Enabling Green Cellular Networks: A Survey and Outlook

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Abstract

In last couple of decades, cellular networks have revolutionized the way users access communication networks but they required a huge effort to operators for the development of a wireless infrastructure which has been designed considering deployment costs with ubiquitous coverage and service quality targets. The traditional "macro" Base Stations (BSs) that have been used so far turned out to be inefficient from the operational costs point of view mainly because of their high energy consumption. Today, green communication is one of the main design goals of future mobile networks and current research aims to enable sustainable growth of broadband wireless infrastructure. Different solutions have been proposed so far for improving the energy efficiency of wireless networks. Small cells based on low-cost low-power Access Points (APs) are a promising solution to limit emission power and improve the spectral efficiency. Dynamic radio resource management can avoid energy wastage by adapting network parameters to load variations while satisfying quality constraints. Flexible hardware platforms enables APs to adapt operational point to changing conditions. The contribution of this survey is threefold. We provide an analysis of the models proposed in literature to evaluate the energy efficiency of current wireless architecture. We present green metrics that have been used and theoretical trade-offs that have been investigated. And finally, following a proposed classification, we present and critically discuss energy efficiency enablers recently proposed by the wireless research community.

Keywords: Green communications; Green metrics; Energy consumption models; Green trade-offs; LTE.

1. Introduction

The tremendous success of mobile cellular services that started with telephony is continuing with broadband data access with an incredible growth rate of traffic. Forecast on telecommunication market states a continuous increase in the number of subscribers, and an exponential increase in generated data traffic [1]. The dense layout of Access Points (APs)[1], which is necessary to satisfy the access capacity requirements of traffic, is resulting in a fast increase of energy consumption with more challenging operational cost for the operators. Hence, all players of wireless market have a tremendous interest for improving the energy efficiency at system level and are stimulating a large research effort for finding innovative solutions.

Actually, mobile networks have a strong potential for energy savings. In the past, the mobile industry has focused on limiting energy consumption at the user side, in order to maximize the battery life of mobile terminals [2]. However, state of the art Macro Base Stations (M-BSs) are the main source of inefficiency in wireless networks [3]. This is mainly due to the *always-on* operation of current systems, which permits full-time coverage but does not adapt energy consumption to traffic load variations.

Vendors, operators, and researchers are cooperating to develop innovative algorithms and technologies for energy efficient operation in mobile networks. In such perspective, the Greentouch consortium [4], the COST action IC1004 [5], and funded projects like EARTH [6], C2POWER [7], TREND [8], and Mobile VCE [9] focus on increasing the sustainability of wireless networks. Moreover, standardization bodies like IEEE, ETSI, and ITU have also undertaken different *green activities*.

A multitude of studies have been recently proposed to improve the Energy Efficiency (EE) in wireless communications. Current research activities are mainly investigating new flexible hardware for enhancing access devices, novel architectures based on small cells deployment, and adaptive management schemes that adjust network capacity with respect to service loads.

[1] In this paper, the terms access point and base station are interchangeable.

A few survey papers have already been published for reviewing existing work, and to assess the fundamental goals of the *green paradigm*.

