the "sleep mode" in base stations. It takes advantage of changing traffic patterns on daily or weekly basis and selectively switches some lightly loaded base stations to low energy consumption modes. As base stations are responsible for the large amount of energy consumed in cellular networks, these approaches have the potential to save a significant amount of energy, as shown in various studies. However, it is noticed that certain simplifying assumptions made in the published papers introduce inaccuracies. This review will discuss these assumptions, particularly, an assumption that ignores the effect of traffic-load-dependent factors on energy consumption. We show here that considering this effect may lead to noticeably lower benefit than in models that ignore this effect. Finally, potential future research directions are discussed.**

***Index Terms*—Cellular network, base station, energy consumption, energy efficiency, green networking, sleep mode.**

I. INTRODUCTION

WITH THE increasing awareness of global warming and environmental consequences of Information and Communications Technology (ICT), researchers and practitioners have been seeking ways to reduce energy consumption [1], [2]. Cellular networks, as a significant component of ICT energy consumption, have drawn considerable attention of many researchers from both academia and industry [3]–[7]. Until recently, the design objectives for cellular networks, since their introduction in the late 1970s, have been maximum throughput, spectral efficiency and meeting Quality of Service (QoS) requirements rather than energy conservation. Another motive for the need to find ways to conserve energy in cellular networks is increasing energy bills for telecommunications service providers. Due to the introduction and popularization of smart phones and tablets, which provide services that involve exchange of large volume of data traffic and motivates new high-speed (and certainly more energy consuming) mobile network standards such as 4G LTE. As a result, expenses related to energy consumption now comprise a large proportion of operating cost for service providers [6].

It is now widely acknowledged that cellular communication networks will have greater economic and ecological impact in the coming years [4], [5]. This issue has been recognized as a matter for both the planet and the wallet. Seeing this, an innovative new research discipline called "green cellular networks," concentrating on environmental influences of cellular networks, has been formed and attracted many researchers. The term "green" is originally a nickname of dedicated efforts to reducing unnecessary green house gases (e.g., CO_2) emissions from industries. For mobile operators in particular, another motivation and objective of "green" approaches is to gain extra commercial benefits, mainly by reducing operating expense related to energy cost [5], [7].

There are various distinctive approaches to reduce energy consumptions in a mobile cellular network. Approaches in previous research can be broadly classified into the following five categories.

1) Improving energy efficiency of hardware components.
2) Turning off components selectively.
3) Optimizing energy efficiency of the radio transmission process.
4) Planning and deploying heterogeneous cells.
5) Adopting renewable energy resources.

Approaches of the first category aim to improve hardware components (such as power amplifier) with more energy-efficient design (e.g., [8]–[12]). The performance of most components used in current cellular network architecture is unsatisfactory from the energy efficiency perspective. Considering, for example, the power amplifier, the component consuming the largest amount of energy in a typical cellular base station (BS), more than 80% of the input energy is dissipated as heat. Generally, the useful output power is only around 5% to 20% of the input power [13]. Studies showed that the potentially optimized ratio of output power to input power for

Manuscript received June 5, 2014; revised November 6, 2014; accepted February 1, 2015. Date of publication February 12, 2015; date of current version May 19, 2015. This work was supported by City University of Hong Kong under Project 9380044.

J. Wu, M. Zukerman, and E. K.-N. Yung are with the Department of Electronic Engineering, City University of Hong Kong, Kowloon, Hong Kong (e-mail: jingjinwu3-c@my.cityu.edu.hk; m.zu@cityu.edu.hk; eeedyung@cityu.edu.hk).

Y. Zhang is with Facebook, Menlo Park, CA 94025 USA (e-mail: yujingz@fb.com).

Digital Object Identifier 10.1109/COMST.2015.2403395

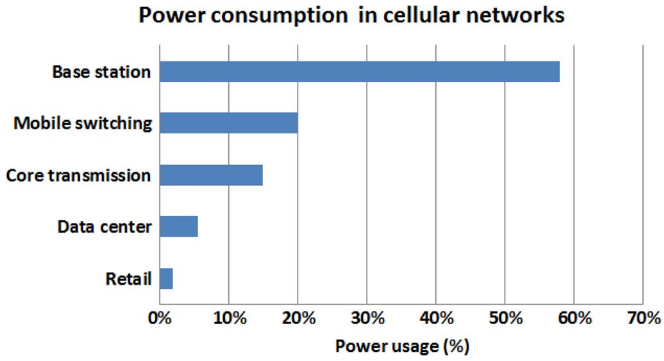


Fig. 1. Breakdown of energy consumption in cellular networks (Source: Vodafone [12]).

power amplifiers (*power efficiency*) could be as high as 70% [13]. Accordingly, substantial amount of energy savings can be achieved if more energy efficient components are adopted in the network. However, the implementation cost for these approaches is high. For example, a power amplifier module with 35% power efficiency for small cell WCDMA or LTE BSs (cover at most an area of a radius of 2 km) costs around $75 [14]. The cost will be even higher for larger coverage or higher power efficiency. Therefore, careful consideration in both operational and economical aspects by network operators is required before decisions on hardware replacement are made.

The second category covers approaches that selectively turn off some resources in the existing network architecture during non-peak traffic hours (e.g., [10], [15]–[19], [161]). Approaches in this category generally try to save energy by monitoring the traffic load in the network and then decide whether to turn off (or switch to *sleep mode*, also referred as *low-power mode* or *deep idle mode* in some literature), or turn on (or switch to *active mode*, *ready mode* or *awake mode*) certain elements of the network. Unnecessary energy consumptions, for example, air conditioning under-loaded BSs, can be avoided by adopting such sleep mode mechanisms. These approaches generally involve switching certain elements including but not limited to power amplifiers, signal processing unit, cooling equipment, the entire BS, or the whole network back and forth between the *sleep mode* and the *active mode* [20]. Most often, sleep mode techniques aim to save energy by selectively turning off BSs during "off-peak" hours. As shown in Fig. 1, BSs consume the highest proportion of energy in cellular networks. On the other hand, dense BSs deployments today lead to small coverage area and more random traffic patterns for individual BS, which make sleep mode operations more desirable. Given the constraint that some components (e.g., a minimum number of BSs) must always stay on to support the basic operation of the network, as well as the execution of the switch operation depends on the fluctuations in traffic profile, the reported energy saving is not as high as that of component-based approaches. Also, while it is good to save energy, BS sleeping might negatively impact Quality of Service (QoS) in the network because of decreasing capacity, unless specific remedial solutions are adopted concurrently [21], [22]. Nonetheless, because sleep mode techniques are based on current architecture, they have the advantage of being easier to test and implement as no replacement of hardware is required and the performance can be evaluated by computer simulation. A potential deficiency of existing studies using this approach is over-simplified models and assumptions, which will be discussed in detail later in this survey.

The third category works on the radio transmission process. Approaches belong to this category work on the physical or MAC layer. Advanced techniques including MIMO technique, cognitive radio transmission, cooperative relaying, channel coding and resource allocation for signaling have been studied to improve energy efficiency of telecommunication networks (e.g., [12], [23]–[33]). A variety of approaches have been proposed to efficiently utilize resources in time, frequency and spatial domains to achieve energy saving. Similar to approaches based on sleep mode, this family of approaches generally does not require upgrade of hardware components in the system. However, trade-offs between energy efficiency and other performance metrics of the network are probably inevitable. Also, measuring errors due to complicated uncertainty issues such as noise and interference have yet been well corrected. Based on information theory, four fundamental trade-offs related to energy efficiency on wireless networks have been acknowledged, namely deployment efficiency—energy efficiency, spectrum efficiency—energy efficiency, bandwidth—power and delay—power [34], [35].

The fourth category tackles the problem by deploying small cells, including micro, pico and femto cells, in the cellular network [36]. These smaller cells serve small areas with dense traffic with low power-consuming cellular BSs (e.g., [10], [32], [37]–[43]), which are affordable for user-deployment and usually support plug-and-play feature. In contrast to conventional homogeneous macro cell deployment, such *heterogeneous deployment* reduces energy consumption in the network by shortening the propagation distance between nodes in the network and utilizing higher frequency bands to support higher data rates. The major constraint of these approaches is the extra small cells bring additional radio interferences as compared to conventional homogeneous macro cell networks, which might negatively affect user experience. Meanwhile, if too many micro, pico or femto cells are deployed, the trend of saving may even be reversed because of extra embodied energy consumed by newly deployed cells as well as overhead introduced in transmission. Therefore, the number of extra smaller cells, as well as their locations, needs to be carefully planned in order to reduce total energy consumption. It has also been noticed that integrating heterogeneous network deployment with sleep mode schemes can potentially achieve significant gains in terms of energy saving [39], [40], [44].

The last category includes approaches that adopt renewable energy resources. Compared to current widely used energy resources such as hydrocarbon which produces greenhouse gases, renewable resources such as hydro, wind and solar power stand out for their sustainability and environmental friendliness [45], [46]. Telecom manufacturers have planned the supply of solar power operated cellular BSs in underdeveloped areas such as Bangladesh and Nigeria, where roads are in poor condition and unsafe, so delivering traditional energy resources for off-grid BSs (e.g., diesel) cannot be guaranteed [47], [48]. Energy harvesting techniques, namely exploiting available energy

TABLE I
COMPARISON OF GREEN CELLULAR NETWORK APPROACHES

Approach	**Example**	**Advantages**	**Limitations**
Improvement on hardware components	Improved power amplifier design; BS site reselection and relocation	Largest reported savings, direct and intuitive	Certain upper limits for improvements, high cost for hardware replacement
Sleep mode techniques	Selectively turns radio transceivers or BSs to sleep mode	Easier and less costly for testing and implementation	Trade-off between performance and saving, current modeling not accurate enough
Optimization in radio transmission process	Cognitive radio transmission, cooperative relaying, channel coding and resource allocation for signalling	Low cost, various applications	Trade-off between performance and saving, errors due to uncertainty issues
Network planning and deployment	Mixed macro, micro, pico and femto-cell deployments	Low cost to implement, user-oriented, high potential savings	Introduces new problems such as radio interference
Adoption of renewable energy resource	Adoption of renewable energy resources such as solar, wind, and water power in BSs	Long-term solution for off-grid BSs	High replacement cost and limited gain for existing on-grid BSs

from such renewable resources to complement existing electric-operated infrastructure, would probably be the long-term environmental solution for the mobile cellular network industry. Especially for those areas without mature network infrastructure, deploying energy harvesting networks would be ideal. For developed countries with completed infrastructure, however, the same question of embodied and replacement cost arises as the component-based approaches. While service migrates from the obsolete electric-operated BSs to the new energy harvesting BSs, it is technically challenging to preserve fault-tolerance and data security without any service interruption.

The advantages and limitations of each approach, are summarized in Table I.

Generally speaking, green cellular network is a relatively new area of research. Most of existing publications are based on ideal models. The fundamental aim, as its name implies, is to make cellular networks "greener" by reducing total power consumption through various approaches described above. For more survey information on the entire field of green technologies in wireless communication networks, the reader is referred to [5], [24], [29], [32], [34], [49] and [50].

In this survey, we focus on the sleep mode techniques in BSs, and provide more details beyond the coverage of previous surveys. As discussed above, sleep mode techniques do not require upgrade of equipment, therefore they have the benefit of low implementation cost since replacement of hardware is avoided. In surveying the literature, we have observed that studies on the topic of applications of sleep mode techniques to mobile networks made different assumptions on system and power models, e.g., the effect of traffic load on energy consumptions. We discuss these inconsistencies in the paper and demonstrate that the benefit of sleep mode techniques is significantly affected by the assumptions.

The remainder of this article is organized as follows. Section II provides recent facts and figures that motivate green cellular networking research. Then, in Section III energy efficiency metrics of interest with respect to BS sleep mode techniques in cellular networks are discussed. Next, Section IV introduces the potential of savings, feasibility and the foundation of techniques for sleep mode in cellular networks. After that, specific research and applications of sleep mode in various network standards are discussed in Section V and performance comparisons of approaches are presented in Section VI. Potential areas for improvement is discussed in Section VII and insightful remarks on future directions are explored in Section VIII. Finally, the survey is concluded in Section IX.

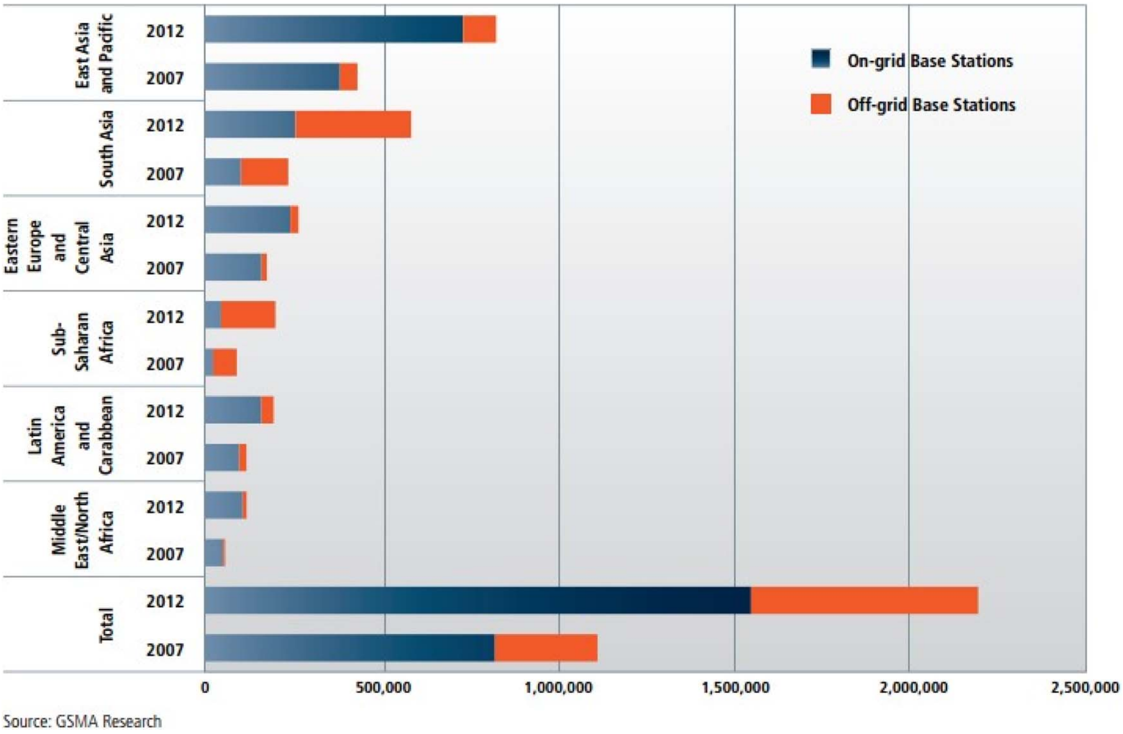
II. FACTS AND FIGURES

A. *Objectives of Traditional Mobile Networks Design*

Previously, mobile networks, or wireless communication networks in general, have been designed with the objective of optimizing coverage, capacity, spectral efficiency or throughput [52], [53]. Clearly, it does not necessarily maximize energy efficiency. Also, traditional facilities were mostly designed to endure peak load and extreme conditions. Many of them are even dimensioned with redundancy, providing extra capacity to possible peak load, in order to allow for unexpected events. As a result, the system is significantly under-utilized during non-peak hours, creating an opportunity for possible energy saving. It is worth noting that traditional design objectives are potentially contradictory to green ones, which makes green networking an interesting and technically challenging research field. Therefore, a new networking paradigm is urgently needed so that existing networks will maintain the same level of QoS while reducing the amount of energy consumed in the future [6], [7].

B. *Energy Consumption of Mobile Networks Today*

It was estimated that ICT roughly accounted for about 10% of global electricity consumption and up to 4% of global carbon dioxide emissions (around 1 billion tons, approximately equal to that of aviation industry and one fourth of emission by cars worldwide) as of early 2013 [54]. ICT's share in global carbon emissions were expected to grow every year, and double to 4% by the year 2020 [55]. Another figure shows that by the end of



Source: GSMA Research

Fig. 2. Growth in the number of BSs (©GSM Association 1999–2015 [51]).

2012, the amount of carbon dioxide emissions from BS towers alone has reached 78 million tons, which is approximately equivalent to emissions from 15 million cars, or 150 000 round-trip flights between Paris and New York [55].

The prevalence of smart phones and tablets accessing cellular network remarkably contributes to the increasing energy consumption. Smart phones were introduced around 2000. However, it was the success of mobile operating systems such as iOS, Android and Windows Phone about a decade later that finally helped them take over traditional feature phones. Tablet computers became popular almost at the same time, marked by the release of the iPad by Apple Inc. With the help of higher data transmission rate in 3G and 4G (and 5G in the future) cellular networks, smart phones and tablets enable users to perform much more tasks than ever before using cellular networks, including, but not limited to, streaming videos, downloading and reading e-books, and social networking. As a consequence, both the number of mobile subscribers (4.5 billion in 2012, estimated 7.6 billion by 2020) and the amount of data traffic requested by each subscriber (on average 10 GB per subscriber per year in 2012, estimated 82 GB per subscriber per year by 2020) have increased explosively [56]. Also, more bursty and dynamic mobile data and video traffic have replaced mobile voice as the dominant traffic in cellular networks. These factors lead to significant increase in energy consumption. Manner *et al.* [57] showed that, in order to provide the same level of coverage, an LTE network has to consume about 60 times amount of energy as compared to a 2G network.

