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# Energy Efficiency of Heterogeneous Cellular Networks: A Review

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**Abstract:** The concept of heterogeneous networks had been proposed as an alternative approach to provide higher capacity and coverage for cellular networks. Along with that, the aspect of "Energy Efficiency" had already received much attention lately due to ecological as well as economic reasons particularly for network operators. This study presented a systematic review on the topic of energy efficiency in heterogeneous cellular networks. The review was divided into three parts; first the typical metrics parameters used to measure energy efficiency and tradeoff relationships with respect to network performance were discussed. Next, the existing issues, approaches and challenges to provide energy efficiency in general cellular networks were addressed. Finally we looked into the current efforts on energy awareness in macro, micro, pico and femtocells. By means of discussions, we highlighted different heterogeneous network scenarios in which network planning and optimization techniques were (or not were) advantageous to provide essential understanding for successful deployment of green heterogeneous cellular networks.

**Key words:** Energy efficiency, heterogeneous network, network deployment, power consumption

## INTRODUCTION

The rapid and tremendous growth of the worldwide development of information and communication technology (ICT) has the potential to be really a major contributor to global energy consumption which is responsible for up to 10% of the world energy consumption already in 2010. Further, about 0.5% of the world energy consumption is consumed by mobile radio networks alone (Dufkova *et al*., 2010). With the increased demand for broadband services, there is a genuine need for denser networks and in this context increased energy prices are expected to constitute a significant challenge in near future (Chen *et al*., 2011a). Energy efficiency considerations recently gained attention due to environmental aspects; lowering $CO_2$ emissions and reducing energy consumption. Furthermore, it is important to assess network energy efficiency from an operator's point of view, since energy costs are increasing and providing ubiquitous high speed mobile access may scale up the operators' operational expenditure (Klessig *et al*., 2011). There are basically two ways to improve the energy efficiency in a mobile network.

The first consists of reducing the power consumption of the main consumer, i.e., the Base Station (BS) either by using more power-efficient hardware, more advanced software to adapt power consumption to the traffic situation as well as to balance between energy consumption and performance. The second is intelligent network deployment strategies where using high density deployment of Low Power Nodes (LPN) or base stations is believed to decrease the power consumption compared to low density deployment of high power macro base stations. The idea being that a Base Station (BS) closer to mobile users lowers the required transmit power due to advantageous path loss conditions (Fehske *et al*., 2009). Network deployment based on smaller cells such as micro, pico or even femtocells is a possible solution to reduce total power consumption of a cellular network. However, as indicated by some of recent researches, network designing needs to be approached with more caution as spreading a high density of small cells will overburden and decrease the power efficiency of the central BS. In addition, the embodied energy consumption may actually dominate and result in an increase in total energy consumption (Humar *et al*., 2011). As such, this paper presented an overview of energy efficiency issues in a heterogeneous cellular network.

## FUNDAMENTALS

Here, the basic fundamentals of energy efficiency metrics and tradeoffs were introduced.

**Energy efficiency (EE) metrics:** According to the purpose of a system, EE can be defined in different perspectives.

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One way is to define EE as the ratio of efficient output energy to total input energy. The other way is to define EE as the performance per unit energy consumption. EE metrics are classified into two categories: absolute metrics which indicate the actually energy consumed for performance and relative metrics which show how EE is improved. For measuring the efficiency of the communication link, several metrics were used in the literatures. The most commonly used metric for the energy efficiency of a communication link was bit per joule $E_e$ which is defined as the ratio of the total network throughput over the energy consumption within a given period, where the unit is bits/Joule (Wang and Shen, 2010):

$$E_e = \frac{R}{P_C} \quad (1)$$

where, R denotes the average date rate provided by a certain base station with consumed power (PC). It can be also measured in bit per second per watt. Although this metric is simple and intuitive, it does not capture network specific aspects such as coverage and user fairness. Also higher layer aspects, e.g., quality of service, were also neglected. Hence, the metric (1) should be complemented by other metrics (Richter *et al*, 2010b). To account for the data rate as well the communication distance, a modified metric of bit meter per joule may be used. This metric described the efficiency of reliably transporting the bits over a distance towards the destination per unit of energy consumed. For a cellular area of coverage, this metric was modified to bits per joule per unit area, so to capture the extent of the coverage area (Auer *et al*., 2010). Mahadevan *et al*. (2009) introduced a concept of Energy Proportionality Index (EPI) which is very important energy measure to illustrate dynamic energy consumption of the equipment. Energy consumption in equipment could be divided into two parts: static energy consumption and dynamic energy consumption. Static energy consumption is energy for maintaining the equipment, independent from processing traffic. Dynamic energy consumption is required energy for processing traffic (Mahadevan *et al*., 2009). However, the standardized energy metrics are usually variations of the following two basic definitions: the energy consumption ratio ECR and the telecommunications energy efficiency ratio TEER (Badic *et al*., 2009; Chen *et al*., 2010a; He *et al*., 2010). The ECR metric is defined as the ratio of the peak power (in Watts) to the peak data throughput, i.e.:

$$ECR = \frac{E}{M} = \frac{PT}{M} = \frac{P}{R} \quad (2)$$

where, E is the energy required to deliver M bits over time T and R = M/T is the data rate in bits per seconds.