Miao et al. have discussed PHY/MAC layer optimization for energy-efficient wireless communications from an information theoretical perspective [10]. The authors analysed energy-efficient transmission techniques across time, frequency, and spatial domains considering both single user and multiple users cases. Furthermore, based on the theoretical results, they investigated the design of radio architectures for sustainable wireless communications. However, cellular network is not the main focus of this survey. Li et al. have extended this work, mainly investigating the energy saving benefits of Multiple-Input and Multiple-Output (MIMO), relaying, and multi-hop techniques in Orthogonal Frequency-Division Multiple Access (OFDMA) systems [11]. The authors pointed out some axes of future research in cooperative transmission scenarios and they have also discussed, in terms of EE, the role of signalling information, which is necessary to perform reliable channel estimation. On the contrary, Meshkati et al. proposed an overview of game-theoretic approaches for energy-efficient resource allocation in Code Division Multiple Access (CDMA) networks with delay constraints [12]. In particular, power control, rate adaptation, and channel coding strategies are investigated. Bianzino et al. surveyed most relevant strategies proposed by the research community to reduce the energy waste in *green networking* [13]. Specifically, the authors focused on energy efficient solutions that adapt the link rate to the traffic level, offloading mechanisms that limit the duty cycle at high power nodes, energy-aware software design, and sustainable infrastructures. They presented most the challenging issues, the mainstream paradigms, and proposed a taxonomy of the analysed strategies. Serrano et al. analysed the main sources of inefficiency in WLAN, PAN, and WMAN systems and critically presented the solutions proposed in literature to overcame these issues [14]. Moreover, a quantitative evaluation of the energy saving achieved by the presented approaches with respect to the network load is performed. Feng et al. reviewed energy efficient solutions for improving the sustainability of cellular networks [15]. They started their analysis by briefly discussing the relations between EE metrics and tradeoffs and then, they have focused on Radio Resource Management (RRM) strategies that reduce the energy consumption by adapting the system capacity to load and latency constraints. Besides RRM, the authors also presented Heterogeneous Network (HetNet) deployment solutions and cooperative communication mechanisms, which may greatly improve the energy efficiency of future wireless systems. Finally, Hasan et al. have first discussed most common metrics used to measure the EE of wireless networks; second, they have presented relevant methods to reduce the power consumption at the base station side (i.e., by using renewable energy resources); third, they analysed the benefits that cognitive and cooperative techniques can lead to cellular systems from the energy saving perspective [16].

With respect to these previous surveys, the contribution of this work is threefold. First, we critically discuss energy consumption models proposed in literature to assess the sustainability of the state of the art cellular networks. Second, in an attempt to make order within different existing proposals, we present a global classification of energy efficiency enablers. Third, following the proposed taxonomy, we present a comprehensive overview of industrial and academic research for improving the energy efficiency in cellular networks. In particular, next section gives to the reader a high-level description of the radio access architecture in current LTE standard that is the state-of-the-art technology used as reference in the description of wireless green approaches. Section 3 introduces the energy efficiency evaluation methodology for cellular networks. In Section 4, we present the most relevant metrics to evaluate the EE of a wireless system. In Section 5, we analyse the theoretical trade-offs that highlight the main optimization strategies for green communications. Then, we classify and critically discuss energy-aware management strategies for LTE cellular networks in Section 6. Finally, we conclude the paper by discussing future axes of research and open issues in Section 7.

2. An overview on 3GPP LTE

The deployment of wireless networks compliant with 3GPP LTE is now progressing worldwide, with providers already offering 4G mobile services. These systems are based on the first releases of LTE, 3GPP Rel-8/Rel-9, which were finalized in December 2008 and 2009, and represent a smooth evolution from previous 3GPP systems [17]. Compared to the 3G systems, the first release of LTE exploits OFDMA in downlink and Single Carrier-Frequency Division Multiplexing Access in the uplink; it has also introduced larger system bandwidth (up to 20 MHz) and higher order of MIMO schemes. LTE Rel-9, amongst other features, supports self-organizing network functionalities and enhanced beamforming. These features result in a more a flexible usage of frequency resources, improved Spectral Efficiency (SE), higher data rate, and reduced latency.

However, 3GPP LTE standardization is continuously evolving to meet the requisites of future wireless systems. LTE Rel-10 was completed in June 2011 and it further extends the performance of LTE to fulfil the requirements for IMT-Advanced technologies as defined by the ITU [18]. This release is indicated as the initial phase of LTE-Advanced (LTE-A) process and offers relaying functionalities, up to 100 MHz of transmission bandwidth (through carrier aggregation), and enhanced inter-cell interference coordination (eICIC) mechanisms for improved support of heterogeneous deployment. Rel-11, which was frozen in March 2013, refines some of the features introduced in LTE-A, introduces enhancements in the coordinated multipoint (CoMP) transmission/reception schemes and energy saving mechanisms for the radio access network. Rel-12 is currently under study and initiates the phase indicated as beyond LTE-Advance (i.e., LTE-B), which plans to boost the capacity of LTE-A and to introduce completely new wireless services. Key technologies developed in this framework are: machine-type-communication, 3D beamforming, LTE-WiFi integration, and non-backward compatible carrier type.