More BSs, data centers and other network equipment are required to support the growth in mobile traffic. Since BSs consume more than half of the total energy in a typical cellular network, the increase in the number of BSs has a significant impact in overall energy consumption [12], [58]. Relevant data (Fig. 2) show that the number of BSs worldwide has approximately doubled from 2007 to 2012, and the number of BSs today has reached more than 4 million [51], [59]. When cellular networks extend to remote districts, or developing or undeveloped regions, off-grid BSs need to be deployed as no electrical grids are available nearby. Compared to their on-grid counterparts, off-grid BSs may cost ten times more to run, since they generally depend on fuel, which is a costly and unreliable power source [5], [25], [59]. On the other hand, hydrocarbon energy, one of primary conventional energy resources that provides 85% of primary energy usage in the United States and releases large amounts of greenhouse gases when combusted, is proved not sustainable and expected to be depleted in the foreseeable future [60].

The BSs serving small cells are known to be much less energy consuming as compared to those serving macro cells. They have been deployed at densely populated area or edges of existing macro cells to improve spectral and energy efficiency. However, due to the tremendous deployment of small cells in the foreseeable future, they will consume around 4.4 TWh of power by the year 2020, constituting an extra 5% of energy consumption of the conventional macro cell network [37], [61].

On the other hand, while the penetration rate of mobile phones in developed areas has exceeded 100%, the rising trend in developing areas is rapid and still far from saturation [62]. For example, China, the biggest developing market for telecommunications, had a 90% mobile phone penetration rate, but only less than 30% of population had access to 3G or more advanced networks, as of October 2013 [63]. All of these indicate great potential for further growth of mobile data traffic and thus, energy consumption.

C. Improvement on Energy Efficiency in User Equipment

There have been significant improvements during the last two decades in carbon footprint per mobile subscriber. In the early 1990s, an average mobile subscriber would be responsible for 100 kg of carbon dioxide emissions per year. This figure had been reduced to one quarter, namely 25 kg per subscriber by the mid-2000s. However, since the number of mobile subscribers has dramatically increased, the total amount of carbon footprint is still rising despite of the reduction in footprint per subscriber [64]. Meanwhile, the increasing number of subscribers also causes total data volume of wireless networks to increase approximately by a factor of ten every five years, which is associated with 16% to 20% increase in energy consumption [65].

The energy consumption in a cellphone, including battery chargers and user equipment (UE, any mobile device used by end users to communicate), had been reduced from 32Wh per day in the early 1990s to 0.83 Wh per day in 2008, with a saving of more than 97%. The achievement in energy saving in UE has made the energy consumption negligible as compared to that in BSs. Nowadays, the main motivation for further improving energy efficiency in cellphones is not ecological or economic impacts, but longer battery life and thus better user experience [50], [66]–[68]. For example, extensive research has been carried out on energy efficiency of data and power consuming applications such as social networking and multimedia streaming, to improve battery life of UE [67], [69], [70]. A comprehensive survey of energy efficient techniques on UE can be found in [50].

D. Problems Faced by Mobile Network Operators

While energy efficiency in UE has been significantly improved, the same work on BSs, which consumes the most amount of energy in mobile network, has been lagged behind. As a result, mobile operators are charged even more with skyrocketing number of BSs.

The fact that energy cost comprises a large proportion of total cost justifies efforts from telecommunication service providers to reduce energy consumption in order to improve their bottom line. Figures show that their energy bills are now comparable to their personnel costs for network operations, which range from 18 percent (in the EU) to 32 percent (in India) of their total operating expense (OPEX) [64], [71]. In Germany, the electricity bill for mobile network operators is more than 200 million Euros per year [3]. It is predicted that the revenue for global mobile network industry will start to shrink from the year 2018 [72]. Apart from direct economic benefits, environmental and marketing reasons (better corporative image can boost sales) are other driving forces for telecom providers to take the green initiative. Evidently, several telecom providers such as PCCW and Vodafone have been taking measures to reduce their energy-related operating cost [73]–[75]. An analysis shows that total energy per unit traffic declined by approximately 20% and energy per connection declined by 5% from 2009 to 2010, indicating that the industry is making significant efforts and progress towards the goals of energy saving [58].

In addition, given the concern regarding carbon dioxide emission, regulatory units, non-for-profit organizations and environmental advocates have together initiated projects to reduce energy consumption in cellular networks, or at least slow down the increasing trend. Nordhaus [76] demonstrated that reducing the global greenhouse gas emissions by a factor of 1/3 will generate economic benefit higher than the investment required to accomplish such reduction. Notable collaborative projects that aim to reduce energy consumption in mobile networks include 3GPP [77], EARTH [56], OPERA-Net [78], C2POWER [79], eWin [80], and TREND [81]. They proposed advanced technologies such as effective utilization of spectrums, innovative component designs, energy efficient network architectures, energy efficient routing protocols, node selection protocols, and clustering techniques. The reported potential saving is up to 50% as compared to the baseline of today's network system.

It is also worth notice that while we have reached the 4G era, 2G (GSM, GPRS, CDMAone, IS-95, EDGE) and 3G (WCDMA, HSPA, UMTS, EV-DO, etc.) networks are expected to coexist in the coming years due to their mature architectures, business models and lower price to subscribe. Besides, the older generations of networks could always act as the "backup" network when higher standard networks are down or temporarily not available. Therefore, energy saving technologies on 2G and 3G networks still have large impacts on the improvement of overall energy efficiency of cellular networks today.

E. Summary

In this section, we have presented the background, achievements and concerns associated with green cellular network research. The increasing trend of energy consumption in mobile networks will probably continue in the foreseeable future. It will adversely affect our civilization in many ways unless adequate measures are taken.

Generally, energy efficiency of UE now draws interest from cellphone manufacturers for the sake of longer battery life [82], while network operators and policy makers are more involved in reducing energy consumption in BSs due to economic and ecological reasons. As the motivation, objectives and techniques for the two sides are drastically different from each other, this paper will mainly focus on energy conservation in BSs.

III. RELEVANT ENERGY EFFICIENCY METRICS

Given various proposals to improve energy efficiency of cellular networks, a framework to evaluate the performance is essential to assess and compare different schemes [65], [83]. In this regard, energy efficiency metrics measuring at different levels have been proposed by both academia and industry.

A. Classical Energy Efficiency Metrics

A classical and widely-used metric to evaluate the energy efficiency of telecommunication networks is Bit-per-Joule [84]. It represents the system throughput (amount of information transmitted) for unit-energy consumption. It is still referenced in recent relevant studies [85]–[87] because of its simplicity. The reciprocal of Bit-per-Joule measurement, namely energy consumption per delivered information bit, is referred as Energy

Consumption Ratio (ECR) [88]. A close variant to the Bit-per-Joule metric is Bit-per-Joule-Hz. Instead of system throughput (bits/s), Bit-per-Joule-Hz uses spectral efficiency (bits/s/Hz) as the performance measurement. It is equal to the ratio of spectral efficiency over the total power consumption [89].

External energy benchmarks, such as JouleSort ([90], which measures energy consumption of a component or system), have also been proposed to assess the scale of improvements in energy efficiency of telecommunication networks. However, as the energy saving in ICT draws global attention from researchers, tailor-made energy efficiency metrics are needed to assess the improvements provided by various approaches.

More recently proposed energy efficiency metrics provide effective means for understanding, measuring, reporting, designing objectives and evaluating the performance of energy efficiency of components, systems and networks. Energy efficiency metrics on component (such as power amplifier), node (BS or BS site) and system levels in mobile cellular networks have been extensively covered [5], [64], [65], [91], [92]. In general, a good metric should be standardized to compare energy consumption of different units in the same class and provide directions for possible research and development targets. They should accurately reflect the energy efficiency and evaluate the performances fairly and objectively, but should not be too complicated that they are difficult to understand and derive.

B. Energy Efficiency Metrics on BS Sleep Mode Techniques

For sleep mode techniques in particular, the fraction of time that the component or BS spends in sleep mode ($T_{sleeping}$) over a certain period (T_{total}) is usually adopted as an approximate saving estimation at component or node level, which can be expressed as:

$$\text{Savings from sleep mode} = \frac{T_{sleeping}}{T_{total}}. \tag{1}$$

Assuming static energy consumption in active mode, zero energy consumption in sleep mode and zero cost for switching operation, the rough approximation of (1) is used in various studies (e.g., [93], [94]). A somewhat more realistic modification considers active mode and sleep mode, each consumes a fixed amount of energy, and the average power consumption during a certain period is obtained by:

$$P_{total} = f_{sleep}p_{sleep} + f_{active}p_{active} \tag{2}$$

where f_{sleep} and f_{active} refer to the fraction of time that the component or BS is in sleep or active state, while p_{sleep} and p_{active} are the power consumption in sleep mode and active mode, respectively [40]. The exact values of p_{sleep} and p_{active} depends on specific implementation. For example, if the entire BS is treated as the unit to be switched, p_{sleep} will be minimal as it only accounted for power consumption of the signal processing unit for transmitting pivot signals, while p_{active} can be described as the sum of fixed power consumption (including air conditioning, signal processing and power supply) and traffic-dependent power consumption. Details of the two elements comprising p_{active} will be discussed in detail later in Section VII.

Another metric on the node level is the Energy Consumption Index (ECI) [91] given by:

$$ECI = \frac{p_{site}}{KPI} \tag{3}$$

where p_{site} refers to total input power of the site (e.g., BS) and KPI (key performance indicator) could be either coverage area or throughput. The ECI measures the efficiency of power utilization for a BS. Lower values of ECI indicate better energy efficiency. Energy saving achieved by sleep mode is taken into consideration in p_{site} as the input power decreases if sleep mode is adopted. A specific example is Energy Consumption Ratio (ECR) discussed in [95] (different from the ECR discussed in previous text, which is the reciprocal of bit-per-joule), in which KPI is the peak data throughput. Another similar example is presented in [21], in which energy efficiency is defined as spectral efficiency per unit of energy consumption.

At the system level, energy efficiency is generally measured in average power consumption per user or per unit area. An example is the performance indicators (PI), proposed by European Telecommunications Standards Institute (ETSI) in [96], defined by

$$PI_{rural} = \frac{\text{Total coverage area}}{\text{Power consumption}} \tag{4}$$

and

$$PI_{urban} = \frac{\text{Number of users in peak hour}}{\text{Power consumption}} \tag{5}$$

where performance in rural areas is measured in average power consumption per coverage area because the density of subscribers is typically low, while average power consumption per user is thought to be a more accurate measurement for urban areas where density of subscribers is high. Higher values of PI indicate better energy efficiency. The performance indicator PI and its close variants can be found in a number of studies on sleep mode, e.g., [38].

Similar to PI, the Area Power Consumption (APC) measures the power consumption in a considered area [95]. The area can be coverage of a certain BS (node level) or the whole network (system level). It is measured by the ratio of power consumption to the area, i.e.,

$$APC = \frac{\text{Power consumption}}{\text{Area}}[\text{W/km}^2]. \tag{6}$$

A new metric integrating ECR and APC is proposed in [95]. Taking both power consumption per unit and requested capacity into account, it is expressed as:

$$\gamma = \frac{\text{Power consumption}}{\text{Requested capacity} \cdot \text{Coverage area}}[\text{W} \cdot \text{km}^{-2} \cdot \text{bps}^{-1}]. \tag{7}$$

For both APC and γ in (7), lower values indicate better energy efficiency.

For small cell network deployment, energy consumption gain (ECG) quantifies the gain in energy saving in radio access network by deploying smaller cells [88]. It is defined by the quotient of energy consumption in large cell deployment divided by that in small cell deployment, namely

$$ECG = \frac{E_{largecell}}{E_{smallcell}}. \tag{8}$$

An interesting metric, called absolute energy efficiency metric, was proposed to incorporate the cost in carbon footprint along with energy consumption [97]. Apart from energy consumption and throughput, absolute temperature is taken into account for its role in carbon emission. A logarithmic example called $dB\epsilon$ is defined by

$$\text{dB}\epsilon = \frac{\text{Power/Bit Rate}}{ln2(kT)} \tag{9}$$

where k is the Boltzmann constant and T is the absolute temperature measured in Kelvin. It can be applied at a device, node or system level. However, this metric is not yet mature, as the logarithmic relationship of [97] still requires stronger justification, and no follow up research can be found so far.

In addition to savings by sleep mode, various costs related to switching between active and sleeping modes, such as cost of exchanging load update messages between BSs, cost of handover between BSs, and cost of collecting traffic load information, are also considered in a few studies (e.g., [98]). However, they are still measured separately so far. A unified metric may better assess the overall performance of different approaches.

Zhang *et al.* [99] proposed a new performance metric to evaluate energy efficiency as well as spectral efficiency of cellular networks. The metric, termed as Generalized Area Spectral Efficiency (*GASE*, denoted by η), is equal to ergodic capacity (denoted by $\overline{C}$) divided by the size of affected area of transmission (denoted by A), namely

$$\eta = \frac{\overline{C}}{A}. \tag{10}$$

It is somehow similar to (Γ) in Eqn. (7), where the measurement involves capacity and the size of coverage area. The authors argued that the proposed metric provided a more comprehensive evaluation of spectral and energy efficiencies of wireless networks, by taking more elements of the network such as relays and secondary transmitters into account. In cellular networks, secondary transmitters refer to unlicensed users offered opportunistic access to the network.

Tabassum *et al.* [100] proposed another area-based energy efficiency measurement for two-tier heterogeneous cellular networks called area green efficiency (*AGE*). The two-tier network is formed by a macro cell in the center and a number of femto cells distributed around the edge of the reference macro cell. *AGE* is defined as:

$$AGE = \frac{\mathcal{P}_m + \mathcal{P}_n}{\pi(R_m + R_n)^2}. \tag{11}$$

The numerator of (11) is the sum of aggregated power savings by sleep mode or other green technologies in the macro cell ($\mathcal{P}_m$, 1st tier) and in femto cells ($\mathcal{P}_n$, 2nd tier). The denominator is the total coverage area of macro cell and the femto cells, with R_m being the radius of macro cell and R_n the radius of femto cell.

C. Discussions and Summary

There have been a number of proposals on various energy efficiency metrics as discussed above. The various metrics actually reflect the fact that energy efficiency is a relatively subjective concept. It depends on the specific model (e.g., homogeneous macro cell or heterogeneous cells), environment (e.g., rural or urban) and information available that which metric should be used.

The first question arise here is the **level of measurement**. Normally, BS sleep mode techniques involve turning off one or more BSs, therefore component level metric might not be appropriate in most cases. The choice between node and system level metrics depends on specific area of interest. System level metrics are more appropriate when the overall performance and energy consumption of the network is concerned, while node level metrics provide useful insights for certain parts of the system covered by a single BS (e.g., most densely populated area).

Another concern for choosing metrics is the **point of view**. If measured from the **service point of view**, metrics should evaluate power or energy consumption against QoS parameters such as throughput, capacity, or blocking probability. Suitable metrics which are discussed previously include ECI, *absolute energy temperature* and ECR (in [95]). On the other hand, when taking a **deployment perspective of view**, parameters such as coverage area, number of users under coverage, and number of BSs are better measurements and thus should be reflected in the metrics used. Therefore, metrics such as PI *area power consumption*, $GASE$ and AGE are considered better candidates. Finally, while classical metrics such as bit-per-joule measures **absolute energy consumption**, metrics comparing energy consumption with and without green approaches would provide insights on **relative savings**. *Fraction of sleeping time* and ECG fulfill such requirements.

While heterogeneous deployment is becoming more and more popular in cellular networks, energy-efficient techniques including sleep mode in such network have also been intensively studied. Metrics **focused on networks with heterogeneous deployments** thus also attracted lots of attention. These tailor-made metrics, including ECG and AGE discussed earlier in the section, quantify the savings in macro and micro or femto cells separately.

Most of energy efficiency metrics discussed above can be used in parallel with each other, if relevant data are available. However, the results may not be consistent in all cases. It should be noticed that energy gain in one component or cell of interest may be the result of energy loss in another component or neighboring cells. Therefore, when there are conflicting results among measurements of different levels, system level metrics should prevail over node and component level metrics, and node level metrics should dominate component level metrics [25].

A potential area for improvement in terms of measuring metrics is that QoS degradation should be taken into account. Intuitively, while BSs are turned off for the sake of energy saving, total capacity, throughput and coverage of the network will be negatively affected as a result of less active BSs. Meanwhile, blocking probability would increase. If the gain in energy saving is not enough to offset the loss due to significantly worsening user experience, it is pointless in implementing such schemes.