This energy metric provides energy consumption in Joules consumed for transportation of one information bit. The ECR metric was evaluated either for the whole Radio Access Network (RAN) as well as for one cell or cell sector of the RAN assuming a given RF average transmission power and a given average throughput in each cell (He *et al*., 2010). The ratio of a system's energy consumption to its capacity (joules/bit) is an indicator of its efficiency and is known as the Energy Consumption Ratio (ECR). A system with a lower ECR is more efficient in its energy use than a system with a higher ECR, as each bit requires less power for transmission (Humar *et al*., 2011). The TEER metric is more general than the ECR metric and it can be written as TEER = useful work/power. The units of the TEER metric depends on the specific quantity considered to be the useful work. It is also possible to express the powers in dB or dBm units and modify the ECR and the TEER metrics accordingly although this possibility is not currently considered in the standards. Also, the standards usually did not explicitly specify the definitions of the power used in the ECR and TEER metrics, e.g., whether or not the power considered accounts for the RF power only (He *et al*., 2010). Parker and Walker (2011) recently proposed an absolute energy efficiency metric (measured in dB) which is given by:

$$dB\varepsilon = 10 \log_{10}\left(\frac{\text{Power}/\text{Bit rate}}{KTe \ln 2}\right) \quad (3)$$

where, K is the Boltzmann constant and Te is the absolute temperature of medium. Since, classical thermodynamics bases its analysis of systems on their absolute temperature, the authors contended that it is a suitable and necessary measure that can be applied across the board as a metric for various types of ICT components (Parker and Walker, 2011). Furthermore, the Energy Consumption Gain (ECG) metric has been defined in the Green Radio (GR) project as a ratio of the ECR metrics o f the two systems under consideration, for example, a baseline reference system and a system with a more energy efficient Radio Access Network (RAN) architecture. Consequently, the ECG metric quantifies the energy consumption improvement relative to the common reference system. In some scenarios, the Energy Reduction Gain (ERG) (expressed in percent) is preferable. The ERG metric was derived from the ECG metric as (He *et al*., 2010):

$$ERG\,(\%) = \left(1 - \frac{1}{ECG}\right) \times 100 \quad (4)$$

The classical optimization criterion for wireless network is the areal spectral efficiency, measured in [bit/sec/Hz/$m^2$] (Alouini and Goldsmith, 1999). Referring to the area spectral efficiency, Richter *et al.* (2009) proposed the concept of the area power consumption for cellular networks. The metric for the area power consumption ρ was defined as (Richter *et al.*, 2009):

$$p = \frac{P_C}{A} \tag{5}$$

where, A is the coverage area. The area power consumption figure cannot be the exclusive metric describing energy efficiency since it does not take into account the provided additional network capacity and higher system spectral efficiency. Nevertheless, this metric makes it possible to evaluate different network topologies with similar performance figures with regard to energy efficiency (Arnold *et al.*, 2010). In order to assess the energy efficiency of the network relative to its size, Wang and Shen (2010) introduced the notion of Area Energy Efficiency (AEE) which is defined as the bit/Joule/unit area supported by a cell. The AEE for a certain station could be expressed as:

$$A_{EE} = \frac{E_e}{A} \tag{6}$$

where, Ee and A denote the energy efficiency in bit/Joule and the area covered by a certain station with the unit of $km^2$, respectively (Wang and Shen, 2010).

Table 1 summarized the typical metrics used to measure energy efficiency but, so far, conventional energy efficiency metrics capture only a small fraction of the overall power budget of the network and may therefore lead to incomplete and potentially misleading conclusions. An up-to-date overview of the energy metrics which were proposed by various standards bodies and then adopted worldwide by the equipment manufacturers and the network operators could be found in (Hamdoun *et al.*, 2012).

**Energy efficiency tradeoffs:** Spectral efficiency SE is a widely used performance indicator for the design of wireless communication systems. For instance, the target downlink SE of the 3rd Generation Partnership Project (3GPP) increased from 0.05-5 b $sec^{-1}$ $Hz^{-1}$ the system evolves from GSM to Long Term Evolution (LTE). SE oriented systems were designed to maximize SE under peak or average power constraints which may lead to transmitting with the maximum allowed power for a long period and thus they deviated from energy efficient design (Chen *et al.*, 2011b). EE in a communication system is not a simple problem. Information theory reveals some insights on the complexity. According to the Shannon formula, the SE and EE of a communication system based on the Additive White Gaussian Noise (AWGN) channel can be written as (Chen *et al.*, 2011a, b):

$$\eta_{SE} = \frac{R}{B} = \log_2\left(1+\frac{P}{BNo}\right) \tag{7}$$

$$\eta_{EE} = \frac{R}{P} = \frac{B}{P}\log_2\left(1+\frac{P}{BNo}\right) \tag{8}$$

As a result, the SE-EE can be expressed as:

$$\eta_{EE} = \frac{\eta_{SE}}{(2^{\eta}SE-1)N_O} \tag{9}$$

where, R is the bit rate of information, P is the received power, B is the bandwidth and $N_0$ is the noise power spectral density.

The unit of the EE metric is then bits per joule which indicates the information units transmitted per one energy unit. Equation 8 shows that if $N_0$ is fixed, EE is the function of power density P/B, but the $\eta_{EE}$ does not monotonically increase with B or P. In a practical system where the bandwidth is a less flexible parameter, the maximum EE of a system is hard to achieve. For a given rate R, using more bandwidth requires less power. If the bandwidth is infinite, the required power is fixed to $P = N_0R \ln 2$. This gives a hint to trade bandwidth with energy. Further the objective to optimize throughput performance is normally conflict with that to maximize EE. Balancing these two objectives complicates the system design. Note that Eq. 8 gives an EE model for a generic communication system. For a wireless system, EE also depends on distance, carrier frequency, efficiency of antennas and so on. Moreover, interference and fading make EE of a wireless system vary according to the radio environment (Chen *et al.*, 2011a,b).