In the following, we aim to present the overall architecture of LTE radio access network, named as E-UTRAN (see Fig.1) [19]. In LTE, a base station and a user equipment are indicated as evolved Node-B (eNB) and UE, respectively. A HetNet deployment may include low-power nodes such as picocells, femtocells (HeNBs), and relays (RNs). A eNB serving a RN is also indicated as a Donor eNB (DeNB); however, this entity can be seen simultaneously as a DeNB from a RN and as a classic serving eNB from a UE. Moreover, a RN is classified as in-band relay, when its radio backhaul link with the DeNB uses the same frequency band as the access link; on the contrary, out-of-band relays use a dedicated band for the backhaul link.

HeNBs are typically deployed by end users to improve radio coverage in indoor environments. Furthermore, the consumer Internet connection (xDSL, cable,..) is used to connect them to the core network of a cellular operator. Three different approaches have been investigated in the past to manage the access at HeNBs: Closed Access, Open Access, and Hybrid Access. In Closed Access, only a restricted set of users is allowed to connect to the femtocell; in Open Access femtocells, a subscriber is always allowed to connect to the closer HeNB; in the Hybrid Access approach, femtocells allow the access to all users but a certain group of subscribers maintain higher access priority.

The S1 interface connects the eNBs to the core network: the Mobility

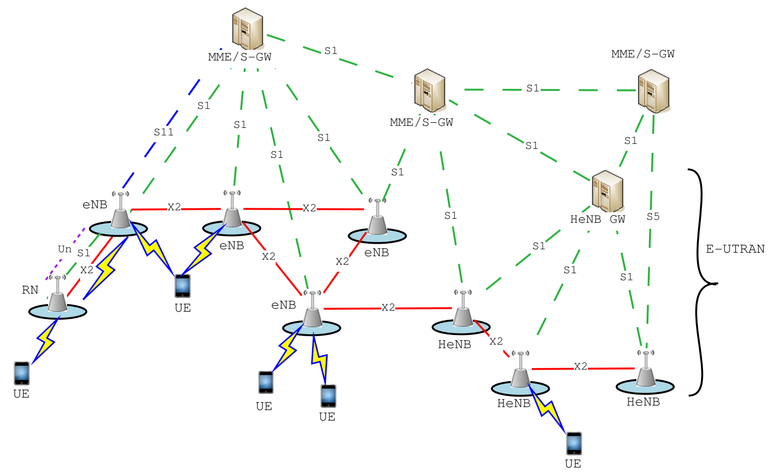

Figure 1: LTE Rel-11 radio access network architecture [19].

Management Entity (MME) and the Serving Gateway (S-GW) serve as local anchors for the control and data plane, respectively. On the contrary, the X2 interface is used to directly inter-connect neighbouring eNBs for enabling functionalities like mobility management, interference mitigation, energy saving procedures, and coordinated transmissions. S1 and X2 interfaces can carry both data and signalling information.

Concerning the relay architecture, the DeNB provides S1 and X2 proxy functionality between the RN and other network nodes (eNBs, MMEs, and S-GWs). Furthermore, the uN interface allows half-duplex operation for the RN. With regard to the HeNB, the LTE architecture may deploy a HeNB Gateway (HeNB GW) that provides locally the control capabilities necessary to manage large clusters of femtocells. Finally, only if the HeNB supports the Local IP Access function, which enables to connect UEs to other IP devices (like printers) via the local HeNB, the latter requires an S5 interface towards the S-GW.

3. Energy Consumption and Cost Models

Traditionally, in cellular systems a quite remarkable research effort has been devoted to the improvement of energy efficiency of UEs, in order to enhance their battery lifetime. The mobile communications research community has recently extended its attention towards energy efficient operation at the BS side. Actually, while mobile terminals consume around the 10% of energy consumed by BSs [20], BSs contribute for between 60% and 80% of the whole cellular network energy consumption [3, 21]. By deploying low power access nodes, such as small cells and relays, Mobile Networks Operators (MNOs) aim at satisfying the ever-growing demand for data traffic and reducing the energy consumption by shortening the distance between the end-users and the serving AP.