TABLE II
ENERGY EFFICIENCY METRICS

Metric	**Level of measurement**	**References**	**Remarks**
Bit-per-Joule	Component, node or system level	[84]–[86]	Classical metric
Bit-per-Joule-Hz	Component, node or system level	[89]	Classical metric
Energy Consumption Ratio (*ECR*) (Joule-per-bit)	Component, node or system level	[88]	Classical metric
JouleSort	Component, node or system level	[90]	External benchmark
Energy Consumption Index (*ECI*)	Node level	Eqn. 3, [21], [91], [95]	Service point of view, focused on heterogeneous networks
Fraction of sleeping time	Node level	Eqn. 1, [93], [94]	Relative saving
Average power consumption	Node level	Eqn. 2, [40]	
Energy Consumption Gain (*ECG*)	System level	Eqn. 8, [88]	Relative saving, focused on heterogeneous networks
Absolute energy efficiency (*dBε*)	Component, node or system level	Eqn. 9, [97]	Service point of view
Performance Indicators (*PI*) for rural areas	System level	Eqn. 4, [38], [96]	Deployment point of view
Performance Indicators (*PI*) for urban areas	System level	Eqn. 5, [38], [96]	Deployment point of view
Area Power Consumption	Node or system level	Eqn. 6, [95]	Deployment point of view
Generalized Area Spectral Efficiency (*GASE*)	System level	Eqn. 10, [99]	Deployment point of view
Area Green Efficiency (*AGE*)	System level	Eqn. 11, [100]	Deployment point of view, focused on heterogeneous networks

Possible negative impacts brought by sleep mode on delay and throughput have been studied in [101]. As discussed, for example, in [102] and [103], this trade-off can be adjusted by tuning some parameters such as guard interval and hysteresis time in implementation. The energy–delay tradeoff is further investigated in [104], in which impacts of BS control policies including close-down time, the number of waiting customers for the BS to reactivate, and delay bound were discussed. It is shown that energy is a decreasing function of delay in most cases. Therefore, it is necessary for mobile operators to find the optimal balance between QoS preservation and energy saving. In the EARTH project, the concept of utility function for energy saving techniques has been proposed to assess the trade-off between system performance and user experience [91]. One of the proposed utility functions is:

$$U = 100 + (\alpha_E \Delta U_E) + (\alpha_Q \Delta U_Q) \tag{12}$$

where 100 is the utility of the reference system (before energy saving technologies are applied), α_E and α_Q are the weights of value of energy and QoS, respectively, and ΔU_E and ΔU_Q are the energy and QoS deviations of the assessed system from the reference system, respectively. It is still an open question how to determine the most suitable values for α_E and α_Q, as well as which specific parameter or combination of parameters should represent QoS (blocking probability, throughput, coverage or others), for different markets, thus providing network operators with explicit objectives. A similar but more complicated system cost function considering flow-level performance and system energy consumption is proposed in [105].

Another shortcoming of existing metrics is that they do not measure the "greenness" based on the source of power supply. It is actually important because one of practical objectives of green technologies is to reduce carbon footprint, and energy sources have different carbon emission level. For example, a certain amount of energy generated by solar source should be considered "greener" than the same amount generated by diesel. A metric incorporating this factor could possibly evaluate the overall environmental effect of certain implementations.

Table II summarizes the energy efficiency metrics discussed in this section. More general and comprehensive energy metrics can be found in the referenced articles.

IV. ENERGY SAVING POTENTIAL AND TECHNICAL FEASIBILITY OF BS SLEEPING

Before implementing sleep mode in BSs, it is important to estimate its potential savings, as well as to establish its technical feasibility. One example of important technical concerns is whether there will be any coverage holes when some BSs are turned into sleep mode. In this section, we will discuss the energy saving potential and technical feasibility of BS sleep mode techniques.

A. *Energy Consumption Breakdown in BSs*

There are three key components in a typical mobile cellular network: (1) UE for end users to access the network, (2) network switching subsystem to route calls and data, and (3) BSs (sometimes referred to as BS subsystem or access network) for commuting mobile traffic and signaling between the previous two components. As discussed, BSs consume the largest proportion of energy in mobile cellular networks.

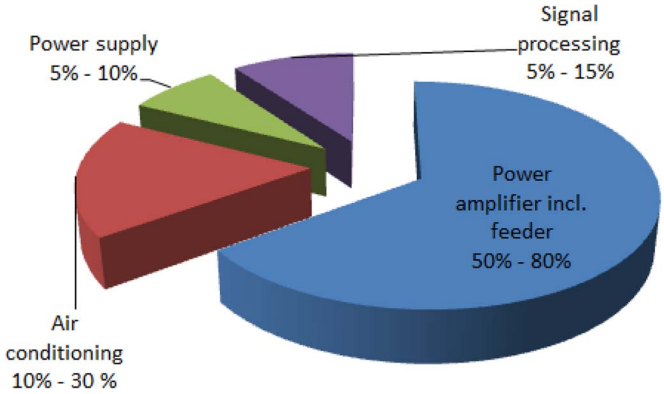


Fig. 3. Power consumption distribution in cellular BSs (Source: [59]).

Power management schemes for UE, such as peer data sharing and load mitigation, have been extensively studied due to the limited power supply in devices like mobile phones and tablets [66], [82], [106], [107]. At the same time, mobile manufacturers have well optimized the energy efficiency of UE due to limited battery power supply. Until recently, there has been less research on the efficient usage of power in BSs, which are actually the major source of energy consumption in mobile cellular networks. Only recently, researchers discovered a significant potential for energy conservation in BS and research efforts on this topic have increased significantly.

As shown above in Fig. 1, BSs are the main targets of sleep mode techniques because of their large share in energy consumption and therefore, their potential saving is the largest. The total power consumption of a BS is composed of fixed (traffic independent) and traffic dependent parts. As shown in Fig. 3, the fixed part, including air conditioning and power supply, accounts for around one fourth of total energy consumption. This amount of energy is wasted when no traffic is served by the BS.

The switching subsystem, on the other hand, consumes only a marginal amount of energy compared to BSs, largely because of the huge number of BSs nowadays and therefore no significant research effort has been made to improve energy efficiency in the switching subsystem.

B. Traffic Variation and Prediction in Cellular Networks

It is evident that the mobile traffic level throughout a day or a week varies periodically with the living pattern of mobile users. In the daytime on weekdays, people mostly concentrate in business areas in a city and are more likely to make phone calls. At night or on weekends, most people move to residential areas. Phone calls are generally less frequent at night than during the day but larger amount of cellular data is transmitted because more data-intensive applications such as social networking, web browsing, video streaming and video chatting are more likely to run. Fig. 4 shows the weekly traffic profile of a network operator in Europe in 2012, classified according to different applications including mobile e-mail, virtual private networks, peer-to-peer transmission, location-based services, video streaming and so on [108]. It has also been noticed that the maximum-to-minimum traffic ratio is larger than five in more than half of observed real cases, while it could be over ten in 30% of all cases [109]. The content is consistent with our previous comments and thus creates opportunities for energy saving by turning off BSs appropriately.

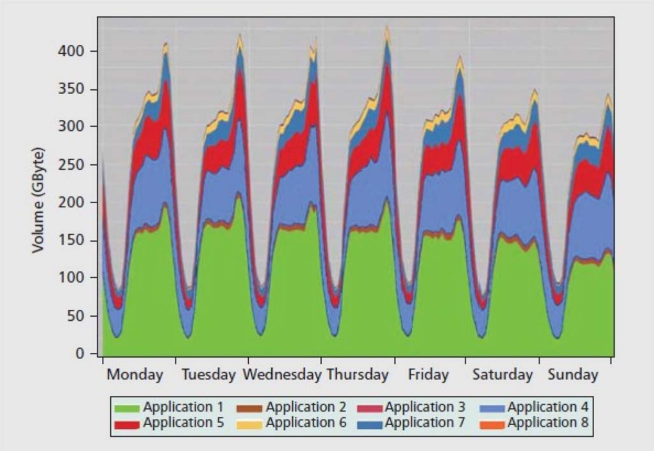


Fig. 4. Measured weekly traffic volumes of a mobile cellular network (Source: [108], [111]).

Given that the traffic in a cellular network approximately fluctuates in such well-known daily and weekly behavior, it is feasible to adapt the level of active over-provisioning by switching some BSs to sleep mode to save energy without noticeable impact on QoS. Cao *et al.* [110] identify different types of regions within the coverage area of cellular networks. In ascending order of traffic intensity, they are called coverage-limited, energy-efficient and capacity-limited regions. The energy-efficient region, namely the region with medium traffic, has the largest potential for energy saving by cooperative dynamic sleep mode schemes. By increasing the density of BSs, the energy-efficient region can be enlarged so that extra savings are possible.

It should be noted that the traffic pattern in cellular networks has been changed since the emerging of smart phones [69], [70], [112]. Many popular apps today such as Facebook (social networking), Skype (Internet telephony), Twitter (microblogging) and WhatsApp (instant messaging) all exhibit different traffic patterns as compared to traditional mobile traffic such as voice, text messages, emails and web pages. Significant changes in individual packet size, burst size, inter-arrival time of packets and streams, behaviour in inactive periods imply that traffic trend analysis based on previous generation of mobile apps may be no longer valid.

While real-time traffic information is relatively difficult to obtain, traffic prediction techniques enable BSs to switch to sleep mode at quasi-optimal times based on the forecasted traffic load. Given cyclical characteristics of traffic load in cellular networks as shown in Fig. 4, predicting future traffic load based on past recorded load is appropriate. An example of traffic prediction technique is the Holt-Winter's forecasting technique, which performs prediction of future values of a time series based on properly weighted previous values, including seasonalized, deseasonlized and trend components [95]. The accuracy of prediction is usually measured by the Mean Absolute Error. Certain mechanisms, such as Artificial Neural Network (ANN) model, have been proposed to improve the accuracy and decrease the complexity of traffic prediction [113].

Li *et al.* [161] also proposed a traffic forecast scheme based on transferred learning expertise from historical periods or neighboring regions, by formulating the traffic variation as a Markov decision process. The proposed scheme is then utilised to minimize the energy consumption of cellular radio access network with the help of BS sleeping operations.

C. Techniques Enabling Sleep Mode in BSs

In order for the sleep mode techniques to function, BSs usually need to cooperate with each other. A BS controller (BSC) facilitates exchange of traffic information between BSs. If certain BSs are selected to sleep, the sleeping BSs release their channel resources to active neighbors, while active BSs make use of obtained resources to cooperatively provide extensive coverage to the mobile users located in the service areas of nearby sleeping BSs. When doing so, QoS requirements such as outage probability need to be carefully monitored as the SNR (signal-to-noise ratio) changes with the distance between the mobile user and its serving BS, and more blocking events might occur due to insufficient available capacity in active BSs [114].

User association, as the word implies, means associating mobile end users with BSs in an energy efficient way without the coordination from BSCs. Users originally connecting to BSs that went asleep need to be associated with new active BSs. This process is required to ensure the QoS does not degrade significantly during BS sleeping operations. User association is determined at a much faster time-scale than that of any dynamic BS operations, which makes them two separated problems with potential aggregated gains. It has also been noticed that simply associating a user to the closest BS may be sub-optimal when traffic distribution is inhomogeneous, because the closest BS, if it is located in a low traffic area, may be preferable to be turned off [105]. Therefore, optimal user association, based on locations of users and BSs, average or instantaneous received signal quality (SINR) as well as traffic load, is an essential condition for sleep mode schemes to be advantageous [21], [105]. Significant effort has been made on optimizing user association, for example, Dufkova *et al.* [101] formulate the problem as an integer linear program in a users-cells affinity graph.

Tabassum *et al.* [22] investigated the user association process in BS sleeping operations. As compared to the conventional user association scheme based on maximum instantaneous received signal power (MRSP), the authors proposed a new user association mechanism based on maximum mean channel access probability (MMAP). In the proposed scheme, any user originally associated to a cell that went asleep chooses its new associated cell based on maximum probability that it can obtain a channel in the new cell. This probability depends on a number of factors, including traffic load in active BSs prior to the sleeping operation, receiving signal power strength, and cumulative interference power from neighboring BSs. The authors showed that the proposed scheme and the conventional scheme both have pros and cons in different scenarios, and suggested that a hybrid approach of the two schemes may achieve best performance in terms of spectral and energy efficiency.

A technique called *self-organizing network* (SON), introduced in the 3GPP standard (see 3GPP TS 32.521 for definition and 3GPP TS 36.902 for cases and solutions) [41], [115]–[117], is intended to be gradually implemented in BSs along with the 4G standards including LTE and WiMAX. It adds automatic network management and intelligence features to the system and thus reduces costs, improves performance and increases flexibility of the cellular system through network optimization and reconfiguration processes. SON enables the BSs to adjust their own configuration when necessary without human intervention, thus more operations such as timed sleep mode, user location prediction and reverse channel sensing are possible in the system [41], [117]. Sleep mode in BSs is one of the various applications of SON, where BSs are enabled to act collectively to save energy by redistributing traffic and sharing traffic information among BSs.

There have been many publications on energy savings in LTE networks based on SON. For example, associations of BSs powered on or off can form collective network elements based on SON [98]. Cell sizes and on/off states can also be optimally adjusted [41]. In LTE, SON-based regulation schemes dynamically minimize the number of active sectors in each evolved Node B (eNB, equivalent to a BS), and thus enable efficient energy consumption [117]. SON-based traffic load redistributing strategies can also complement and support BS sleep mode techniques by intelligently balancing or concentrating traffic at appropriate times, resulting in more BSs available to be turned off [118].

Cell zooming or *cell breathing* is a similar concept to SON but it provides higher level of flexibility. As introduced in [19], [119]–[121], cell zooming is a network layer technique adaptively adjusting the cell size according to traffic conditions by adjusting antenna tilt angles, height, or transmit power. It is much simpler than switching on/off BSs from an implementation perspective [121]. It can be applied to balance the traffic load and reduce the energy consumption. When the traffic load in a certain cell increases, the cell will zoom in to reduce the coverage area and therefore avoid possible congestion. The "service hole" will be taken care of by the neighboring cells with less traffic, which are supposed to zoom out. A cell zooming server, which can be implemented virtually at the gateway, or distributed in the BSs, controls the procedure of cell zooming. It sets the zooming parameters based on the traffic load distribution, user requirements, as well as channel state information. In fact, zooming in the cell coverage to 0 is equal to switch off the entire BS. Therefore, cell zooming can be perceived as a generalization of BS sleep mode.

Heterogeneous deployment is now common in cellular networks. The ultra-dense small cells are very energy consuming if not managed properly. Fortunately, the underlying macro cells are able to provide coverage when the micro cells go to sleep [122]. BS sleeping in heterogeneous cellular networks is thus both feasible and desirable. More details of BS sleep mode in heterogeneous networks will be covered in Section V.

D. Summary

The fact that BSs have been designed to serve peak traffic leads to wastage of energy during low traffic hours. Sleep mode operations exploit the opportunity by turning lightly loaded BSs to sleep and to save fixed part of energy consumption, e.g., air conditioning. Traffic prediction and estimation techniques help

TABLE III
SUMMARY OF TECHNIQUES ENABLING BS SLEEPING

Technique	Application scenario	Key point
User association	UE transfers connection with sleeping BSs to active BSs	Maximize efficiency in capturing the impact of access condition and channel information
SON	BSs adjust their own configurations (sleep/wakeup) upon change of shared traffic information	Minimize the number of active BSs subject to preserve required QoS by BS cooperation
Cell zooming	BSs adaptively change their coverage area according to changes in traffic condition	Optimize the performance-complexity tradeoff of zooming algorithms by BS cooperation
Traffic prediction	BSs predict future traffic trend based on past record	Maintain accuracy by adaptation to changing traffic patterns due to new usage patterns
Heterogeneous deployment	Macro cells remain active for controlling while small cells go asleep	Maintain optimal densities for all BSs (both macro and micro)

BS controllers turns BSs off at quasi-optimal times when real-time traffic information is not available.

Energy-efficient user association schemes, SON and cell zooming techniques enable the cells to adaptively switch their state based on current traffic load, while user association mechanism ensures that mobile users find an active BS in an energy-efficient manner when the originally associated BS is switched off. Macro cells maintain coverage when small cells are switched off in heterogeneous cellular networks. On the other hand, hardware operations such as optimization in antenna tilt angles, height and vertical beam-width complement the aforementioned techniques. It has been proven that turning off some BSs to achieve energy conservation while preserving coverage is technically feasible. Therefore, BS sleep mode techniques have been justified as an effective method in green cellular networks research.

A summary of discussions in this section is presented in Table III.

V. BS SLEEP MODE APPLICATIONS

In this section, we will discuss specific energy saving applications based on BS sleep mode techniques. We will start with general design principles and methodologies, followed by applications in different network standards and environments. Integration of BS sleep mode techniques with other energy saving strategies will also be discussed.

A. Design Principles and Methodologies

Implementation of sleep mode operations should follow certain design principles. In general, geographical location of BSs, coverage area of BSs, traffic load (arrival/departure/handover rates and blocking/dropping probabilities) and propagation environment (signal-to-noise ratio, path loss or fading) along with energy consumption are the main elements that should be taken into account for implementation and evaluation [120]. Methodologies in most existing research involve either **queuing theory/teletraffic** or **information theory**, or both. The relationship of the methodologies and the key elements considered is summarized in Table IV below.