From Eq. 9, $\eta_{EE}$ converges to a constant, $1/(N_0 \ln 2)$ when $\eta_{SE}$ approaches zero. On the contrary, $\eta_{EE}$ approaches zero when $\eta_{SE}$ tends to infinity (Chen *et al.*, 2011b). A trade-off can be found between SE and EE by exploiting the available time and frequency resources, the

Table 1: Typical energy efficiency metrics and abbreviations

| Metric | Abbreviation | Unit |
|---|---|---|
| Energy efficiency | $E_e$ | bits $J^{-1}$ or b $sec^{-1}$ $W^{-1}$ |
| Energy proportionality index | EPI | % |
| Energy consumption ratio | ECR | W $b^{-1}$ $sec^{-1}$ or J $bit^{-1}$ |
| Absolute energy efficiency | dBε | dB |
| Energy consumption gain | ECG | % |
| Energy reduction gain | ERG | % |
| Area power consumption | APC | W $km^{-2}$ |
| Area energy efficiency | AEE | b $J^{-1}$ $km^{-2}$ |

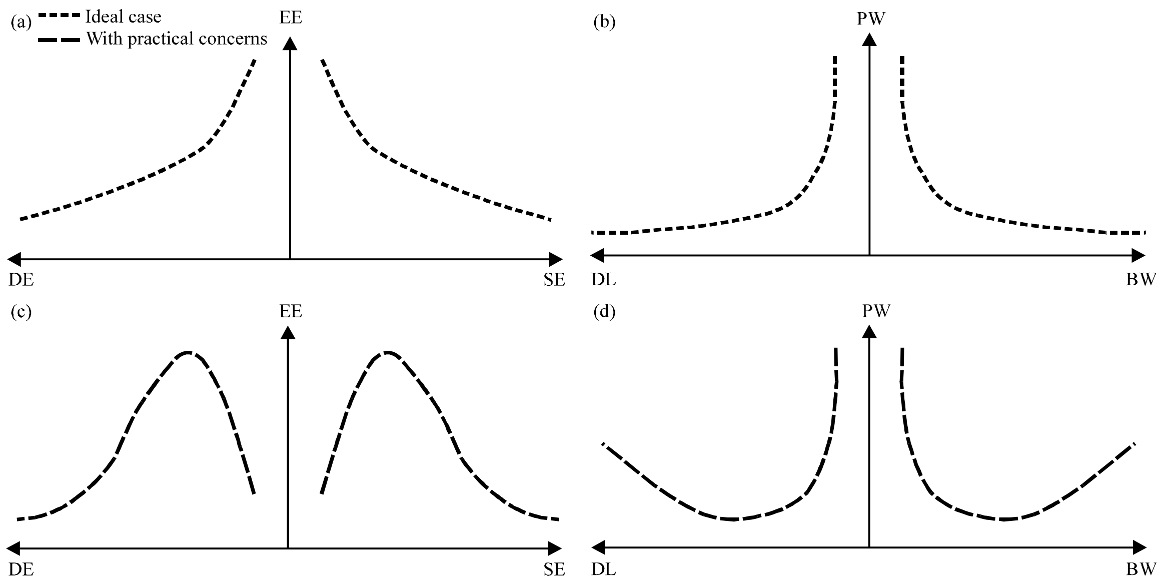


Fig. 1(a-d): Sketch of the four trade-off relations without and with practical concerns, (a) Deployment efficiency (DE) and spectrum efficiency (SE) vs. energy efficiency (EE) without practical concerns, (b) Delay (DL) and bandwidth (BW) vs. power (PW) without practical concerns, (c) Delay (DL) and spectrum efficiency (SE) vs. energy efficiency (EE) with practical concerns and (d) Delay (DL) and bandwidth (BW) vs. power (PW) with practical concerns (Chen *et al.*, 2011b)

operation and transmit modes of the base stations. For example, when a theoretical power model is assumed, i.e., the total consumed power is equal to the transmit power, the EE can be improved mainly through receive diversity in low-SE regime and the use of Multiple Input-Multiple Output (MIMO) has a large potential for improving the EE, especially in the high-SE regime (Bohn *et al.*, 2010). However, in multicell scenarios the interference powers generated by the neighboring cells not only reduce the maximum achievable EE but also degrade SE and EE and thus degrade the energy efficiency of multi-cell cellular networks (Ge *et al.*, 2010; Miao *et al.*, 2009). In this case, the results from the simple point-to-point case are not applicable and a systematic approach to multi-user/multicell systems shall be developed to build on the theoretical fundamentals of energy-efficient wireless transmissions (Chen *et al.*, 2011a,b). Deployment efficiency DE is another important network performance indicator for mobile operators. The deployment cost consists of both Capital Expenditure (CapEx) and Operational Expenditure (OpEx). It can be defined the deployment efficiency to describe the effectiveness of BS deployment and the energy efficiency to evaluate the effectiveness of energy use.