In order to assess the impact of different system components on the energy efficiency of wireless networks, and to compare possible technical solutions it is necessary to define models that are able to provide accurate estimation of the energy consumption. However, modelling consumption is not enough, it also necessary to analyse the structure of the overall Total Cost of Ownership (TCO) of the cellular network (see Figure 2). Indeed, introducing novel energy saving solutions may have an impact on both OPerational EXpenditure (OPEX) and CAPital EXpenditure (CAPEX). Hence, several researchers have recently started to investigate models that are able to describe the relationships amongst main sources of costs and energy consumption in wireless networks.

In this section, we aim at discussing the most relevant models proposed in literature, which enable to assess the economical and ecological impact of different energy saving solutions. Therefore, we first overview the two main frameworks proposed in literature to capture the TCO of cellular networks. Then, we present in details those models able to evaluate the power consumption of the components of the radio access network. In particular, we discuss power consumption models for different type of BSs, radio architectures, and backhaul networks.

Tombaz et al. have proposed a simple model that describes the TCO of a cellular network as a function of spectrum leasing ($C_{Spectrum}$), infrastructure (C_{Infra}), and operational costs (C_{Oper}) [22]:

$$C_{TCO} = C_{Spectrum} + C_{Oper} + C_{Infra} = c_0 W + c_1 P_{RAN} + c_2 N_{BS}, \qquad (1)$$

where W, P_{RAN}, and N_{BS} are respectively the system bandwidth, the Radio Access Network (RAN) power consumption, and the number of deployed BSs. Moreover, c_0 [\$/MHz], c_1 [\$/W], and c_2 [\$/BS] are the annualized spectrum cost, the annual cost of energy, and the annual cost per BS.

The authors have investigated the impact of the three cost terms in Eq. (1), and they have drawn fundamental guidelines for the future design of

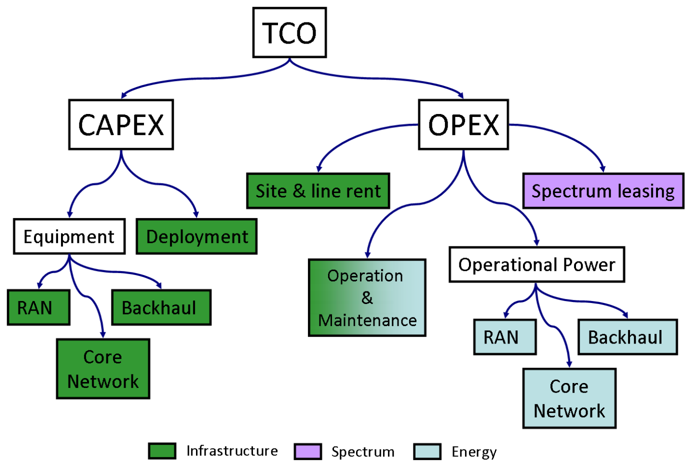

Figure 2: Total Cost of Ownership (TCO) in cellular networks.

sustainable wireless networks [22]. However, their analysis does not consider HetNets, which is one of the major solutions to simultaneously improve capacity and EE in cellular networks. In particular, the type of the deployed BS impacts both infrastructure and operational costs.