TABLE IV
CORRESPONDING RELATIONSHIP BETWEEN METHODOLOGIES AND KEY ELEMENTS IN SLEEP MODE RESEARCH

Methodology	Elements considered	References
Queuing theory/teletraffic	Traffic load (arrival, departure, handover rates and blocking rate) and capacity requirements	[15], [21], [87], [109], [123]–[127], [161]
Information theory	Capacity, coverage area and propagation environment (signal-to-noise ratio, path loss and fading, etc.)	[15], [21], [95], [120], [123], [124], [127]–[131]

Queuing theory and/or teletraffic consider characteristics of traffic profiles. QoS related measures are mainly based on steady-state parameters such as blocking/dropping rate and data throughput. They can be derived based on given arrival, departure and handover rates. When some BSs alternate between active and sleeping modes, the transition probabilities among states are updated accordingly to reflect the change in the system condition. On the other hand, information theory mainly considers path loss and fading effects for evaluation of QoS in various scenarios. For example, if the signal-to-noise ratio falls below a certain threshold, the connection is dropped. Ideally, the two theories would complement each other to obtain a more complete picture of probable blocking or dropping events in the network [21], [123], [124], [127].

B. BS Sleep Mode in 4G Cellular Networks

4G is the newest commercially available cellular network standard today. Some novel features enable possibilities for dedicated energy-efficient research exclusively applicable to 4G networks. For example, in WCDMA, HSPA and earlier (e.g., GSM) network standards, both UE and BSs need to comply with certain minimum amount of transmissions (e.g., pilot and control signals) even when no user data is transmitted. Consequently, the entire BS needs to be switched off in order to achieve energy saving, which is a fairly complex and costly operation. On the contrary, in 4G network standards including LTE, LTE-advanced and WiMAX, by the introduction of the discontinuous transmission (DTX) and discontinuous reception (DRX) and the multiplexing scheme deployed orthogonal frequency division multiple access (OFDMA), individual transceivers could be switched off whenever there is no data to transmit or receive [132]. Seeing this, some provisions for power saving protocols based on sleep mode of transceivers have been proposed for 4G standards.

There have been proposals to lower power consumption of LTE networks by exploiting DTX and DRX schemes to switch certain energy consuming components in UE or BSs into sleep mode in idle periods [59]. Basically, both DTX and DRX reduce transceiver duty cycle while it is in active operation, but no packet is being transmitted. DRX focuses on the uplink transmission and power of UE [69], [70], while DTX works on the downlink and thus it is relevant to energy consumption of BSs. Here we focus on DTX.

Frenger *et al.* [17] introduced and discussed the feasibility of the so-called cell DTX (where certain number of cells in a site are set to operate in DTX mode) in LTE by only transmitting mandatory synchronization signals in a downlink radio frame, leaving six out of ten sub-frames empty. In this way, the radio transmitter can be turned off. They also compared the performance of the traditional cell micro DTX scheme and an enhanced cell DTX scheme. The enhanced scheme was claimed to achieve 89% savings in a realistic traffic scenario compared to the scenario without cell DTX while the micro cell DTX provided an energy reduction of 61%. In a similar study, Wang *et al.* [133] proposed a novel time-domain sleep mode design in BSs. By optimally selecting the number of active subframes in each frame according to the traffic load, the energy efficiency in LTE networks can be improved. The authors presented that an energy reduction of up to 90% can be obtained at low traffic load.

In [98], the authors considered the energy saving reconfiguration based on traffic conditions applied as an SON function in radio access networks. They further proposed the concept of "energy partitions," that is, to form associations of powered on and off BSs by a collective decision of network elements. In a more recent work, Ghosh *et al.* [134] take traffic dependent energy consumption and penetration loss into consideration in an LTE configuration. The authors integrate sleep/active modes operations with optimization in antenna variables such as tilt, height, vertical beam-width and transmit power, subject to constraints in the Signal to Interference and Noise Ratio (SINR), spectral efficiency and user throughput.

Bousia *et al.* [135] proposed another power saving algorithm in LTE. The feature of their scheme is to switch off eNBs not only based on traffic load, but also according to the average distance of its associated users. The authors argue that greater average distance leads to greater transmission power, therefore this factor has to be taken into account when deciding which eNBs are to be switched off. The proposed scheme outperformed the random switching off scheme in terms of both the absolute energy saving and bit-per-joule measurement.

CoMP (coordinated multi-point transmission) is another feature of LTE standard which can also be utilized for sleep mode applications. It eliminates the need for increasing transmission power of active BSs to maintain the coverage of sleeping BSs. An optimized approach based on CoMP is presented in [131] such that the amount of power saving less extra power consumed in backhaul and signal processing is maximized, by selecting an optimized set of points for coordination.

A stochastic analytical framework for BS sleeping in LTE networks with OFDMA as the physical layer transmission technology is presented in [127]. The authors extended the theoretical model quantifying the key metrics of the outage probability (e.g., SINR) and the average user capacity to account for the effect of BS sleeping, such that optimal energy saving can be obtained while outage probability is held constant. Furthermore, the authors proposed a modified non-singular path loss model appropriate for small distance between the user equipment and the BS, which is more realistic for micro cells.

Dual connectivity is another new feature in LTE networks that could provide new insights of sleep mode research [136]. It enables a mobile devoice to be simultaneously connected to BSs in different tiers, for example, a macro cell and a micro cell. While the macro cells take the responsibility for the frame control, sending pilot signals and low-rate transmission, the micro cell can focus on high rate transmissions. This dual connectivity allows longer sleep periods for micro cells as they do not need to wake up every time to transmit control messages. It is shown that such functionality separation scheme could increase energy savings of sleep mode operations by more than a third [137].

Research on sleep mode in another 4G standard, WiMAX (IEEE 812.16 family) is also widely available. Jang *et al.* [138] introduced sleep mode for mobile subscriber stations and relevant power saving strategies. WiMAX enables a sleep window size dynamically changes adaptively to traffic conditions. If no traffic is destined to a sleep BS during its sleeping interval, the interval (window size) will be increased in the next active-sleeping cycle, and vice versa. The authors stated that by optimally select initial, maximum and minimum window sizes according to different traffic types, remarkable energy saving can be achieved without a significant increase in delay. Li *et al.* [44] also compared the performance of the periodical discontinuous transmission (PDTX) scheme proposed in IEEE 812.16m with other novel proposed sleep mode schemes.

C. BS Sleep Mode in General Cellular Networks

In contrast to DTX and DRX in 4G, the entire device or BS must be perceived as the smallest unit to be turned on or off in 2G and 3G networks. This has been studied more extensively. The basic idea is when some BSs are switched off, radio coverage and service provisioning are assumed to be taken care of by the stations that remain active. In this way, service is guaranteed to be available over the entire service area at all times.

Saker *et al.* [139] first proposed an energy-aware system selection scheme that splits the mobile traffic between 2G and 3G systems optimally, which can save up to 10% of total energy consumption while satisfying QoS requirements. They further proposed a sleep mode for either 2G or 3G systems. It turned out that in low to medium traffic hours, large amount of energy saving can be achieved without significant degradation in QoS. In a later study by the same research group [140], they developed a generic framework for applying sleep mode to mobile cellular networks. They proposed two schemes. The first scheme is a dynamic one where BSs are put to sleep or waken up based on the instantaneous number of users in the cell (the time scale of sleep/wake corresponds to minutes), while the second one is semi-static where the resources need to stay in a mode for some tens of minutes, or even for hours, in order to minimize the sleep/wake commands. The numerical results showed that the dynamic scheme led to much more energy saving in high traffic periods, while the performance of the two schemes was comparable in low traffic periods. The same group of authors also discussed practical issues for sleep mode implementation in BSs [102]. A guard period was proposed in order to avoid calls being blocked when the resources are being activated (takes around 3–5 seconds). They also introduced the hysteresis time, which keeps resources on for an additional period of time compared to the ideal sleep mode case, where unnecessary sleep/wake switches happen due to minor traffic variations. Based on their simulation and analysis, it is concluded that both guard interval and hysteresis time would provide better QoS while reduce the gain in energy savings. Elayoubi *et al.* [103] studied practical implementation issues of sleep mode operations in an HSDPA network with a Markovian model. The authors derived an optimal switching policy where energy saving is maximized while QoS is not degraded by solving a set of balance equations.

BS sleep mode techniques have also been applied on real mobile traffic profile to evaluate saving. Oh *et al.* [141] studied dynamically switching off scheme of redundant BSs during periods of low traffic, by analyzing temporal and spatial traces of real cellular traffic in a part of Manchester, United Kingdom. The authors estimated that, by sharing and cooperating traffic between BSs, between 32 and 60 kWh of absolute power could be saved for an area of roughly 12 square km in Manchester. The energy savings can be further translated to 200 to 375 metric tons of annual carbon dioxide emission or about \$42 000 to \$78 000 on the bill for the owners of the BSs. They also suggested in the paper that cooperation between operators would be even more profitable, particularly in metropolitan areas where dense deployments are required for every operator.

Marsan *et al.* [93] discussed different switching-off schemes in cellular access networks. They compared different fixed switching schemes, each of which switches off a different fraction of cells when the traffic falls below a certain threshold. The results in the paper indicated that for different traffic profiles, the optimal configuration is also different. If the rate of change in traffic is high, then it is more desirable to turn off a larger proportion of cells for shorter period of time rather than turn off a smaller proportion of cells for longer period of time. In a following study [142], the same authors discussed the possibility of cooperation between multiple mobile operators, where the users of the sleeping operator roam to the network of the active provider without violating QoS constraints. Several strategies, including balanced switch-off frequencies, balanced roaming costs, balanced energy savings and maximum saved energy are discussed. It is shown that remarkable savings are possible if operators are willing to cooperate. The same group of authors developed analytical models to identify optimal fixed BS switch-off times as a function of the daily traffic pattern [94]. They compared the cases of only one switch-off per day versus several progressive switch-offs (switching off certain number of BSs at a time in increasing order of load) per day. They also argued that when the number of switch-off configurations per day increases, the complexity in operation will also increase. By analyzing homogeneous networks and heterogeneous networks, as well as a case study given by a realistic cell deployment, they reached the conclusion that the extra energy saving gained by multiple switch-offs over single switch off is only marginal. Thus they recommended limited effort on the side of network management would be beneficial enough in terms of energy saving.

Niu *et al.* [119] discussed the performance evaluation of centralized and distributed cell zooming algorithms and also compared them with static configurations. The results showed that the centralized algorithm performs superior to the distributed algorithm (ignoring the overhead), while both of them outperform the static configuration. Son *et al.* [105] proposed and verified a framework for BS energy saving that encompasses user association and BS operation. A simple greedy turning on and off algorithm is proved to perform close to the optimal solution. Badic *et al.* [88] discussed the potential of energy saving by reducing cell size and including sleep mode feature in an HSDPA radio access network. Solely reducing the cell size would reduce the ECR but does not change ECG, which can be however improved by powering-off unused cells. It is concluded in the paper that under constant user density, the ECG is linearly correlated to the number of cells within a given service area when BS sleep mode techniques are enabled.

Guo *et al.* [87] proposed three strategies for BS sleeping on a queuing model. The three strategies differ in how BSs detect incoming customers while sleeping. The authors noted that a number of parameters including delay constraint, BS setup time and pre-determined time length for sleeping would affect the performances of different strategies. Particularly, if sniffing cost is high enough, more complicated strategies may not necessarily outperform simple strategy even if optimal switching time is achieved.

Network planning may influence the effect of BS sleep mode techniques. To achieve optimal savings, the locations of BSs must be planned carefully. Parameters including user density, coverage area of single BS, inter-BS distance, number of active BSs and energy consumption are interlinked. Too high density of BSs would result in waste of energy while too low density simply would not suffice. Wu *et al.* [143] discussed energy efficiency planning of BSs in cellular networks that would increase potential energy savings. Notably, an analytical method is presented in the work to approximate real performance in various scenarios.

D. BS Sleep Mode and Heterogeneous Network Deployment

As discussed in Section I, heterogeneous network deployment schemes were originally designed to improve the spectral efficiency in cellular networks by offloading traffic from classical macro cells, and may lead to increase in energy consumption because of the extra cells deployed. Nevertheless, by introducing sleep mode in BSs, heterogeneous cellular networks can now outperform traditional macro-cell-only counterparts in terms of energy efficiency. During peak traffic hours, more energy-efficient smaller cells can be deployed, replacing some of macro cells in the macro-cell-only network. Then, those smaller cells are turned to sleep during light traffic hours when remaining macro cells are capable of maintaining throughput and coverage [129].

For example, Ashraf *et al.* [18] studied the application of dynamic sleep mode in BSs with pico-cell deployments. Heterogeneous network planning can improve the coverage of the cellular network, but will likely result in even more severe over-provisioning and thus consume more energy if the cells are unable to adapt to traffic load. The solution proposed by the authors is to introduce the dynamic sleep and wake modes in the pico-cells. The result shows that the network with both macro-cells and pico-cells, where dynamic sleep mode algorithm is applied in pico-cells, consumes less amount of energy than the network with only macro-cells. Cai *et al.* [128] proposed an energy model for heterogeneous cellular network and a cross-layer optimization method. Several pico cells (lower layer) are in the coverage area of one macro cell (upper layer). The problem to solve is how to associate users to the group of macro cell and pico cells, so that energy consumption is minimized after lightly-loaded pico cells turned to sleep. Similar models are also presented in [95] and [129].

Soh *et al.* [21] particularly addressed inter-tier interference among multi-tier heterogeneous cells. In their work, macro BSs are modeled by a Poisson Point Process (PPP) while users are distributed according to different stationary point processes. A Bernoulli trail-based random sleeping technique and a strategic sleeping technique aiming at maintaining coverage are examined for both homogeneous and heterogeneous cases. The strategic sleeping, based on activity of macro cell users, is designed to maintain or improve coverage probability of users as in the non-sleeping case. Numerical results show that random sleeping harms rather than benefits energy efficiency of the system, as energy saved from sleeping mode is not sufficient to compensate for the decrease in coverage and data throughput. Strategic sleeping, on the other hand, actually improves both coverage and energy efficiency. The authors also showed that gain in energy efficiency saturate as the density of smaller cells reaches a certain level.

Wildemeersch *et al.* [126] investigated how small cell access points (SAPs) can play a role enhancing energy efficiency of heterogeneous cellular networks. Sleep mode of SAPs actually corresponds to the trade-off between energy consumption and false alarm rate. The authors note that bursty transmissions from macro-cell traffic, due to mobility of users, makes duty cycling of sleep mode in smaller cells more complicated. PPP is also used to model the locations of SAPs and macro BSs.

Saker *et al.* [125] proposed a similar sleeping strategy that femto cells are switched off when the cell itself is not heavily loaded and the macro cell can serve the overall traffic without deteriorating the QoS. Based mainly on queuing theories, the work utilizes a Continuous Time Markov Decision Process (CTMDP), in which states represent load status of each BS. Every user brings a certain load to its connected BS. Each possible action for the state and transition probabilities is assigned a value of rewards/cost. The cost function is defined as an increasing function of energy consumption and a decreasing function of target throughput, a QoS measure. The switching operation is added to the state space as a new dimension. Apart from the straightforward case that BSs have complete information of its associated traffic, optimal solutions have also been found for partial traffic information (based on Partially Observable MDP) and delayed information (by transforming their MDPs into equivalent MDPs without delay).

In another study, Li *et al.* [44] proposed a clustering based power saving algorithm for self-organized sleep mode in femto-cell networks. In the cluster construction process, the leader of each cluster is first elected based on the sum of received pilot signal power and the distribution density, and then other femto BSs determines whether they are to be attached to the leader on the basis of the pilot signal power. The leader and members in the same cluster will then exchange information collected by a sniffer installed with each femto BS. The member will only turn on the pilot transmission and the processing if notified by the leader and the received signal energy rise above a certain threshold within a predefined period of time. The proposed scheme is shown to outperform other three main traditional schemes.

The locations of BSs, either macro or micro, in heterogeneous networks are often assumed to follow a Poisson Point Process (PPP) [127], [144]. In this regard, capacity extension by additional micro cells (increase density of BSs) and energy saving by BS sleeping (decrease density of BSs) can be generalized into a single optimization problem on BS density based on the cost per micro BS. Cao *et al.* [144] illustrated numerical calculation to obtain the optimal BS density for both homogeneous and heterogeneous networks.

Huang *et al.* [122] considered a scenario where users in macro cells and micro cells have different traffic patterns. They assume that micro cells serve hotspots with higher traffic volume. The authors investigated three energy saving approaches including micro cell BS sleeping and expansion/shrinking coverage of micro cells (similar to cell zooming). The coverage and power consumption of macro cells are held constant. It is shown that each approach is effective under different traffic conditions. The crucial factor affecting the performances of different approaches is traffic rate ratio, namely the ratio of traffic rate per unit area in hotspots to that in non-hotspots.