The relation of DE and EE is not simple and becomes more complex when considering practical aspects and there might not always be a trade-off between DE and EE while it depends on a specific deployment scenarios but, these two aspects are interacting with each other and the design of energy efficient architecture needs a holistic consideration of both and the energy efficiency analysis is need to expand to the whole system, not only to the base station (Chen *et al.*, 2010b). When the energy cost is high, the total cost is minimized for dense base station deployments while for high-density deployments, the idle power of the base stations and backhaul will become a significant factor. In addition, the energy cost is also strongly dependent on the amount of available spectrum. Significant savings in both energy and infrastructure cost can be made in total cost if more spectrum can be made available (Tombaz *et al.*, 2011a). Chen *et al.* (2011a,b) identified four key trade-offs of energy efficiency EE with network performance; Deployment Efficiency (DE)-Energy Efficiency (EE) trade-off (balancing the deployment cost, throughput and energy consumption in the network), Spectrum Efficiency (SE)-EE trade-off (balancing the achievable rate and energy consumption), bandwidth (BW)-power (PW) tradeoff (balancing the bandwidth utilized and the power needed for transmission) and delay (DL)-PW trade-off (balancing average end-to-end service delay and average power consumed in transmission. With the help of the four fundamental tradeoffs, they demonstrated that key network performance/cost indicators are all stringed together. Figure 1 showed the four trade-off relations curves without and with practical concerns (Chen *et al.*, 2011a,b). To address the challenge of increasing power efficiency in future wireless networks and thereby to maintain profitability, it is crucial to consider energy efficient wireless architectures and protocols, efficient BS redesign, smart grids, cognitive radio, relaying and heterogeneous network deployment based on smaller cells.

## BASIC CONCEPT OF HETEROGENEOUS CELLULAR NETWORK

Heterogeneous network concept was proposed in the framework of LTE-Advanced to increase the spectral efficiency. Since, radio link performance is approaching the theoretical limits with 3G, network topology is seemed a way to increase system performance (Khandekar *et al.*, 2010). In this strategy, macro base stations are used to provide blanket coverage, on the other hand small, low power base stations are introduced to eliminate the coverage holes and at the same time increase the system capacity in hotspots. Furthermore, heterogeneous networks provide an opportunity for network providers to optimize overall costs, revenues and customer satisfaction (Johansson, 2007).

Macrocells are mainly used to provide a widespread coverage area but they can only support low data rate services. One obvious approach to make the cellular networks more power efficient and thereby sustaining high speed data-traffic is by reducing the propagation distance between nodes, hence reducing the transmission power. Therefore, network deployment solutions based on smaller cells such as micro, pico and femtocells are very promising in this context. A typical heterogeneous network deployment is shown in Fig. 2. Smaller micro, pico or femtocell structures can be used for providing high data-rate service to smaller areas with a high density of traffic. Micro/picocells can cater to many devices within the range of a few hundred meters while femtocells are mostly used for indoor or home area.

Due to their short range, femtocells are more power efficient and are usually used for private indoor communication, often wired directly to a private owners' cable broadband connection or a homeowner's Digital Subscriber Line (DSL) (Hasan *et al.*, 2011). Performance measurement and analysis of heterogeneous wireless were investigated by Chieng and Ting (2011) and Chieng *et al.* (2011). They focused on capacity and coverage study of heterogeneous wireless networks but the aspect of energy efficiency was not addressed (Chieng and Ting, 2011; Chieng *et al.*, 2011). The importance of the heterogeneous network concept and the work that's going on in standards bodies, such as the Institute of Electrical and Electronics Engineers Inc. (IEEE) and 3GPP, is that it will define how all those different-sized cells will work together, how hand-off among them will be achieved, how interference among them will be minimized and how spectrum and energy efficiencies will be optimized. Heterogeneous networks are also proposed to increase the energy efficiency of the network and hence

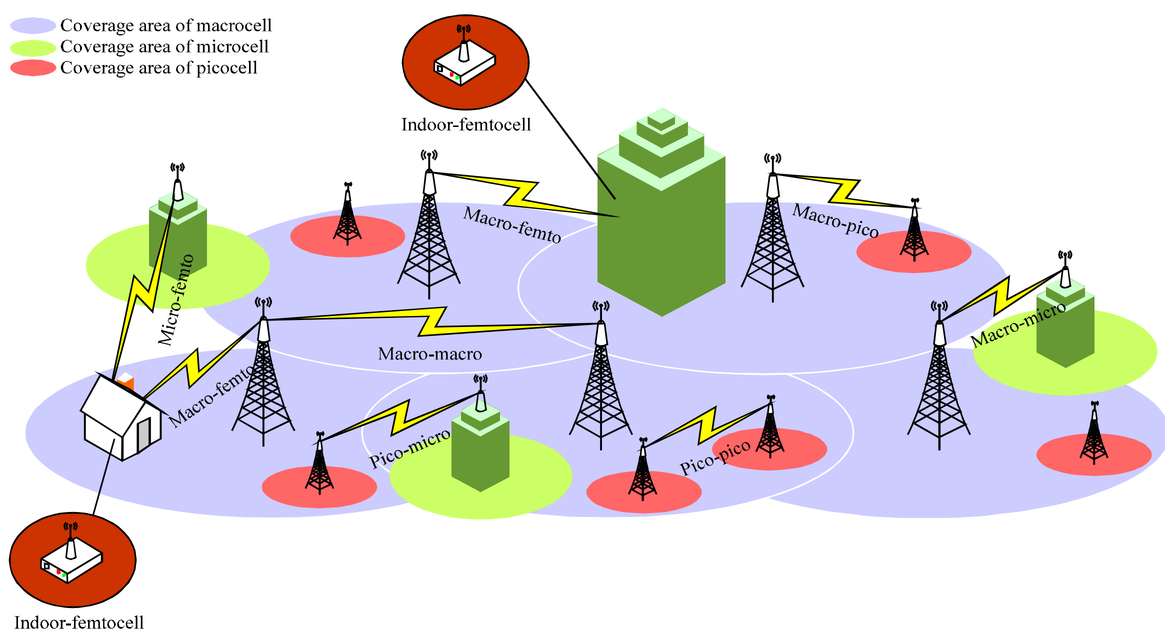


Fig. 2: Heterogeneous cellular network Hasan *et al.* (2011)