In fact, Chen et al., starting from the work of Johansson [23], modelled the annual average cell deployment cost ($\bar{c}_{CO}$) as a function of the cell radius (R) to compare the Macro ($R \geq 0.5\ Km$) and Micro BS ($0.1\ Km \leq R < 0.5\ Km$) deployment options [24]

$$\bar{c}_{CO}(R) = \frac{\bar{c}_{Ca}(R)}{T_{lc}} + \bar{c}_{Op}(R) = \begin{cases} 0.86c_o + c_1\bar{E}_{site}(R), & R \geq 0.5 \\ 0.57c_o + c_1\bar{E}_{site}(R), & 0.1 \leq R < 0.5 \end{cases} \tag{2}$$

where $\bar{c}_{Ca}$ is the total CAPEX, $\bar{c}_{Op}$ is the annual OPEX, c_o is equipment cost of a macro BS, and c_1 is the electricity cost per Joule. Moreover, $\bar{E}_{site}$ is the per-site average energy consumption and the CAPEX weighting factors are based on a CAPEX and OPEX breakdown that considers nodes with a life-cycle of 10 years (T_{lc}) for both Macro and Micro BSs (see Table 1).

However, this study does not reflect the fact that the life-time of a M-BS is likely to be the double of the life-cycle of relays and small cells (10 years vs 5 years) [25, 20]. Henceforth, the contribution of the embodied energy (which includes manufacturing, installation, etc.) on the aggregate energy consumption of low power nodes may be more relevant with respect to the M-BS case.

Total CAPEX	c^C_{BS}	c^C_{Site}	c^C_{BT}	c^C_{RNC}
Macro	c_o	$\frac{1}{4}c_o$	$\frac{1}{4}c_o$	$\frac{3}{2}c_o$
Micro	$\frac{1}{2}c_o$	$\frac{1}{4}c_o$	$\frac{1}{4}c_o$	$\frac{1}{2}c_o$
Annual OPEX	c^o_{BT}	c^o_{Site}	c^o_{OM}	c^o_{Pw}
Macro	$\frac{1}{4}c_o$	$\frac{1}{4}c_o$	$\frac{1}{16}c_o$	$c_1\bar{E}_{site}(R)$
Micro	$\frac{1}{4}c_o$	$\frac{1}{8}c_o$	$\frac{1}{20}c_o$	$c_1\bar{E}_{site}(R)$

Table 1: CAPEX and OPEX breakdown for Macro/Micro BSs [24]. c^C_{BS}, c^C_{BT}, c^C_{RNC} represent the CAPEX related to the BS, backhaul, and radio network controller equipment. c^C_{Site} models the costs due to the site installation and buildout. c^o_{BT}, c^o_{Site}, c^o_{OM}, and c^o_{Pw} represent the OPEX related to the backhaul transmissions, site leasing, operation and maintenance, and BS operations, respectively.

From the energy perspective, it is necessary to include in the RAN power model not only the impact of the BSs but also the effect of the backhaul and the other network elements. Then, the overall power consumption P_{RAN} can be further described as a function of the number of BSs and the actual load of the network [22]

$$P_{RAN} = \sum_{j=1}^{N_{BS}} P_{in,j} + \sum_{j=1}^{N_{BS}} (P_{BH,j} + \beta L_j) + d, \tag{3}$$

where $P_{in,j}$, $P_{BH,j}$, L_j and β, are respectively the BS j power consumption, the backhaul transceiver power consumption at the BS j, the load at BS j, and the load-dependent power consumption of the backhaul and network switches. Moreover, d represents the switch power that is independent by both N_{BS} and L. BSs represent by far the main contribution in Eq. 3: accordingly, ETSI has standardized measurement methodologies, reference BS configurations, and load scenarios to enable fair comparison amongst different radio equipments [26].

Moreover, understanding the impact of the BS components on the aggregate energy consumption is necessary to evaluate the effects of novel enabling mechanisms and architecture for energy saving. The EARTH Energy Efficiency Evaluation Framework (E^3F) maps the radiated RF power (P_{out}) to the power supply of a BS site and underlines the relationship between the BS load and its power consumption [3]. Such a study is based on the analysis of the power consumption of various LTE BS types as of 2010. The effect of the various components of the BS transceivers is considered: Antenna Interface, Power Amplifier (PA), the small-signal RF transceiver, baseband interface, a DC-DC power supply, cooling, and AC-DC supply. Therefore, the E^3F proposes a linear power consumption model that approximates the dependency of the BS power consumption to the cell load:

$$P_{in} = \begin{cases} N_{TRX} P_0 + \Delta_p P_{out}, & 0 < P_{out} \leq P_{max} \\ N_{TRX} P_{sleep}, & P_{out} = 0 \end{cases} \tag{4}$$

where Δ_p is the slope of the load-dependent power consumption, N_{TRX} is the number of transceiver chains, and P_{max} is the RF output power at maximum load. Moreover, P_0 and P_{sleep} indicate the power consumption at minimum non-zero load, and in sleep mode, respectively.