E. BS Sleep Mode and Cooperative Relays

The mobility of end users in cellular network can be also exploited to provide coverage when some of BSs are in the sleep mode. As an alternative and complimentary method, migrating traffic by moving nodes in cellular networks is more cost effective than increasing radiation power from neighboring active BSs, since typical relays usually consume negligible energy when compared to BSs. Another benefit of adopting relays is to postpone communication to future time instances when an effective contact is available for message forwarding. For delay-insensitive traffic, the compromise in delivery time is worthwhile for savings in power consumption. Relay selection strategies involving which, when and where to relay need to be optimized to minimize overall energy consumption.

Cao *et al.* [110] introduced wireless relays in addition to sleep mode in BSs. It is shown that, if the energy cost of wireless relays is small enough relative to that of BSs, the system with wireless relays will outperform the one with pure BS cooperation strategy. Kolios *et al.* [145] considered moving vehicles as relaying nodes and propose a mathematical programming formulation for finding the optimal forwarding policies that minimize the weighted sum of energy, delivery delay and fixed cost of operating the BSs. The authors argue that when the traffic is more delay-tolerant, it is more beneficial to exploit the relays to migrating traffic between active and sleeping cells.

F. BS Sleep Mode and Renewable Energy Resources

Renewable energy sources such as solar and wind are not available at all times, constrained by natural condition. Therefore, it is essential to distinguish them from traditional energy sources when applying BS sleep mode techniques on a network powered by both sources. When there is a lack of power supply, BSs operated by renewable energy resources could possibly not be able to support its associated traffic and might be forced to switch off. To overcome this possible shortage, **energy harvesting** technique is proposed to exploit renewable energy sources [68], [130]. Spare energy from renewable resources is stored and used when input power from the source does not suffice. Furthermore, stored energy could be even used to maintain the coverage of sleeping conventional BSs, thus reduce (more expensive and unsustainable) energy consumption from traditional sources.

The design principle for energy harvesting is to save energy in conventional BSs, and minimize possible energy outage in renewable energy operated BSs. In this work [130], a greedy way of utilizing stored energy has been proved to be inefficient and could lead to frequent outages. Instead, dynamic programming algorithms based on the number of battery states in each BS have been discussed to optimize network performance, evaluated by a weighted combination of blocking probability and energy consumption.

G. Discussions and Summary

BS sleep mode techniques have a variety of potential applications in modern cellular networks. Certain applications have been adopted by mobile operators. Shutting down the entire BS during low traffic hours is commonly seen in industry. For example, the flagship network operator in the Caribbean region, Digicel Jamaica, has reported a energy saving of 23%, which is equivalent to a carbon footprint deduction of 1.9kt or a cost reduction of $1.4 million by adopting sleeping techniques in BSs [146].

Newer techniques such as DTX in LTE, are currently more seen in research papers than actual operations. Nevertheless, the feasibility has been proven and the technology foundations for implementation are ready. Therefore, large potential remains untapped as market share of LTE grows in the future years.

The research methodologies are not significantly different among different network standards, with the exception of techniques exclusively available in one particular standard, e.g., DTX. Traffic load is always the major concern when deciding which BSs to switch off. Accordingly, a method that has been found to be successful for one standard, may be considered for other standards.

Heterogeneous deployment is expected to be more popular in cellular networks due to denser traffic in hotspots. Therefore, research on integrating BS sleeping with heterogeneous deployment deserves to receive more attention. Applying green techniques such as BS sleeping, heterogeneous deployment, cooperative relay and energy harvesting could take advantage of each technique, e.g., heterogeneous deployment for higher spectral efficiency and cooperative relay for even further reduction of power consumption.

VI. PERFORMANCE COMPARISON

As we discussed in the previous section, there are many schemes, protocols and algorithms proposed to reduce energy consumption in cellular networks by implementing sleep mode or equivalent in BSs. While we have illustrated the performance comparison between BS sleeping and other green technologies in Section I, in this section we will compare the performances of the different approaches within the scope of BS sleeping.

A. Fixed Switch Schemes vs. Dynamic Switch Schemes

There have been several comparisons between fixed schemes, where the number of switches in a certain period of time is fixed, and dynamic schemes, where the system switches as many times as necessary based on real-time or predicted traffic information [94], [95], [119], [125], [140]. The results are generally in favor of dynamic schemes or of increasing frequency of switching operations in fixed schemes. In [119], both the centralized and distributed dynamic algorithms outperform the static switching-off scheme (1/2 or 1/3 off). In [140], the semi static sleep mode prevails in lower traffic hours while the dynamic sleep mode saves more energy under medium to high traffic. In [110], the authors argues that performance of fixed and dynamic schemes depends partly on the traffic load of the system. They show that in the coverage-limited (low traffic) region, offline fixed algorithms would be more suitable due to the constraint in coverage requirement, while in the energy-efficient (medium traffic) region, online dynamic algorithms are superior because the energy saving performance largely depends on instant traffic load.

According to [94], the amount of energy saving increases (although only marginally) as the number of switching operations per day increases. Dynamic schemes generally require more switching operations as compared to fixed schemes, especially when the traffic pattern is unpredictable and highly fluctuated. Therefore, another trade-off to consider is between more absolute energy saving in sleep mode and the cost of switching operations, which includes but is not limited to overhead, transient time, delay constraint, extra power for monitoring and switching, and impact to the operational lifetime of BSs.

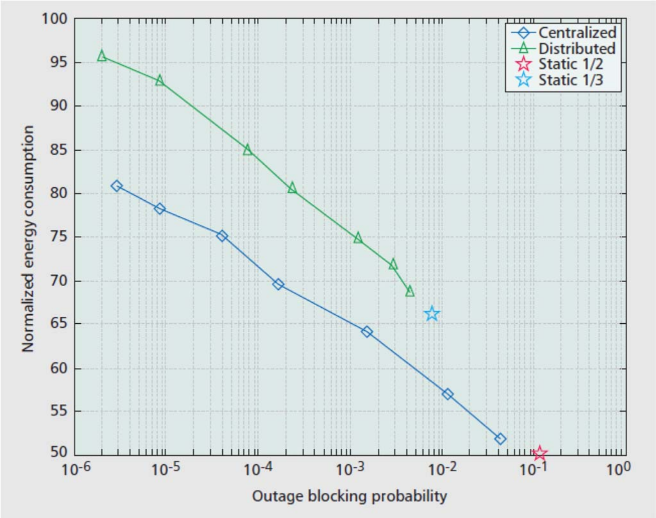


Fig. 5. Comparison of different BS sleeping algorithms (Source: [119]).

B. Centralized Switching Schemes vs. Distributed Switching Schemes

While both of the centralized and distributed switching algorithms belong to dynamic schemes, the fundamental difference between the two classes lies in which part of the network coordinates the switching operation [98], [119], [151]. In centralized switching schemes, the BSs take the coordination role. As BSs possess more network real time information, this approach is advantageous in eliminating possible coverage holes and dropouts [150]. The BSs collect feedback about channel conditions and rate requirements from the UE in the coordination stage, and then decide the UE they want to associate according to the available resources [125], [129]. In [44], the proposed scheme is actually a hierarchical centralized scheme, where a femto server with global knowledge of the network elects the leader in each cluster, and then the leader controls the on/off patterns of the members in its cluster.

In contrast, user-initiated association algorithms such as [101] can be classified as distributed schemes. In distributed switching algorithms, no coordination from the BSs is required. The UE is responsible to select the BSs they want to associate with according to the information about the network condition it possesses. It is generally believed that centralized algorithms achieve more energy saving because the BS subsystem have a more complete picture on the network condition than any single UE, which leads to more accurate switching operations. However, the extra overheads produced in the coordination stage of centralized algorithms need to be considered when assessing the holistic impact of the algorithm on the entire system. Another advantage of distributed schemes is lower outage probability under the same traffic intensity due to more BSs in active state [151]. Again, tradeoff between energy saving and QoS exists.

C. Summary

Fig. 5 is a typical figure showing the performances of fixed, centralized and distributed sleeping algorithms. Given the same outage probability, dynamic algorithm controlled centrally saves more energy than distributed algorithm, while both of the dynamic algorithms outperform static schemes. A summary of comparison among different categories of BS sleeping schemes is presented in Table V.

VII. PRACTICAL ISSUES AND AREAS FOR POTENTIAL IMPROVEMENT

As discussed in previous sections, there have been a considerable number of studies aiming at improving the energy efficiency of cellular networks by BS sleep mode techniques. While the contributions and achievements made have been substantial, certain deficiencies cannot be ignored.

A. Over-Simplified Models and Assumptions

One common problem with current research in this area is that the system, traffic or energy models are usually over-simplified and some assumptions are too rigid. Certain conditions that are unrealistic are adopted in the experiments. For example, uniform traffic distribution and arrival pattern in all cells at all times, zero or constant delays in switching operations, infinite number of switching operations in a limited period of time, energy consumption of BSs only related to the state of the system (sleep/wake), but not by other factors such as traffic load. In fact, the activity levels of both BSs and associated mobile users are limited to only two, i.e., active or sleeping (inactive) in most work. A smart phone today transmitting at different data rate would consume different amount of energy, not to mention much more complicated BSs.

The negative impact on QoS when switching some BSs to sleep mode has also been ignored in various publications. However, this must be taken into account as one can always save 100% energy by turning off all BSs without considering the deteriorated QoS. Especially in rural areas where the layouts of BSs are sparse, blocking rate will increase significantly as more BSs go asleep [94].

Another problem is most work implicitly assumes that BSs are able to alternate states between sleeping and active as frequently as possible. Although the most recent BSs have already been designed for frequently entering sleep modes, still most of the existing BSs in use today were designed foreseeing only occasional switch-on and switch-off, otherwise the failure rate of components or BSs would be increased dramatically. In this regard, the use of sleep modes for these devices might be restricted [94], [150].

Meanwhile, a number of publications also implicitly assume UE is stationary in their models. This does not seem to be the case in real mobile cellular networks, where handovers (handoff) between cells are essential [52]. Another important point which has been ignored, due to uncertainties and difficulties in estimation, is the embodied energy consumption (energy consumed in the manufacturing, installation and maintenance process of the equipment), which actually presents around 30% to 40% of total energy consumption for the lifetime of a cellular BS [12], [71]. As discussed previously, a denser BS deployment enlarges the potential saving of sleep mode schemes as more BSs can possibly be switched off under the same amount of

TABLE V
COMPARISON OF BS SLEEPING SCHEMES

Category	Complexity	Pros	Cons
Fixed scheme	Low	Simple, least number of operations	Cannot adjust switching operations according to actual traffic fluctuations
Dynamic scheme: centralized control	High	Switch optimally based on traffic variation, highest theoretical savings	Highest overhead and sniffing cost
Dynamic scheme: distributed control	Medium	Less overhead than centralized control scheme, more theoretical savings than fixed scheme	UE may not have sufficient information and power to achieve optimal switching operations

TABLE VI
COMPARISON OF MODEL ASSUMPTIONS AND REAL SCENARIOS

Models/Assumptions	Reality	References
Traffic distribution is uniform and arrival patterns are homogeneous.	Traffic load and arrival pattern varies spatially and temporally.	[93], [139], [141], [147]
Delays in switching operations are zero or constant.	The system may require variable time to respond to the switching command.	[17], [18], [148]
Transmission channel is modeled with Addictive White Gaussian Noise (AWGN).	AWGN model does not account for many practical issues such as fading and dispersion.	[149]
BSs can change states as frequently as possible.	Most BSs deployed today are designed for occasional switch-on and switch-offs only, and too frequent operations may shorten BS life	[94], [148], [150]
The number of states is finite when calculating energy consumption, e.g. active and sleep.	Energy consumption is related to a variety of factors other than sleep or active mode, e.g. carried traffic.	[10], [17], [21], [34], [39], [40], [71], [101]
UE is assumed to be fixed.	Mobile users may move between different cells while in an active call.	[52], [101], [147]
Negative impact on QoS is ignored when some of BSs are switched to sleep mode.	QoS such as blocking probability may be degraded due to switching-off of BSs, the impact needs to be considered.	[101], [104], [133], [139]
Embodied energy consumption is ignored,	Embodied energy represents around 30% to 40% of total energy consumption and needs to be taken into consideration.	[12], [71]

traffic, but on the contrary, the embodied energy of a newly deployed BS adds to the total energy. This arising trade-off averts from previous suggestions that more energy savings can be simply achieved with denser BSs deployment with reduced transmission power and enabled sleep mode. Therefore, the optimal strategy for energy saving diverts from the case where embodied energy is ignored [71], [143].

The common differences between modeling assumptions and the real world conditions are summarized in Table VI.

B. Case Study: The Effect of Traffic Load on Power Consumption

The aforementioned assumptions can lead to inaccuracies in reported energy savings. For example, the effect of traffic load is not negligible. According to Fig. 3, power consumption related to transmission (power amplifiers including feeders) constitutes more than half the amount of power consumed in a BS. The rationale for energy consumption dependence on the traffic load is that more power is needed for radio transmissions when the traffic intensity is high. In the case of LTE, around 60 percent of radio power consumption in a BS scales with traffic load as shown in Fig. 6 [152].

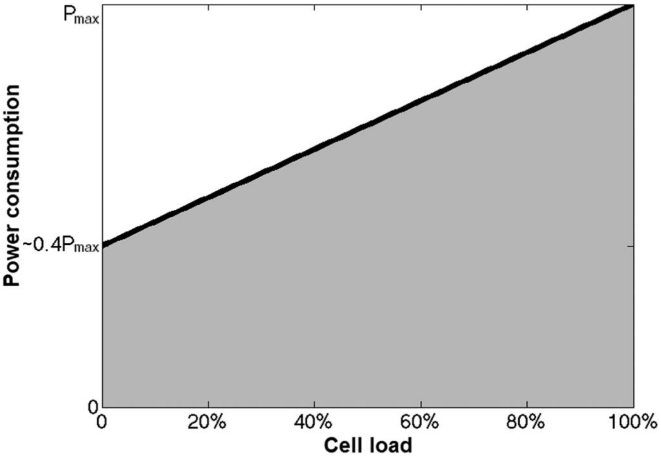


Fig. 6. Traffic load and BS power consumption [152].

In fact, the effect of traffic load on energy consumption has been acknowledged in various previous publications (e.g., [10], [17], [34], [35], [39], [40], [71], [101]), but largely ignored in modeling until more recently (e.g., [22], [87], [129], [134], [135], [153], [161]). Instead, many publications adopt a

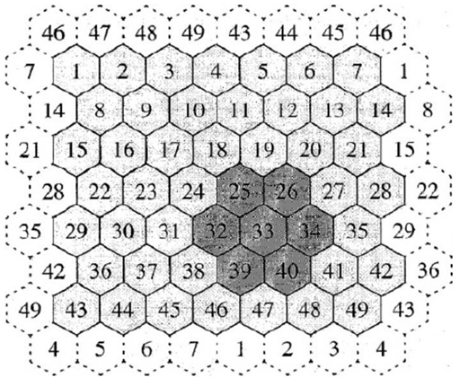


Fig. 7. 49-cell hexagonal configuration network model with wrapped-around design [156].

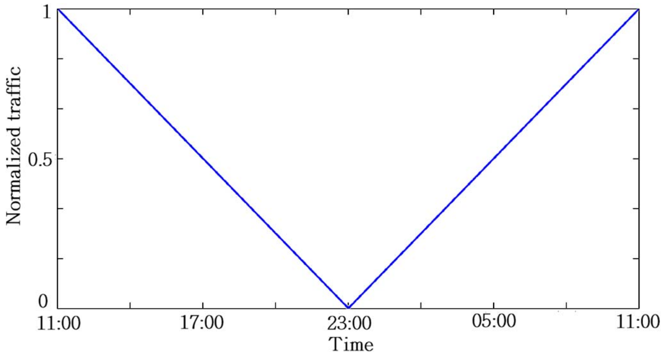


Fig. 8. Trapezoidal traffic pattern.

simple "on–off" power profile where an active BS is assumed to consume a fixed amount of energy while a sleeping BS consumes none or a quite small fraction of that amount (e.g., [93], [119]). With the increasing number of micro, pico and femto cells in the network, the increased volume of traffic and the adoption of digital power amplifiers with large peak-to-average power ratio, the traffic-dependent portion of energy consumption will become even more significant [101], [154], [155].

To illustrate this effect, we have performed a Markov Chain simulation in MATLAB based on a 49-cell hexagonal configuration network model with wrapped-around design (shown in Fig. 7) assessing the energy saving performance of dynamic and static switching schemes. The wrapped-up design eliminates the border effect so that all cells are identical. For example, cell 1 borders cells 2, 7, 8, 14, 46, and 47. To reflect user mobility, during the course of a call, it may be handed over to one of its active neighboring cells [156]. Each cell is served by a single BS.

The two traffic profiles used for simulation are an ideal trapezoidal traffic pattern shown in Fig. 8 and a real traffic profile shown in Fig. 9 derived from an Italian broadband service provider as provided in [93].