Table 2: Summary of energy efficiency issues, approaches and challenges

| Issues | Approaches and trends | Challenges |
|---|---|---|
| Network capital expenses | Density, cell size and location optimization, transmission algorithms schemes, scheduling | Improve the network DE-EE trade-off relation |
| Network operational expenses | Sleep mode, self-organizing techniques, cell zooming | Tracing spatial and temporal traffic load fluctuations, energy scaling traffic load |
| LPN-interference, energy scaling traffic load | Sleep mode, power control methods | Macro-LPN coordination, Interference management |
| Coverage holes | Power control methods | Interference avoidance |
| Backhauling power consumption | Backhauling strategies | Providing sufficient backhauling to offload traffic |

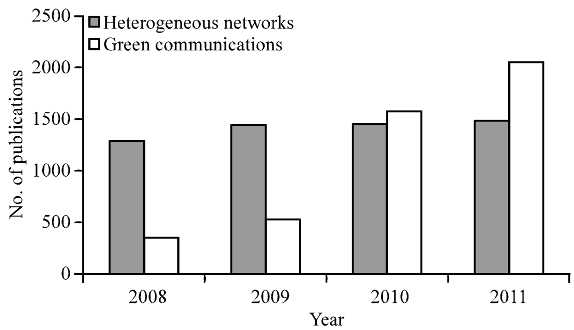


Fig. 3: IEEE publications on Green Communication and heterogeneous networks

considered as a promising trend toward holistic green communications and networking. For instance, Fig. 3 gives some insights on publications size on green communication and heterogeneous networks in IEEEXplore which are in increasing rate. However, from energy efficiency perspective there are some issues and challenges in small cells and heterogeneous deployments such as:

- The network capital expenses increase with the increasing number of sites while the latter need more infrastructure costs, backhaul transmission equipment site installation and radio network controller equipment. Also for high-density deployments, the idle power of the base stations and backhaul will become a significant factor (Chen *et al*., 2011a; Jada, 2011; Tombaz *et al*., 2011b)
- The deployment, operation and maintenance of additional macro/micro/pico/femtocells cause heavy operational expenses (OpExs) (Hoydis *et al*., 2011). For example, deployment of femtocells may lead to a situation where numerous small access points are turned on and spending energy even when traffic is nonexistent (Jada, 2011)
- One of the main challenges of heterogeneous networks is the severe inter-cell interference or the inter-tier interference when different tier of heterogeneous networks are deployed with the same frequency (Jiang *et al*., 2011)
- Small, lower power nodes such as femto may create coverage holes or use spectrum that would otherwise be available for the macro layer (Landstrom *et al*., 2011)
- Small cells density is limited to backhaul availability and wireless nodes will spend part of the transmission power on backhaul communication
- (Saleh *et al*., 2009)

Table 2 summarized some of the issues, approaches and challenges that are related to the energy efficiency in heterogeneous cellular network.

## ENERGY-AWARENESS IN HETEROGENEOUS CELLULAR NETWORK

Here, discussed the current efforts on energy-awareness in different parts of the heterogeneous cellular networks.

**Base station's energy-awareness:** According to Han *et al*. (2011), about 57% of power consumption of a typical cellular network is consumed by the BS. The explosive demand for high data rate of mobile users has caused BSs to be the dominant total energy consumer within the mobile cellular networks. It has been shown that the energy consumption for an LTE network has to increase about 60 times compared to a 2G network to offer the same level of coverage (Manner *et al*., 2010). Due to this, most studies on energy efficiency in mobile cellular radio networks focused on the BS side. The base stations' energy efficiency has become a major consideration when designing cellular network. Most efforts which were made for reducing power consumption were focused on the hardware, manufacture, deployment and operation. Next generation base stations go even as far as using more efficient power amplifiers and natural resources for cooling (Oh *et al*., 2011; Liu *et al*., 2011). However, it has been stated (Fettweis and Zimmermann, 2008) that for a given coverage and/or spectral efficiency, the deployment of large number of small base stations, each requiring less power and located close to the users, may reduce the energy consumption as compared to the deployment of few large base stations (Fettweis and Zimmermann, 2008). There are many parameters affecting the energy efficiency, power consumption and the coverage area of the network such as frequency band, shadowing, path loss and the receiver sensitivity. An investigation and analysis on the impact of these factors on energy efficiency and coverage area of macrocell network has been done (Abdulkafi *et al*., 2012). They showed that optimal cell radius and minimum transmit power that utilizing minimum area power consumption can be obtained for different percentage requirement of coverage area (Abdulkafi *et al*., 2012; Fehske *et al*., 2009) presented the tradeoffs between gains in cell throughput that can be expected from coordinated multi point transmission and reception technologies and the increased energy consumption that they induced in cellular base stations. For the power model used in their research, where base station transmit powers were adjusted to the network density, the contributions of processing and backhauling power dominate power related to transmission for small site distances. Adigun and Politis (2011) analyzed the energy efficiency in term of ECR of MIMO schemes applicable for 3GPP LTE on different antenna configuration. They showed that Close Loop Spatial Multiplexing (CLSM) was to be the most energy efficiency transmission modes except in the case of CLSM (SU-MIMO) 2×2. The Open Loop Spatial Multiplexing (OLSM) modes when the number of transmit antenna equals the number of receive antenna were the next most energy efficiency modes, followed by the Transmit Diversity (T×D) modes. The Single Input-Single Output (SISO) mode was the least energy efficient mode when compared with MIMO schemes (Adigun and Politis, 2011). Besides, adaptive antenna techniques have a significant impact on the efficient use of the radiated power and they use lower power as compared to sectorized antenna by steering and directing the beam toward the known positions of users. Also they can effectively reduce the power consumption if an evolutionary optimization approaches like genetic algorithms are integrated into adaptive beam forming technique (Kiong *et al*., 2005, 2006; Elgabli *et al*., 2007; Badjian *et al*., 2010). The adoption of these techniques in future heterogeneous cellular networks is expected to have a significant impact on the efficient use of the energy usage, the minimization of the consumed power and hence improve the energy efficiency of the whole network.