Table 2 shows the reference values of N_{TRX}, P_{max}, P_0, Δ_p, and P_{sleep} for M-BSs, Remote Radio Heads (RRHs), Micro, Pico, and Femto APs, respectively. Current systems mostly lack of sleep capabilities, however, P_{sleep} depends on the hardware components that are deactivated during sleep intervals. Furthermore, more deactivated hardware components result in a longer activation process.

BS type	N_{TRX}	P_{max} [W]	P_0 [W]	Δ_p	$P_{sleep}[W]$
Macro	6	20	130	4.7	75
RRH	6	20	84	2.8	56
Micro	2	6.3	56	2.6	39
Pico	2	0.13	6.8	4	4.3
Femto	2	0.05	4.8	8	2.9

Table 2: BS parameters for the power model in Eq. (4).

Figure 3 shows the operating power consumption of the analysed BS types with respect to the traffic load according the E^3F model [3].

Analysing the BS power consumption as a function of the cell load, we can observe that:

- The Macro and Micro BS power consumption is related to the load, thus, data offloading via low power nodes deployment may enhance the overall cellular network EE;

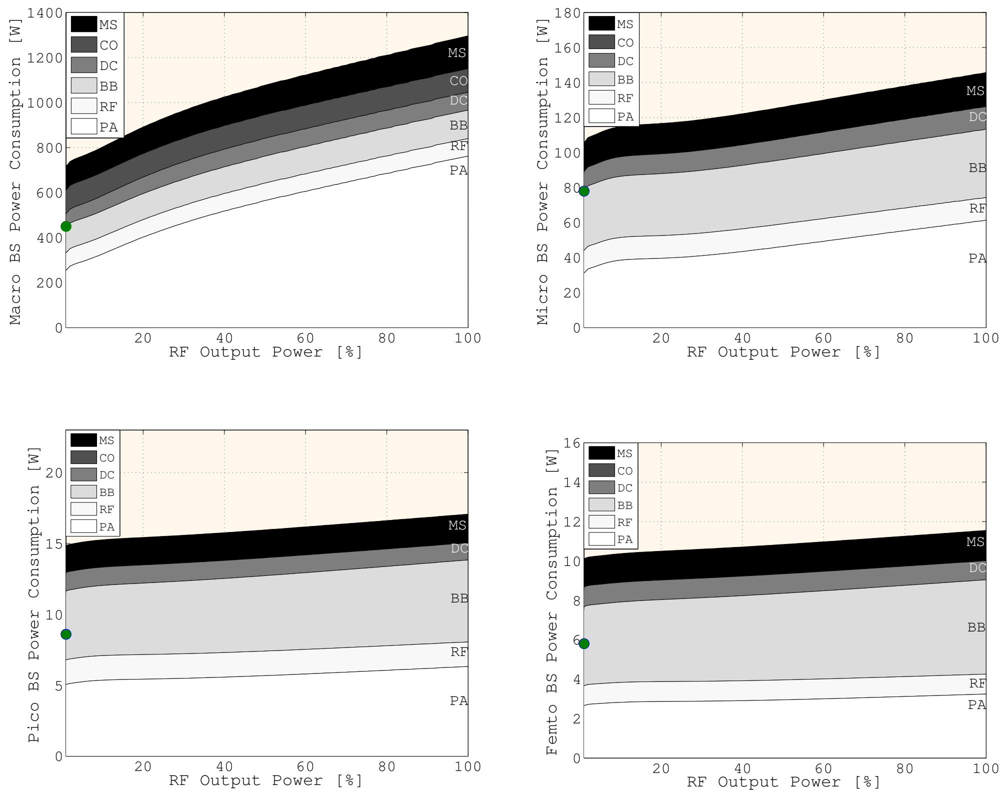

Figure 3: BS power consumption dependency on relative output power [3]. Legend: PA=Power Amplifier, RF=small signal RF transceiver, BB=Baseband processor, DC: DC-DC converters, CO: Cooling (only applicable to the M-BS), MS: AC/DC Power Supply. The circle indicates the BS power consumption in sleep mode.