The two switch-off schemes we used are a scheme in [93] which statically turns off 6 cells in a 7-cell cluster off and a dynamic algorithm similar to the one in [140] which determines the on/off status of each BS based on real-time traffic. Under the dynamic scheme, when the number of users in a BS is under a certain threshold and at least one of its neighboring cells is active, the lightly-loaded BS will be switched off and its customers will be handed over to one of the active neighbors.

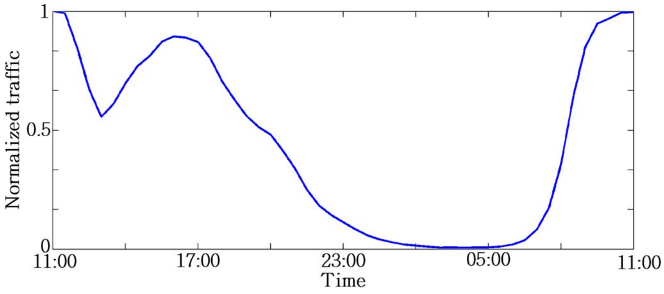


Fig. 9. Real traffic pattern (Source: [93]).

TABLE VII
PARAMETERS FOR 49-CELL NETWORK SIMULATION

Parameter	Value
Arrival rate (λ)	Peaked at 30 arrivals/minute, following real traffic patterns [93]
Departure rate (μ)	4 departures/minute
Handover rate (δ)	1 handover/minute
Power consumption of a BS in sleep mode (P_s)	94.8W [10]
Power consumption of a BS under full load (P_f)	1430W [10]
Number of available channels in a BS (N)	20
Minimum time interval between two switching operations	10 minutes [150]

The threshold in the dynamic algorithm is tuned to maintain similar blocking probability as the fixed scheme. After much trial and error, we set the threshold to 30% of the maximum capacity of each cell such that blocking probabilities of both schemes are around 0.5%. Our aim, as stated previously, is to compare the cases with and without consideration to the impact of traffic load on energy consumption. Refer back to the discussions in Section VI-A, dynamically schemes are generally believed to significantly outperform static schemes in most cases.

As existing studies assume different proportion (denoted by α) of traffic-dependent power in overall power consumption, here we present results where traffic-dependent power is assumed to comprise between 0–50%. Other parameters for the simulation are shown in Table VII. Note that they are also necessary parameters to perform an acceptable analysis based on queuing theories. As our focus here is to investigate the traffic load effect, some other factors such as transient periods in switching operations and path loss are ignored.

Power consumption in cell i is calculated as:

$$P_i = P_s + 1_A(x_i)\left(\alpha(P_f - P_s)\frac{N_{ci}}{N} + (1-\alpha)(P_f - P_s)\right), \tag{13}$$

$$1_A(x_i) = \begin{cases} 1 & \text{if } cell_i \text{ is active,} \\ 0 & \text{if } cell_i \text{ is sleeping;} \end{cases} \tag{14}$$

where N_{ci} is the current number of customers in cell i.

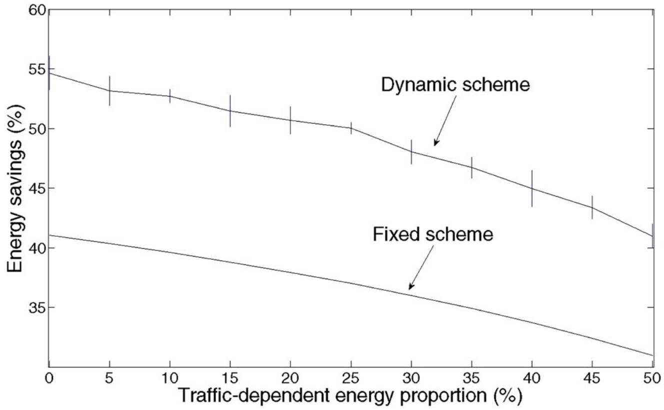


Fig. 10. Effect of traffic load on energy savings of fixed and dynamic switch-off schemes on real traffic profile.

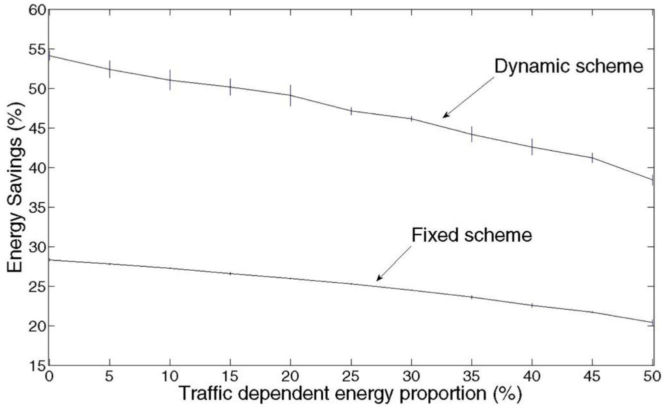


Fig. 11. Effect of traffic load on energy savings of fixed and dynamic switch-off schemes on ideal trapezoidal traffic profile.

For the whole system, power consumption is simply the sum of power consumption in all 49 cells:

$$P_{system} = \sum_{i=1}^{49} P_i. \tag{15}$$

We present our simulation results in Figs. 10 and 11. The figures show reduction in energy saving of all cases when the proportion of traffic dependent power increases. An intuitive explanation for the trend is that BSs with low traffic are the ones to be switched off, therefore, as traffic accounts for more power consumption, the benefit of switching off lightly loaded BSs diminishes.

Another observation we can make is that when using real traffic traces, the difference in the savings between dynamic and fixed switch-off schemes somehow depends on how much the model considers the dependency of energy consumption on traffic load. As shown in the figures, the gap significantly narrows as energy consumption relies more on traffic load. Therefore, the conclusion reached in some papers (e.g., [119]) that dynamic schemes are far better than fixed schemes is questionable without considering the effect of traffic on energy consumption. We can reasonably believe that, as more rigid assumptions in Table VI are relaxed, the results presented in more papers may be subject to further review.

C. Improvements Made So Far

Efforts have been made to bridge the gap between theoretical models and practical situations. For example, traffic estimation and prediction techniques in BSs were included as future work in [147] and [151] and have been discussed in [95]. The feasibility and approach for adapting users to cell associations to actual traffic were discussed in [101]. Bousia *et al.* [135] acknowledged that average distance of associated users as an additional factor to traffic load when selecting eNBs to be switched off. User activity has been modeled as a uniform [0,1] variable rather than simply binary states as in [21].

Marsan *et al.* [93] considered the "introduction of sleep modes in the operations of BSs one of the most promising approaches" to reduce energy consumption of mobile cellular networks, but also acknowledge existence of discrepancies between existing research and operational networks in practice. They discussed in their paper the effect of the transient periods when a BS is waking up from sleep to active mode, or the other way around (i.e., the transition cannot be completely instantaneous). The duration and impact of the transient periods were studied in the paper based on theoretical structures as well as a real case in Bologna, Italy. The authors concluded that the transient periods are fairly short (of the order of 1 minute at most) and thus do not reduce significantly the energy savings of BS sleep mode techniques. They also suggested the sleep modes could be pushed even more aggressively than in the present proposals, that is, switching off BSs for shorter periods, such as, one or several quarters of an hour (current research usually suggest one hour or more).

Han *et al.* [114] included QoS guarantee and traffic-dependent energy consumption in their study. The result shows that, if QoS needs to be maintained above or equal to the level in the case where all BSs are active and under peak traffic, switching off more BSs will not always result in more energy saving as extra transmit power required to maintain the QoS level may offset the energy saved by switching off more BSs since the signal strength attenuates faster with increasing distance.

VIII. THE WAY FORWARD

Apart from improvement on the authenticity of the models discussed in the previous section, there are a number of other challenges that need to be carefully tackled in this research field. One important point is that the state-of-art in the development of cellular networks is moving fast. Therefore, green technologies need to catch up with such evolvement. The discussions on energy efficient metrics in Section III and heterogeneous networks in Section V are examples of areas that researchers need to pay more attention to.

A crucial development, namely the newest generation of cellular networks, 5G, is on track to be implemented in the near future [157]. We have discussed sleep mode on 4G and previous generations of cellular networks in Section IV. The revolutionized new features in 5G, such as massive MIMO, group cooperative arrays and pervasive networks, will significantly improve QoS but also consume much larger amount of energy. The significant differences in network architecture pose new challenges for research on energy saving approaches including sleep mode. Methods based on spectrum management [158] and renewable energy resources [157] have been proposed. For BS sleep mode, it is acknowledged the reduced symbol durations and duty cycle could increase the flexibility in implementation [159]. However, no specific research has been done at the time of writing to the best of our knowledge. We believe that sleep mode in 5G cellular networks could be a research area with many innovative ideas in the foreseeable future.

On the other hand, as mentioned before, it is possible to adopt different green technologies together in cellular networks. Aggregated savings could probably be achieved because the technologies are not conflicting. Meanwhile, by implementing other techniques such as adjustments in antenna tilt and height, it is possible to offset the degradation in QoS due to sleeping BSs [134]. Incorporating different technologies may require significant effort by researchers with a wide range of backgrounds, but the benefit will justify the effort. For example, Chiaraviglio *et al.* [153] considered three network planning strategies: the first one minimizes the number of transmitters (TX), the second one minimizes the power consumption (MP), while the last one is the hybrid strategy (H) combining the previous two strategies. While the TX strategy effectively lowers the capital expenditure (CAPEX) for mobile operator in the BS planning stage, the MP strategy minimizes the operating expense (OPEX) by turning under-utilized BSs into sleep mode to reduce energy consumption. The result shows energy savings between 11% and 28% are achievable even for already energy-efficiency-optimized BSs deployment. Therefore, by adopting the H strategy, the total expenditure of the mobile operator could be significantly reduced.

IX. CONCLUDING REMARKS

This paper has surveyed recent advancement in the research of BS sleep mode techniques in cellular networks, which is one of the major methods to reduce total energy consumption. Increasing energy consumption has been a major concern and many studies on energy saving strategies in networking and telecommunication sectors have been published after the first work concerning the energy issue in the mainstream networking area published in 2003, which refers to the greening of the Internet [160]. The fact that cellular networks were designed with the primary goal of maximum throughput and coverage indicates significant gains are possible by effective power management schemes. It is now widely accepted that the energy consumption reduction in cellular networks will bring both operating profit for mobile operators and environmental benefit for the planet. The importance of this area has been therefore quickly realized and it is now a popular topic because of its huge environmental, economic, financial and social impacts. Various technologies to achieve the goal, as well as the broad scope of knowledge required at different stage of implementation, make it open to researchers with diverse background.

For BS sleep mode techniques, the main saving comes from the fixed part of energy consumption in under-utilized BSs. The potential for energy saving is large in areas where the traffic is highly variant and relative low as compared with full capacity of BS, and where BSs are densely deployed. Also, the larger the fixed proportion of energy consumption in BSs is (the case in macro BSs), the larger amount of saving can be possibly attained.

In summary, the sleep mode technologies as well as the whole green cellular network are promising areas of research. It will probably remain a popular research topic for the coming years, since there are bright prospective as well as issues waiting to be solved.

REFERENCES

[1] GreenTouch. [Online]. Available: http://www.greentouch.org/

[2] Int. Telecommun. Union, “ITU Green Standards Week,” Geneva, Switzerland, Sep. 2011. [Online]. Available: http://www.itu.int/ITU-T/climatechange/gsw/201102/index.html

[3] G. Fettweis and E. Zimmermann, “ICT energy consumption—Trends and challenges,” in *Proc. 11th Int. Symp. Wireless Pers. Multimedia Commun.*, Lapland, Finland, Sep. 2008, pp. 1–4.

[4] O. Blume, H. Eckhardt, S. Klein, E. Kuehn, and W. M. Wajda, “Energy savings in mobile networks based on adaptation to traffic statistics,” *Bell Labs Tech. J.*, vol. 15, no. 2, pp. 77–94, Sep. 2010.

[5] Z. Hasan, H. Boostanimehr, and V. K. Bhargava, “Green cellular networks: A survey, some research issues and challenges,” *IEEE Commun. Surveys Tuts.*, vol. 13, no. 4, pp. 524–540, 2011.

[6] Y. Zhang, P. Chowdhury, M. Tornatore, and B. Mukherjee, “Energy efficiency in telecom optical networks,” *IEEE Commun. Surveys Tuts.*, vol. 12, no. 4, pp. 441–458, 2010.

[7] A. P. Bianzino, C. Chaudet, D. Rossi, and J. Rougier, “A survey of green networking research,” *IEEE Commun. Surveys Tuts.*, vol. 14, no. 1, pp. 3–20, 2012.

[8] D. Kimball *et al.*, “High-efficiency WCDMA envelope tracking base-station amplifier implemented with GaAs HVHBTs,” *IEEE J. Solid-State Circuits*, vol. 44, no. 10, pp. 2629–2639, Oct. 2009.

[9] K. Cho, J. Kim, and S. Stapleton, “A highly efficient Doherty feedforward linear power amplifier for W-CDMA base station applications,” *IEEE Trans. Microw. Theory Techn.*, vol. 53, no. 1, pp. 292–300, Jan. 2005.

[10] O. Arnold, F. Richter, G. Fettweis, and O. Blume, “Power consumption modelling of different base station types in heterogeneous cellular networks,” in *Proc. Future Netw. Mobile Summit*, Dresden, Germany, Jun. 2010, pp. 1–8.

[11] Y. Wei, J. Staudinger, and M. Miller, “High efficiency linear GaAs MMIC amplifier for wireless base station and femto cell applications,” in *Proc. IEEE Topical Conf. PAWR*, Tempe, AZ, USA, Jan. 2012, pp. 49–52.

[12] C. Han *et al.*, “Green radio: Radio techniques to enable energy-efficient wireless networks,” *IEEE Commun. Mag.*, vol. 49, no. 6, pp. 46–54, Jun. 2011.

[13] H. Claussen, L. Ho, and F. Pivit, “Effects of joint macrocell and residential picocell deployment on the network energy efficiency,” in *Proc. IEEE 19th Int. Symp. PIMRC*, Sep. 2008, pp. 1–6.

[14] TriQuint, “RF Power Amplifier Module: TGA2450-SM.” [Online]. Available: http://store.triquint.com/ProductDetail/TGA2450-SM-TriQuint-Semiconductor-Inc/472292/

[15] J. Wu, S. Zhou, and Z. Niu, “Traffic-aware base station sleeping control and power matching for energy–delay tradeoffs in green cellular networks,” *IEEE Trans. Wireless Commun.*, vol. 12, no. 8, pp. 4196–4209, Aug. 2013.

[16] J. Louhi, “Energy efficiency of modern cellular base stations,” in *Proc. 29th INTELEC*, Sep./Oct. 2007, pp. 475–476.

[17] P. Frenger, P. Moberg, J. Malmodin, Y. Jading, and I. Godor, “Reducing energy consumption in LTE with cell DTX,” in *Proc. IEEE 73rd VTC Spring*, Linkoping, Sweden, May 2011, pp. 1–5.

[18] I. Ashraf, F. Boccardi, and L. Ho, “Sleep mode techniques for small cell deployments,” *IEEE Commun. Mag.*, vol. 49, no. 8, pp. 72–79, Aug. 2011.

[19] G. Micallef, P. Mogensen, and H. Sch, “Cell size breathing and possibilities to introduce cell sleep mode,” in *Proc. EW Conf.*, Lucca, Italy, Apr. 2010, pp. 111–115.

[20] M. A. Marsan, L. Chiaraviglio, D. Ciullo, and M. Meo, “On the effectiveness of single and multiple base station sleep modes in cellular networks,” *Comput. Netw.*, vol. 57, no. 17, pp. 3276–3290, Dec. 2013.

[21] Y. S. Soh, T. Quek, M. Kountouris, and H. Shin, "Energy efficient heterogeneous cellular networks," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 5, pp. 840–850, May 2013.

[22] H. Tabassum, U. Siddique, E. Hossain, and M. Hossain, "Downlink performance of cellular systems with base station sleeping, user association, scheduling," *IEEE Trans. Wireless Commun.*, vol. 13, no. 10, pp. 5752–5767, Oct. 2014.

[23] S. Cui, A. Goldsmith, and A. Bahai, "Energy-efficiency of MIMO and cooperative MIMO techniques in sensor networks," *IEEE J. Sel. Areas Commun.*, vol. 22, no. 6, pp. 1089–1098, Aug. 2004.

[24] G. Li *et al.*, "Energy-efficient wireless communications: Tutorial, survey and open issues," *IEEE Wireless Commun.*, vol. 18, no. 6, pp. 28–35, Dec. 2011.

[25] M. Butt *et al.*, "On the energy–bandwidth trade-off in green wireless networks: System level results," in *Proc. 1st IEEE ICCC*, Beijing, China, Aug. 2012, pp. 91–95.

[26] Y. Zou, J. Zhu, and R. Zhang, "Exploiting network cooperation in green wireless communication," *IEEE Trans. Commun.*, vol. 61, no. 3, pp. 999–1010, Mar. 2013.