A discussion of the key levers for energy efficient radio components was provided by Ferling *et al*. (2010). They elaborated on radio node level issues addressed by Energy Aware Radio and Network Technologies (EARTH) project which aims to identify concepts that will further improve the energy efficiency of wireless access networks. It has been shown that energy-efficiency optimization on system level can be fundamentally improved by changes to the base station design together with the introduction of complementary new physical layer concepts. Auer *et al*. (2011) proposed an evaluation framework with some enhancement which applied to quantify the energy efficiency of the downlink of a 3GPP LTE radio access network. Their results revealed that in the current network design and operation, the power consumption is mostly independent of the traffic load. This clearly indicates that there is a vast potential for energy savings by improving the energy efficiency of BSs at low load (Auer *et al*., 2011). The effects of cell size on energy saving and system capacity based future mobile communication systems in terms of energy efficiency was investigated (Leem *et al*., 2010). It has been shown that it is possible to establish more energy efficient, high data rate services by deploying more numerous but lower powered cells in a network. Badic *et al*. (2009) work has been done in optimizing the network architecture by balancing the advantages of large and small cells. Further, additional power saving can be achieved by switching off cells with inactive users whilst maintaining the total capacity of the networks. Simulation results of this proposed scheme were encouraging with a drop in total ECR due to cell size reduction (Badic *et al*., 2009).

Gonzalez-Brevis *et al*. (2011) investigated techniques to optimize the number of base stations and their locations, in order to minimize energy consumption take into account non-uniform user distributions across the coverage area by using approaches from optimization theory that deal with the facility location problem (Gonzalez-Brevis *et al*., 2011). Humar *et al*. (2011), the inclusion of embodied energy, as suggested by the authors lead to a new energy efficiency model for cellular networks. This model allowed for the investigation of optimizing the number of cells and their coverage area. Analysis using this model indicated that embodied energy contributes significantly towards the total energy consumption of the base station. Thus, the model disagreed with other predictors that indicated a reduction in base station power and number would lead to significant energy savings (Humar *et al*., 2011). Guo *et al*. (2011) focused on the optimization of network architectures, with the aim of significantly reducing energy consumption, whilst maintaining or improving the Quality of Service (QoS). They demonstrated that significant energy reductions and improvements to radio transmission energy efficiency can be made by optimizing a network's parameters with the QoS as a constraint. The operational energy reductions (ERG) yielded by varying the cell radius have shown that, whilst smaller cells were more transmission energy efficient (ECR), larger cells consumed up to 80% less operation energy than smaller cells (Guo *et al*., 2011). Chong and Jorswieck (2011) provided some analytical tools for optimizing the EE of a base station through power control, focusing on elastic traffic in the downlink. They showed that optimization problem can be formulated utilizing rate maximization algorithms (Chong and Jorswieck, 2011). In addition, with adaptive power control the near-far interference can be effectively minimized and the link signal quality can be improved. Energy per bit to noise density can be used to measure the link signal quality. Interference reduction will enhance system capacity via lower energy per bit to noise density requirement and hence achieve better energy efficiency (Kiong *et al*., 2003). In order to obtain energy efficiency limits, an analytical relationship between the energy efficiency improvements and the traffic characteristics was established (Lange and Gladisch, 2011). The energy saving potential of adaptive networks with respect to a reference network with constant power usage based on network traffic characteristics was studied. The results showed that adaptive networking can help to reduce the energy consumption of networks significantly (Auer *et al*., 2010). A first order approximation has been determined by Oh *et al*. (2011) for the amount of energy saving achieved by selectively switching off cells with low traffic while maintaining connectivity using traffic tracing and base station location (Oh *et al*., 2011). Son *et al*. (2011) developed a framework for BS energy saving that encompasses both dynamic BS operation and user association by formulating a total cost minimization problem that allows for a flexible tradeoff between flow-level performance and energy consumption. Based on the acquired real BS topologies under practical configurations, they showed that the proposed energy-efficient user association and BS operation algorithms can dramatically reduce the total energy consumption by up to 70-80%, depending on the arrival rate of traffic and its spatial distribution as well as the density of BS deployment (Son *et al*., 2011).