[27] C. Xiong, G. Li, S. Zhang, Y. Chen, and S. Xu, "Energy- and spectral-efficiency tradeoff in downlink OFDMA networks," *IEEE Trans. Wireless Commun.*, vol. 10, no. 11, pp. 3874–3886, Nov. 2011.

[28] C. Xiong, G. Y. Li, S. Zhang, Y. Chen, and S. Xu, "Energy-efficient resource allocation in OFDMA networks," *IEEE Trans. Commun.*, vol. 60, no. 12, pp. 3767–3778, Dec. 2012.

[29] D. Feng *et al.*, "A survey of energy-efficient wireless communications," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 1, pp. 167–178, 2013.

[30] A. Attar, H. Li, and V. C. M. Leung, "Green last mile: How fiber-connected massively distributed antenna systems can save energy," *IEEE Wireless Commun.*, vol. 18, no. 5, pp. 66–74, Oct. 2011.

[31] Y. Zou, Y.-D. Yao, and B. Zheng, "Opportunistic distributed space–time coding for decode-and-forward cooperation systems," *IEEE Trans. Signal Process.*, vol. 60, no. 4, pp. 1766–1781, Apr. 2012.

[32] H. ElSawy, E. Hossain, and M. Haenggi, "Stochastic geometry for modeling, analysis, design of multi-tier and cognitive cellular wireless networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 3, pp. 996–1019, 2013.

[33] M. Li, P. Li, X. Huang, Y. Fang, and S. Glisic, "Energy consumption optimization for multihop cognitive cellular networks," *IEEE Trans. Mobile Comput.*, vol. 14, no. 2, pp. 358–372, Feb. 2015.

[34] Y. Chen, S. Zhang, S. Xu, and G. Y. Li, "Fundamental trade-offs on green wireless networks," *IEEE Commun. Mag.*, vol. 49, no. 6, pp. 30–37, Jun. 2011.

[35] G. He, S. Zhang, Y. Chen, and S. Xu, "Fundamental tradeoffs and evaluation methodology for future green wireless networks," in *Proc. 1st IEEE ICCC*, 2012, pp. 74–78.

[36] V. Chandrasekhar, J. Andrews, and A. Gatherer, "Femtocell networks: A survey," *IEEE Commun. Mag.*, vol. 46, no. 9, pp. 59–67, Sep. 2008.

[37] A. R. Ekti, M. Z. Shakir, E. Serpedin, and K. A. Qaraqe, "Downlink power consumption of HetNets based on the probabilistic traffic model of mobile users," in *Proc. IEEE 24th Int. Symp. PIMRC*, Sep. 2013, pp. 2797–2802.

[38] F. Richter, A. Tehske, and G. Fettweis, "Energy efficiency aspects of base station deployment strategies for cellular networks," in *Proc. IEEE 70th VTC Fall*, Sep. 2009, pp. 1–5.

[39] W. Guo and T. O'Farrell, "Green cellular network: Deployment solutions, sensitivity and tradeoffs," in *Proc. WiAd*, London, U.K., Jun. 2011, pp. 42–47.

[40] H. Claussen, I. Ashraf, and L. Ho, "Dynamic idle mode procedures for femtocells," *Bell Labs Tech. J.*, vol. 15, no. 2, pp. 95–116, Sep. 2010.

[41] S. Bhaumik, G. Narlikar, S. Chattopadhyay, and S. Kanugovi, "Breathe to stay cool: Adjusting cell sizes to reduce energy consumption," in *Proc. 1st ACM SIGCOMM Workshop Green Netw.*, Aug./Sep. 2010, pp. 41–46.

[42] C. Li, J. Zhang, and K. Letaief, "Energy efficiency analysis of small cell networks," in *Proc. IEEE ICC*, 2013, pp. 4404–4408.

[43] A. Mukherjee, S. Bhattacherjee, S. Pal, and D. De, "Femtocell based green power consumption methods for mobile network," *Comput. Netw.*, vol. 57, no. 1, pp. 162–178, Jan. 2013. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1389128612003295

[44] W. Li, W. Zheng, Y. Xue, and X. Wen, "Clustering based power saving algorithm for self-organized sleep mode in femtocell networks," in *Proc. 15th Int. Symp. WPMC*, 2012, pp. 379–383.

[45] I. H. Rowlands, P. Parker, and D. Scott, "Consumer perceptions of "green power"," *J. Consum. Marketing*, vol. 19, no. 2, pp. 112–129, 2002.

[46] Y.-K. Chia, S. Sun, and R. Zhang, "Energy cooperation in cellular networks with renewable powered base stations," in *Proc. IEEE WCNC*, Apr. 2013, pp. 2542–2547.

[47] Y. Chan, "China's Huawei to supply solar-powered base stations to Bangladesh," Business Green, London, U.K., Aug. 2009. [Online]. Available: http://www.businessgreen.com/bg/news/1802444/chinas-huawei-supply-solar-powered-base-stations-bangladesh

[48] C. Okoye, "Airtel base stations to be solar powered," Daily Times Nigeria, Lagos, Nigeria, Dec. 2011. [Online]. Available: http://dailytimes.com.ng/article/airtel-base-stations-be-solar-powered

[49] X. Wang, A. V. Vasilakos, M. Chen, Y. Liu, and T. T. Kwon, "A survey of green mobile networks: Opportunities and challenges," *Mobile Netw. Appl.*, vol. 17, no. 1, pp. 4–20, Feb. 2012.

[50] M. Ismail, W. Zhuang, E. Serpedin, K. Qaraqe, "A survey on green mobile networking: From the perspectives of network operators and mobile users," *IEEE Commun. Surveys Tuts*, to be published. [Online]. Available: http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=6949027

[51] GSMA, "Community power: Using mobile to extend the grid," London, U.K., Jan. 2010. [Online]. Available: http://www.gsma.com/mobilefordevelopment/wp-content/uploads/2012/05/Community-Power-Using-Mobile-to-Extend-the-Grid-January-2010.pdf

[52] D. Everitt, "Traffic engineering of the radio interface for cellular mobile networks," *Proc. IEEE*, vol. 82, no. 9, pp. 1371–1382, Sep. 1994.

[53] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, "NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey," *Comput. Netw.*, vol. 50, no. 13, pp. 2127–2159, Sep. 2006. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1389128606001009

[54] Eur. Commission Release, "Digital agenda: Global tech sector measures its carbon footprint," Brussels, Belgium, Mar. 2013. [Online]. Available: http://europa.eu/rapid/press-release_IP-13-231_en.htm

[55] T. Langedem, "Reducing the carbon footprint of ICT devices, platforms and networks," GreenTouch, Amsterdam, The Netherlands, Nov. 2012. [Online]. Available: http://www.greentouch.org/uploads/documents/Van%20Landegem%20GeSI%20Reducing%20Carbon%20Footprint%20May%202012.pdf

[56] Energy Aware Radio and neTwork tecHnologies (EARTH). [Online]. Available: https://www.ict-earth.eu/

[57] J. Manner, M. Luoma, J. Ott, and J. Hamalainen, "Mobile networks unplugged," in *Proc. 1st Int. Conf. Energy-Efficient Comput. Netw.*, 2010, pp. 71–74.

[58] GSMA, "Mobile's green manifesto," London, U.K., 2012. [Online]. Available: http://www.gsma.com/publicpolicy/wp-content/uploads/2012/06/Green-Manifesto-2012.pdf

[59] L. Correia, "Challenges and enabling technologies for energy aware mobile radio networks," *IEEE Commun. Mag.*, vol. 48, no. 11, pp. 66–72, Nov. 2010.

[60] Energy Information Administration Brochures, "Greenhouse gases, climate change, energy," May 2008. [Online]. Available: http://www.eia.gov/oiaf/1605/ggccebro/chapter1.html

[61] M. Shakir *et al.*, "Green heterogeneous small-cell networks: Toward reducing the CO_2 emissions of mobile communications industry using uplink power adaptation," *IEEE Commun. Mag.*, vol. 51, no. 6, pp. 52–61, Jun. 2013.

[62] Int. Telecommun. Union, "Key global telecom indicators for the world telecommunication service sector," Geneva, Switzerland, Nov. 2011. [Online]. Available http://www.itu.int/ITU-D/ict/statistics/at_glance/KeyTelecom.html

[63] MobiThinking, "Global mobile statistics." [Online]. Available: http://mobithinking.com/mobile-marketing-tools/latest-mobile-stats

[64] G. Auer *et al.*, "Enablers for energy efficient wireless networks," in *Proc. IEEE 72nd VTC-Fall*, Sep. 2010, pp. 1–5.

[65] T. Chen, H. Kin, and Y. Yang, "Energy efficiency metrics for green wireless communications," in *Proc. Int. Conf. WCSP*, Oct. 2010, pp. 1–6.

[66] M. Etoh, T. Ohya, and Y. Nakayama, "Energy consumption issues on mobile network systems," in *Proc. Int. SAINT*, Turku, Jul. 2008, pp. 365–368.

[67] M. Hoque, M. Siekkinen, and J. Nurminen, "Energy efficient multimedia streaming to mobile devices 2014: A survey," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 1, pp. 579–597, 2014.

[68] H. Chen, Y. Li, J. Rebelatto, B. Filho, and B. Vucetic, "Harvest-then-cooperate: Wireless-powered cooperative communications," *IEEE Trans. Signal Process.*, vol. 63, no. 7, pp. 1700–1711, Apr. 2015.

[69] A. Koc, S. Jha, R. Vannithamby, and M. TORLAK, "Device power saving and latency optimization in LTE-A networks through DRX configuration," *IEEE Trans. Wireless Commun.*, vol. 13, no. 5, pp. 2614–2625, May 2014.

[70] M. Gupta, S. Jha, A. Koc, and R. Vannithamby, "Energy impact of emerging mobile Internet applications on LTE networks: Issues and solutions," *IEEE Commun. Mag.*, vol. 51, no. 2, pp. 90–97, Feb. 2013.

[71] I. Humar *et al.*, "Rethinking energy efficiency models of cellular networks with embodied energy," *IEEE Netw.*, vol. 25, no. 2, pp. 40–49, Mar./Apr. 2011.

[72] S. Taylor, R. Klemann, I. Verjee, and P. Ford, "Digging for the new mobile gold: The next generation of mobile monetization," White Paper, May 2014. [Online]. Available: ttp://www.cisco.com/c/en/us/solutions/collateral/service-provider/mobile-Internet/white-paper-c11-731757.pdf

[73] PCCW, "Environmental policy." [Online]. Available: http://www.pccw.com/About+PCCW/Corporate+Social+Responsibility/Environment/Environmental+Policy

[74] Vodafone, "Carbon and energy." [Online]. Available: http://www.vodafone.co.uk/our-responsibilities/our-environment/carbon-and-energy/

[75] A. J. Fehske, G. Fettweis, J. Malmodin, and G. Biczok, "The global footprint of mobile communications: The ecological and economic perspective," *IEEE Commun. Mag.*, vol. 49, no. 8, pp. 55–62, Aug. 2011.

[76] W. Nordhaus, "To slow or not to slow: The economics of the greenhouse effect," *Econ. J.*, vol. 101, no. 407, pp. 920–937, Jul. 1991.

[77] 3rd Generation Partnership Project (3GPP). [Online]. Available: http://www.3gpp.org/

[78] OPREA-Net, "Optimising power efficiency in mobile radio networks project." [Online]. Available: http://opera-net.org/

[79] Cognitive Radio and Cooperative Strategies for POWER saving in multi-standard wireless devices (C2POWER). [Online]. Available: http://www.ict-c2power.eu/

[80] Wireless@KTH, "eWin: Energy-efficient wireless networking." [Online]. Available: http://www.wireless.kth.se/research/projects/19-ewin

[81] Towards Real Energy-efficient Network Design (TREND). [Online]. Available: http://www.fp7-trend.eu/

[82] C. Bontu, "DRX mechanism for power saving in LTE," *IEEE Commun. Mag.*, vol. 47, no. 6, pp. 48–55, Jun. 2009.

[83] "The energy consumption rating initiative, energy efficiency for network equipment: Two steps beyond greenwashing (white paper)," Aug. 2008. [Online]. Available: http://www.ecrinitiative.org/pdfs/ECR-TSBG_1_0.pdf

[84] H. Kwon and T. Birdsall, "Channel capacity in bits per joule," *IEEE J. Ocean. Eng.*, vol. 11, no. 1, pp. 97–99, Jan. 1986.

[85] V. Rodoplu and T. Meng, "Bits-per-joule capacity of energy-limited wireless networks," *IEEE Trans. Wireless Commun.*, vol. 6, no. 3, pp. 857–865, Mar. 2007.

[86] A. J. Fehske, P. Marsch, and P. Fettweis, "Bit per joule efficiency of cooperating base stations in cellular networks," in *Proc. IEEE GC Wkshps*, Dresden, Germany, Dec. 2010, pp. 1406–1411.

[87] X. Guo, S. Zhou, Z. Niu, and P. Kumar, "Optimal wake-up mechanism for single base station with sleep mode," in *Proc. 25th ITC*, Sep. 2013, pp. 1–8.

[88] B. Badic, T. O'Farrell, P. Loskot, and J. He, "Energy efficient radio access architectures for green radio: Large versus small cell size deployment," in *Proc. IEEE 70th VTC-Fall*, Anchorage, AK, USA, Sep. 2009, pp. 1–5.

[89] C. He, B. Sheng, P. Zhu, and X. You, "Energy efficiency and spectral efficiency tradeoff in downlink distributed antenna systems," *IEEE Wireless Commun. Lett.*, vol. 1, no. 3, pp. 153–156, Jun. 2012.

[90] S. Rivoire, M. Shah, P. Ranganthan, and C. Kozyrakis, "JouleSort: A balanced energy efficiency benchmark," in *Proc. SIGMOD*, Beijing, China, Jun. 2007, pp. 365–376.

[91] EARTH, "EARTH Deliverable D2.4 Aware Radio Netw. Technol., Most suitable efficiency metrics and utility functions," Jan. 2012. [Online]. Available: https://bscw.ict-earth.eu/pub/bscw.cgi/d70454/EARTH_WP2_D2.4.pdf

[92] A. P. Bianzino, A. K. Raju, and D. Rossi, "Apple-to-apple: A framework analysis for energy-efficiency in networks," *ACM SIGMETRICS Perform. Eval. Rev.*, vol. 38, no. 3, pp. 81–85, Dec. 2010.

[93] M. A. Marsan, L. Chiaraviglio, D. Ciullo, and M. Meo, "Optimal energy savings in cellular access networks," in *Proc. IEEE ICC Workshops*, Dresden, Germany, Jun. 2009, pp. 1–5.

[94] M. Marsan, L. Chiaraviglio, D. Ciullo, and M. Meo, "Multiple daily base station switch-offs in cellular networks," in *Proc. 4th ICCE*, Hue, Vietnam, Aug. 2012, pp. 245–250.

[95] S. Morosi, P. Piunti, and E. Del Re, "Improving cellular network energy efficiency by joint management of sleep mode and transmission power," in *Proc. 24th TIWDC—Green ICT*, Sep. 2013, pp. 1–6.

[96] Eur. Telecommun. Standard Inst., "Environmental engineering (EE) energy efficiency of wireless access network equipment," Sophia-Antipolis Cedex, France, ETSI TS 102 706-v 1.1.1, Aug. 2009.

[97] M. Parker, S. Nagraj, and S. Walker, "Absolute energy efficiency metric for carbon footprint resource management and network optimisation," in *Proc. Int. Conf. Clean Elect. Power*, Capri, Italy, Jun. 2009, pp. 111–116.

[98] K. Samdanis, D. Kutscher, and M. Brunner, "Self-organized energy efficient cellular networks," in *Proc. 21st Annu. IEEE Int. Symp. Pers., Indoor Mobile Radio Commun.*, Istanbul, Turkey, Sep. 2010, pp. 1665–1670.

[99] L. Zhang, H.-C. Yang, and M. Hasna, "Generalized area spectral efficiency: An effective performance metric for green wireless communications," *IEEE Trans. Commun.*, vol. 62, no. 2, pp. 747–757, Feb. 2014.

[100] H. Tabassum, M. Shakir, and M. Alouini, "Area green efficiency (AGE) of two tier heterogeneous cellular networks," in *Proc. IEEE GC Wkshps*, Dec. 2012, pp. 529–534.

[101] K. Dufkova, M. Bjelica, B. Moon, L. Kencl, and J.-Y. Le Boudec, "Energy savings for cellular network with evaluation of impact on data traffic performance," in *Proc. EW Conf.*, Apr. 2010, pp. 916–923.

[102] L. Saker and S. Elayoubi, "Sleep mode implementation issues in green base stations," in *Proc. IEEE 21st Int. Symp. PIMRC*, Istanbul, Turkey, Sep. 2010, pp. 1683–1688.

[103] S. Elayoubi, L. Saker, and T. Chahed, "Optimal control for base station sleep mode in energy efficient radio access networks," in *Proc. IEEE INFOCOM*, Shanghai, China, Apr. 2011, pp. 106–110.