**Macrocell-microcell deployment:** For a given average area spectral efficiency and uniform user distribution, a heterogeneous deployments using micro and macro base stations can achieve a moderate power saving in the network without any optimization on the specific location of the micro-cells (Richter *et al*., 2009). Fehske *et al*. (2009), a way to optimize the cell structure and breakdown of the network was given by the authors which took into account the average micro sites per macro cell and the macro cell size itself, by altering the number of micro and macro sites to achieve similar system performance under full load conditions (Fehske *et al*., 2009). However, it has been proved that the homogeneous deployment using micro base stations only was not beneficial in terms of energy efficiency (Richter and Fettweis, 2010). Arnold *et al*. (2010) developed a power models for macro and micro base stations focusing on component level. For a typical BS, the components including power amplifier PA, signal processing, Analogue to Digital (A/D) converter, antenna, feeder, power supply, battery backup and cooling dominate the total power consumption. It has been commented that a shift from no load to high load at a BS contributed only to a mere 2-3% increase in the total power consumption (Richter and Fettweis, 2010). The effect of user association and frequency band allocation schemes on energy consumption and capacity of downlink LTE networks was investigated by Tesfay *et al*. (2011). The significant energy saving and traffic capacity gain could be obtained by deploying low power micro base stations and by carefully choosing other network design parameters. Dufkova *et al*. (2011) have quantified the energy consumptions of two alternative strategies to increase capacity in future LTE network deployments with deployment of redundant micro base stations by telecom operators at locations where traffic load is high and deployment of femto base stations by home users focusing on downlink traffic. They illustrated that these two strategies have similar energy consumption which was different from previous results where it stated that deployment of femto base stations was considerably more energy efficient (Dufkova *et al*., 2011). Richter *et al*. (2010a), the power consumption model has been adapted to traffic load variation and it has been proved that more micro sites are required for better energy efficiency in case of higher user densities. The study investigated the energy efficiency in heterogeneous networks for uniformly distributed traffic and showed that the reductions in energy consumption can be achieved by turning transceivers on and off, matching the diurnal variations in traffic demand (Richter *et al*., 2010a). Xu and Qiu (2011) proposed energy saving framework with joint short-term micro-sleep and long-term sleep. They leveraged on the Area Spectral Efficiency (ASE), Area Delivered Bits (ADB), Area Power Consumption (APC), Area Energy Consumption (AEC) and Area Energy Efficiency (AEE) as the tools to address the joint optimization problem. It was pointed out that there are two main tradeoffs in the joint design. The first one was between transmit energy and linear part energy which was determined by active and micro-sleep length.

The second one was between energy saved via long-term sleep and that saved via micro-sleep. The proposed joint optimization scheme with transmit power reduction could exploit the two tradeoffs well and improve the energy efficiency significantly (Xu and Qiu, 2011). A network condensation using micro base stations only is beneficial for medium and high load scenarios, at least in the considered range of network densities. For low traffic load, a network condensation using a mix of macro and micro cells is almost as efficient as a pure micro system. In case of limited capacity demand, heterogeneous deployments with optimal numbers of additional micro base stations are better suited than homogeneous micro cell deployments (Richter *et al*., 2010a). Klessig *et al*. (2011) has focused on the effect of randomly utilizing micro sites within a network with varying density to consider the efficiency of energy use as well as any co-channel interference that may arise due to fluctuating traffic in the different areas. For high traffic demand deploying micro sites increase the network energy efficiency by enhancing the area spectral efficiency, however, the macro site then only serves as a low data rate coverage provider in the areas in between micro cells (Klessig *et al*., 2011; Di Piazza *et al*., 2011) compared different power allocation schemes for Orthogonal Frequency-Division Multiple Access (OFDMA) systems with a reuse factor equal to 1, in a heterogeneous macro-micro cellular environment. In order to focus on the power allocation only, they considered a single user per-cell and neglected the impact of user scheduling on the network performance. They considered greedy allocation schemes, i.e., schemes utilizing all the carriers available in each cell and non-greedy schemes, i.e., schemes leaving some resources empty, in order to reduce interference with other cells. They proved that in most cases greedy policies performed better than non-greedy ones (Di Piazza *et al*., 2011). Tombaz *et al*. (2011a) have reviewed various techniques which involve new spectrum availability, more efficient physical layer implementations and defined strategies for different cell deployment and backhauling to reduce overall system cost. In their network deployment strategies, they emphasized the need to customize the design of micro cells to suit traffic needs in order to ensure overall power saving from larger macro cells that use high powered base stations Tombaz *et al*. (2011b).

**Macrocell-picocell deployment:** Picocells are regular BS with the only difference of having lower transmitted power than conventional macro cells. They are typically equipped with omni-directional antennas and are deployed indoors or outdoors often in a planned (hot-spot) manner (Damnjanovic *et al*., 2011). Picocells can be considered a good network densification option in terms of achieving a higher throughput at reasonable energy cost. Claussen *et al*. (2008) have looked into the power savings of pico cells for residential end-user connectivity to macro cells that were commonly used to provide coverage to a region (Claussen *et al*., 2008). Wang and Shen (2010) demonstrated through system-level simulation of two-tier networks with macro and pico cells that both cell energy efficiency and area energy efficiency can be improved by deploying low power pico stations combined with reduction of macro transmission power (Wang and Shen, 2010). The evaluation performance of two-tier networks in terms of energy efficiency and fairness of resource allocation was presented in (Quek *et al*., 2011) based on analytical expressions of success probabilities for each tier when a disjoint set of subchannels. The work confirmed that there exists an optimal pico-macro density ratio that maximizes the overall energy efficiency of such a two tier network. Meanwhile, a new power consumption model for a mobile radio network considering backhaul for mobile radio network was proposed in (Tombaz *et al*., 2011b). Numerical simulation analysis showed that backhaul seems to have a large impact in three different heterogeneous network deployments: macro base stations, macro and pico base stations, macro base stations and WLAN access points (Tombaz *et al*., 2011a). Liu *et al*. (2011) proposed an energy saving strategy for LTE heterogeneous network with overlapping picos which uses the remaining resources of neighboring picocells and macrocell to accept the users of picocell to be switched off. Simulations showed that the proposed approach has better performance in improving the energy efficiency of the system Liu *et al*. (2011).

**Macrocell-femtocell deployment:** Femtocells are generally consumer deployed (unplanned) network nodes for indoor application with a network backhaul facilitated by the consumer's home Digital Subscriber Line (DSL) or cable modem. Femtocells are typically equipped with omnidirectional antennas and their transmit power is 100 MW or less (Damnjanovic *et al*., 2011). As stated in (Zheng *et al*., 2011) femtocells could indeed improve energy efficiency of the network. They corroborated that femtocell technology is an energy-efficient solution for indoor coverage in LTE-A cellular networks. Femtocell deployment could have a 7:1 operational energy advantage ratio over the expansion of the macrocell network to provide approximately similar indoor coverage (Forster *et al*., 2009). In contrast, the work in (Cao and Fan, 2010) has observed that the macrocell

Table 3: Some methods used for energy efficiency improvement: summary of EE improvement methods discussed

| | Method | | |
|---|---|---|---|
| Description | Hardware design | Deployment | Operation |
| Macro | Efficient PA and natural resources | No. of BS, cell size, location optimization | Transmission technologies, power-down strategy, user association algorithm |
| Micro | - | No. of micro BS, cell size, location optimization | Power-down strategy, energy-efficient user association algorithm |
| Pico | - | No. of pico BS per macro and cell size optimization | Power-down strategy |
| Femto | - | - | Sleep mode, power control methods |
| Heterogeneous | - | No. of BS and cell size optimization | Power-down strategy, power control methods |

throughput degradation will increase with increasing femtocell deployment density. The femtocell solution could significantly improve energy efficiency in terms of some commonly used energy consumption metrics and there is a tradeoff between energy efficiency and system throughput in deploying femtocells (Cao and Fan, 2010). Hou and Laurenson (2010) showed that combining cellular communications with femtocells can significantly reduce overall power consumption, depending on the uptake of femtocell usage. Also, they suggested that the femtocell implementation rate should be limited under a certain degree, around 60%, in consideration of power efficiency (Hou and Laurenson, 2010). It has been suggested by Ashraf *et al*. (2010) that femtocell networks can be made more energy efficient by implementing cell sleep and idle modes controlled by user behavior and activity. Up to 37.5% decrease in energy use can be attained with some voice traffic models and a five-fold decrease in mobility events as compared to fixed pilot transmission (Ashraf *et al*., 2010). Power control algorithms to reduce cross-tier interference could be implemented in cases that the system fails to achieve its SINR target by lowering the transmission power of the strongest interfering cells. Due to their distributed nature, such power control methods provided minimal overhead in practical implementations. (Chandrasekhar *et al*., 2009). Huang *et al*. (2011) analyzed the energy efficiency of the fixed power supply FPS and Minimum Power Consumption (MPC) method and then proposed the Maximum Energy Efficiency (MEE) power control method. The proposed MEE method improved the energy efficiency of two-tier femtocells networks and obtained a good tradeoff between the energy efficiency and spectrum efficiency. The energy efficiency of MPC method was not high and increased very slowly even more femtocells was installed. Meanwhile, the energy efficiency of the FPS method would become worse in dense deployment scenario, because of severe cross-tier interference (Huang *et al*., 2011). Table 3 summarized some of the discussed methods that were tried to improve the energy efficiency in different parts of the heterogeneous network. Overall, deployment heterogeneity in cellular network is considered one of the comprehensive solutions to satisfy the demand of the data traffic growth and improve the energy efficiency of the cellular networks. Nevertheless, future deployments of heterogeneous cellular networks which support macro, micro, picos and femtos coexisting on the same spectrum in the same geographical area, poses significant and new challenges at all levels such as interference management. The ultimate enhancement of energy efficiency in heterogeneous cellular networks is likely to require an approach for small cells optimization as well as macrocell. For instance, optimizing the inter site distance that achieve minimum area power consumption can further improve the energy efficiency of the whole networks. Besides, optimizing the number of small cells per macro BS as well as their size and location for different areas and environments may lead to more energy efficient network design.

## CONCLUSION

The energy efficiency is critical issue from the viewpoint of cellular network operators in minimizing their operational costs and reducing their energy footprint for environmental reasons. In the context of energy efficiency of cellular networks, this paper outlined the efforts with respect to energy efficiency in cellular networks and the commonly used energy metrics and explored the tradeoffs inherent between energy use and network performance. However, there is a need to define appropriate energy efficiency metrics that capture the overall power budget of the whole network in order to quantify and qualify gains achieved by employing energy aware techniques in network planning. To move towards green cellular network, it is essential to balance between network performance improvement and the required energy consumption in the design of the network. It is anticipated that the heterogeneous network is a significant technique that can improve the energy efficiency of a cellular network. Nevertheless, a careful design for this network is required to avoid reducing the energy efficiency of the macro BS but on the other hand increasing in total energy consumption. Besides, optimization techniques are demanded to find the optimal energy efficiency of the whole networks with respect to the number of all types of base stations, their size and locations.

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