[104] Z. Niu, J. Zhang, X. Guo, and S. Zhou, "On energy–delay tradeoff in base station sleep mode operation," in *Proc. IEEE ICCS*, Singapore, Nov. 2012, pp. 235–239.

[105] K. Son, H. Kim, Y. Yi, and B. Krishnamachari, "Base station operation and user association mechanisms for energy–delay tradeoffs in green cellular networks," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 8, pp. 1525–1536, Sep. 2011.

[106] K. Pentikosis, "In search of energy-efficient mobile networking," *IEEE Commun. Mag.*, vol. 48, no. 1, pp. 95–103, Jan. 2010.

[107] Y. Ko, K. Lee, and T. Nandagopal, "CAPS: A peer data sharing system for load mitigation in cellular data networks," in *Proc. IEEE GLOBECOM*, Dec. 2003, vol. 2, pp. 656–660.

[108] Alcatel-Lucent, "9900 wireless network guardian," White paper, Aug. 2012. [Online]. Available: http://www3.alcatel-lucent.com/wps/DocumentStreamerServlet?LMSG_CABINET=Docs_and_Resource_Ctr&LMSG_CONTENT_FILE=White_PapersGuardian_EN_Tech_WhitePaper.pdf

[109] C. Peng, S.-B. Lee, S. Lu, H. Luo, and H. Li, "Traffic-driven power saving in operational 3G cellular networks," in *Proc. 17th Annu. Int. Conf. Mobile Comput. Netw.*, Las Vegas, NV, USA, 2011, pp. 121–132.

[110] D. Cao, S. Zhou, C. Zhang, and Z. Niu, "Energy saving performance comparison of coordinated multi-point transmission and wireless relaying," in *Proc. IEEE GLOBECOM*, Miami, FL, USA, Dec. 2010, pp. 1–5.

[111] L. Suarez, L. Nuaymi, and J. Bonnin, "An overview and classification of research approaches in green wireless networks," *EURASIP J. Wireless Commun. Netw.*, vol. 142, pp. 1–18, Apr. 2012.

[112] Y. Zhang and A. Arvidsson, "Understanding the characteristics of cellular data traffic," in *Proc. ACM SIGCOMM Workshop Cellular Netw., Oper., Challenges, Future Des.*, 2012, pp. 13–18.

[113] G. Wang, C. Guo, S. Wang, and C. Feng, "A traffic prediction based sleeping mechanism with low complexity in femtocell networks," in *Proc. IEEE ICC*, Jun. 2013, pp. 560–565.

[114] F. Han, Z. Safar, W. Lin, Y. Chen, and K. Liu, "Energy-efficient cellular network operation via base station cooperation," in *Proc. IEEE ICC*, Ottawa, ON, Canada, Jun. 2012, pp. 4374–4378.

[115] 3rd Generation Partnership Project, "3GPP Specification: 3GPP TS 32.521," Telecommunication management; Self-Organizing Networks (SON) Policy Network Resource Model (NRM) Integration Reference Point (IRP); requirements, Cedex, France, 2012. [Online]. Available: http://www.3gpp.org/ftp/Specs/html-info/32521.htm

[116] Nokia-Siemens Networks, "Self-Organizing Network (SON): Introducing the Nokia Siemens SON Suite—An efficient, future-platform for SON, Espoo, Finland. [Online]. Available: http://www.nokiasiemensnetworks.com

[117] M. Hossain, K. Munasinghe, and A. Jamalipour, "Toward self-organizing sectorization of LTE eNBs for energy efficient network operation under QoS constraints," in *Proc. IEEE WCNC*, Shanghai, China, Apr. 2013, pp. 1279–1284.

[118] L. Xu, Y. Chen, and Y. Gao, "Self-organizing load balancing for relay based cellular networks," in *Proc. IEEE 10th Int. Conf. CIT*, Bradford, U.K., Jun. 2010, pp. 791–796.

[119] Z. Niu, Y. Wu, J. Gong, and Z. Yang, "Cell zooming for cost-efficient green cellular networks," *IEEE Commun. Mag.*, vol. 48, no. 11, pp. 74–79, Nov. 2010.

[120] A. Baumgartner and T. Bauschert, "Greening cellular radio access networks: A numerical method for the selection of detachable base stations in low traffic scenarios," in *Proc. 24th TIWDC—Green ICT*, Sep. 2013, pp. 1–6.

[121] R. Balasubramaniam, S. Nagaraj, M. Sarkar, C. Paolini, and P. Khaitan, "Cell zooming for power efficient base station operation," in *Proc. 9th IWCMC*, Jul. 2013, pp. 556–560.

[122] K. Huang and V. Lau, "Enabling wireless power transfer in cellular networks: Architecture, modeling and deployment," *IEEE Trans. Wireless Commun.*, vol. 13, no. 2, pp. 902–912, Feb. 2014.

[123] S.-R. Cho and W. Choi, "Energy-efficient repulsive cell activation for heterogeneous cellular networks," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 5, pp. 870–882, May 2013.

[124] U. Paul, A. Subramanian, M. Buddhikot, and S. Das, "Understanding traffic dynamics in cellular data networks," in *Proc. IEEE INFOCOM*, Apr. 2011, pp. 882–890.

[125] L. Saker, S.-E. Elayoubi, R. Combes, and T. Chahed, "Optimal control of wake up mechanisms of femtocells in heterogeneous networks," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 3, pp. 664–672, Apr. 2012.

[126] M. Wildemeersch, T. Quek, C. Slump, and A. Rabbachin, "Cognitive small cell networks: Energy efficiency and trade-offs," *IEEE Trans. Commun.*, vol. 61, no. 9, pp. 4016–4029, Sep. 2013.

[127] D. Tsilimantos, J.-M. Gorce, and E. Altman, "Stochastic analysis of energy savings with sleep mode in OFDMA wireless networks," in *Proc. IEEE INFOCOM*, Apr. 2013, pp. 1097–1105.

[128] S. Cai, L. Xiao, H. Yang, J. Wang, and S. Zhou, "A cross-layer optimization of the joint macro- and picocell deployment with sleep mode for green communications," in *Proc. 22nd WOCC*, May 2013, pp. 225–230.

[129] P. Dini, M. Miozzo, N. Bui, and N. Baldo, "A model to analyze the energy savings of base station sleep mode in LTE HetNets," in *Proc. IEEE GreenCom, IEEE iThings/CPSCom*, Aug. 2013, pp. 1375–1380.

[130] S. Zhou, J. Gong, and Z. Niu, "Sleep control for base stations powered by heterogeneous energy sources," in *Proc. ICTC*, Oct. 2013, pp. 666–670.

[131] G. Cili, H. Yanikomeroglu, and F. Yu, "Cell switch off technique combined with coordinated multi-point (CoMP) transmission for energy efficiency in beyond-LTE cellular networks," in *Proc. IEEE ICC*, Jun. 2012, pp. 5931–5935.

[132] R. Kumar and J. Gurugubelli, "How green the LTE technology can be?" in *Proc. 2nd Int. Conf. Wireless VITAE*, Chennai, India, Mar. 2011, pp. 1–5.

[133] R. Wang, J. Thompson, and H. Haas, "A novel time-domain sleep mode design for energy-efficient LTE," in *Proc. 4th ISCCSP*, Limassol, Cyprus, Mar. 2010, pp. 1–4.

[134] P. Ghosh, S. Das, S. Naravaram, and P. Chandhar, "Energy saving in OFDMA cellular systems using base-station sleep mode: 3GPP-LTE a case study," in *Proc. NCC*, Kharagpur, India, Feb. 2012, pp. 1–5.

[135] A. Bousia, A. Antonopoulos, L. Alonso, and C. Verikoukis, "'Green' distance-aware base station sleeping algorithm in LTE-Advanced," in *Proc. IEEE ICC*, 2012, pp. 1–5.

[136] D. Astely, E. Dahlman, G. Fodor, S. Parkvall, and J. Sachs, "LTE release 12 and beyond," *IEEE Commun. Mag.*, vol. 51, no. 7, pp. 154–160, Jul. 2013.

[137] A. Zakrzewska, D. Lopez-Perez, S. Kucera, and H. Claussen, "Dual connectivity in LTE HetNets with split control- and user-plane," in *Proc. IEEE GC Wkshps*, Dec. 2013, pp. 391–396.

[138] J. Jang, K. Han, and S. Choi, "Adaptive power saving strategies for IEEE 802.16e mobile broadband wireless access," in *Proc. APCC*, Busan, Korea, Dec. 2006, pp. 1–5.

[139] L. Saker, S. Elayoubi, and H. Scheck, "System selection and sleep mode for energy saving in cooperative 2G/3G networks," in *Proc. IEEE 70th VTC-Fall*, Anchorage, AK, USA, Jan. 2009, pp. 1–5.

[140] L. Saker, S. Elayoubi, and T. Chahed, "Minimizing energy consumption via sleep mode in green base station," in *Proc. IEEE WCNC*, Sydney, NSW, Australia, Apr. 2010, pp. 1–6.

[141] E. Oh, B. Krishnamachari, X. Liu, and Z. Niu, "Toward dynamic energy-efficient operation of cellular network infrastructure," *IEEE Commun. Mag.*, vol. 49, no. 6, pp. 56–61, Jun. 2011.

[142] M. A. Marsan and M. Meo, "Energy efficient management of two cellular access networks," *ACM SIGMETRICS Perform. Eval. Rev.*, vol. 37, no. 4, pp. 69–73, Mar. 2010.

[143] Y. Wu, G. He, S. Zhang, Y. Chen, and S. Xu, "Energy efficient coverage planning in cellular networks with sleep mode," in *Proc. IEEE 24th Int. Symp. PIMRC*, Sep. 2013, pp. 2586–2590.

[144] D. Cao, S. Zhou, and Z. Niu, "Optimal combination of base station densities for energy-efficient two-tier heterogeneous cellular networks," *IEEE Trans. Wireless Commun.*, vol. 12, no. 9, pp. 4350–4362, Sep. 2013.

[145] P. Kolios, V. Friderikos, and K. Papadaki, "Switching off low utilization base stations via store carry and forward relaying," in *Proc. IEEE 21st Int. Symp. PIMRC Workshops*, Sep. 2010, pp. 312–316.

[146] GSMA, "Sleep mode for mobile base stations cuts Jamaican operators' carbon footprint," London, U.K., Feb. 2013. [Online]. Available: http://www.gsma.com/publicpolicy/sleep-mode-for-mobile-base-stations-cuts-jamaican-operators-carbon

[147] J. Gong, S. Zhou, Z. Niu, and P. Yang, "Traffic-aware base station sleeping in dense cellular networks," in *Proc. 18th IWQoS*, Beijing, China, Jun. 2010, pp. 1–2.

[148] M. Marsan, L. Chiaraviglio, D. Ciullo, and M. Meo, "Switch-off transients in cellular access networks with sleep modes," in *Proc. IEEE ICC*, Kyoto, Japan, Jun. 2011, pp. 1–6.

[149] Z. Niu, "TANGO: Traffic-aware network planning and green operation," *IEEE Wireless Commun.*, vol. 18, no. 5, pp. 25–29, Oct. 2011.

[150] Y. Zhang *et al.*, "An overview of energy-efficient base station management techniques," in *Proc. 24th TIWDC—Green ICT*, Sep. 2013, pp. 1–6.

[151] S. Zhou, J. Gong, Z. Yang, Z. Niu, and P. Yang, "Green mobile access network with dynamic base station energy saving," in *Proc. ACM MobiCom*, Beijing, China, Sep. 2009, pp. 1–2.

[152] A. Conte, "Power consumption of base stations," in *Proc. TREND Plenary Meet.*, Feb. 2012, pp. 1–19.

[153] L. Chiaraviglio, D. Ciullo, G. Koutitas, M. Meo, and L. Tassiulas, "Energy-efficient planning and management of cellular networks," in *Proc. 9th Annu. Conf. WONS*, Courmayeur, Italy, Feb. 2012, pp. 159–166.

[154] A. J. Fehske, F. Richter, and G. Fettweis, "Energy efficiency improvements through micro sites in cellular mobile radio networks," in *Proc. IEEE GreenComm*, Honolulu, HI, USA, Dec. 2009, pp. 1–5.

[155] G. Auer *et al.*, "Cellular energy efficiency evaluation framework," in *Proc. IEEE 73rd VTC Spring*, Yokohama, Japan, May 2011, pp. 1–6.

[156] M. Zukerman, "Introduction to queueing theory and stochastic teletraffic models," 2014. [Online]. Available: http://www.ee.cityu.edu.hk/zukerman/classnotes.pdf

[157] L.-C. Wang and S. Rangapillai, "A survey on green 5G cellular networks," in *Proc. Int. Conf. SPCOM*, Jul. 2012, pp. 1–5.

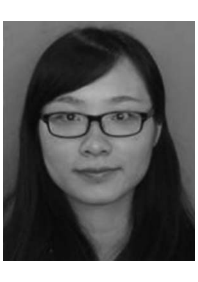
[158] R. Hu and Y. Qian, "An energy efficient and spectrum efficient wireless heterogeneous network framework for 5G systems," *IEEE Commun. Mag.*, vol. 52, no. 5, pp. 94–101, May 2014.

[159] T. Levanen, J. Pirskanen, T. Koskela, J. Talvitie, and M. Valkama, "Radio interface evolution towards 5G and enhanced local area communications," *IEEE Access*, vol. 2, pp. 1005–1029, Sep. 2014.

[160] M. Gupta and S. Singh, "Greening of the Internet," in *Proc. ACM SIGCOMM*, Karlsruhe, Germany, Aug. 2003, pp. 19–26.

[161] R. Li, Z. Zhao, X. Chen, J. Palicot, and H. Zhang, "TACT: A Transfer Actor-Critic learning framework for energy saving in cellular radio sccess networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 4, pp. 2000–2011, Apr. 2014.

Jingjin Wu received the B.Eng. degree (with first-class honors) in information engineering (with finance minor) in 2011 from City University of Hong Kong, Kowloon, Hong Kong, where he is currently working toward the Ph.D. degree with the Department of Electronic Engineering. His current research focuses on performance evaluation and energy conservation of cellular networks.



Yujing Zhang received the B.Eng. degree (with first-class honors) in information engineering (with business intelligence minor) from City University of Hong Kong, Kowloon, Hong Kong, in 2012 and the M.S. degree in information networking from Carnegie Mellon University, Pittsburgh, PA, USA, in 2014. She is currently a Software Engineer with Facebook, Menlo Park, CA, USA. Her current research interests include telecommunication networks and networked and distributed computer systems.

Moshe Zukerman (M'87–SM'91–F'07) received the B.Sc. degree in industrial engineering and management and the M.Sc. degree in operations research from the Technion—Israel Institute of Technology, Haifa, Israel, and the Ph.D. degree in engineering from the University of California, Los Angeles, CA, USA, in 1985. He was an independent Consultant with the IRI Corporation and a Postdoctoral Fellow with the University of California, Los Angeles, in 1985–1986. In 1986–1997, he was with the Telstra Research Laboratories (TRL), first as a Research Engineer and, in 1988–1997, as a Project Leader. He also taught and supervised graduate students at Monash University in 1990–2001. During 1997–2008, he was with The University of Melbourne, Melbourne, Australia. In 2008, he joined City University of Hong Kong, Kowloon, Hong Kong, as a Chair Professor of Information Engineering and a Group Leader. Dr. Zukerman has served on various Editorial Boards such as *Computer Networks*, IEEE COMMUNICATIONS MAGAZINE, IEEE JOURNAL OF SELECTED ARES IN COMMUNICATIONS, IEEE/ACM TRANSACTIONS ON NETWORKING, and the *International Journal of Communication Systems*.

Edward Kai-Ning Yung (M'85–SM'85–F'12) was born in Hong Kong. He received the B.S., M.S., and Ph.D. degrees from the University of Mississippi, University, MS, USA, in 1972, 1974, and 1977, respectively. He worked briefly at the Electromagnetic Laboratory, University of Illinois at Urbana-Champaign. He returned to Hong Kong in 1978 and began his teaching career at the Hong Kong Polytechnic. He joined the newly established City University of Hong Kong, Kowloon, Hong Kong, in 1984 and was instrumental in setting up a new department. He was promoted to Full Professor in 1989, and in 1994, he was awarded one of the first two personal chairs in the University. He is the Founding Director of the Wireless Communications Research Center, formerly known as the Telecommunications Research Center. Despite his heavy administrative load, he remains active in research in microwave devices and antenna designs for wireless communications. He is the Principal Investigator of many projects worth tens of million Hong Kong dollars. He is the author of over 450 papers, including 270 in referred journals. He is also active in applied research, consultancy, and other technology transfers. Prof. Yung is a Fellow of the Chinese Institution of Electronics, the Institute of Electrical Engineers, and the Hong Kong Institution of Engineers. He is also a member of the Electromagnetics Academy. He was the recipient of many awards in applied research, including the Grand Prize in the Texas Instrument Design Championship and the Silver Medal in the Chinese International Invention Exposition. He is listed in the *Who's Who in the World* and *Who's Who in Science and Engineering in the World*.