- Due to the low value of P_{max}, the Femto and Pico APs power consumption does not vary much with the load, thus, the EE of these cells is reduced in lightly load scenarios;

- Retransmissions have a higher impact on macro/micro cell performance and slightly affect pico/femto energy consumption;

- Low-cost PAs designed to scale their power consumption with the load could improve the performance of small cells;

- Dynamic cell switch off techniques can adapt pico and femto cells activity to their load in order to operate only in high EE state.

It is important to note that femtocells normally work in low load scenarios. Due to the limited number of UEs that can be simultaneously served by a Femto AP and the short distance between the access device and the user terminal, spectrum/power resources are often under utilized at femtocells. Furthermore, the small cells density in urban scenarios is expected to be very high. A high number of inefficient BSs can have a detrimental effect on the aggregate cellular network performance.

To introduce more flexibility into the classical low-power node architecture, Attar et al. have investigated a Distributed Antenna System (DAS) with centralised processing capability, connected through optical fiber [27]. In this architecture, Antenna Elements (AEs), which are responsible for transmitting and receiving the signal over the air and to manage the optical-to-wireless conversion (and vice versa), are deployed ad-hoc by the end-users. N_c AEs are logically grouped forming a Coordinated Multi-Point (CoMP) cluster, where transmission is cooperatively managed to limit interference and increase system capacity. However, all signal processing functionalities are implemented in the central unit; hence, the operational power consumption of the proposed architecture can be modelled as

$$P_{DAS} = P_{RoF} N_{AE} + P_{sp}, \tag{5}$$

where P_{RoF} is the power consumption per AE due to the optical medium and RF transmission. On the contrary, P_{sp} represents the power consumption at the signal processing unit, which depends on the number of clusters managed at the central unit and on the number of AEs that form a single cluster.

HetNets and CoMP are currently seen as enabling architectures to improve cellular network capacity and cell-edge user experience while enhancing the system EE. The major counterpart for this advantages is represented by the stringent requirements on the backhaul, which is necessary to perform ICIC, Channel State Information (CSI) exchange, and cooperative transmissions. Nowadays, backhaul solutions are mainly based on copper, fiber, and micro-wave. Furthermore, the worldwide opening of unlicensed spectra around 60 GHz has triggered great interest in developing backhaul based on millimeter-wave technology [28]. Up to now, copper lines have represented by far the most common choice for backhaul implementations. Due to the high cost of deployment, optical fiber has been used only in areas characterized by high traffic. On the contrary, micro-wave is a viable approach for locations where wired backhaul is difficult to deploy. However, OPEX in copper technology scales linearly with the required capacity and current research is focussing on more sustainable solutions for supporting high data rate requirements. Although the backhaul power consumption may have notable impact on the overall network EE, especially when inter-cell coordination is implemented, most of the research in the radio access networks have ignored this aspect [29].

Fehske et al. have investigated the impact of a micro-wave backhaul in CoMP architecture by modelling the backhaul as a set of wireless links whose power consumption is calculated as

$$P_{BH} = \frac{C_{BS} P_{mw}}{C_{mw}}, \tag{6}$$

where C_{BS} is the BS backhaul requirement, C_{mw} is the capacity of the wireless link (assumed to be 100Mbit/s), and P_{mw} is the associated power consumption (50W) [30]. However, the proposed model does not include neither the effect of the backhaul network topology, which strongly affects the aggregate power consumption, nor the impact of the other components of the backhaul network (such as hubs and switches). More recently, researchers have compared the energy efficiency of micro-wave and optical backhaul in HetNets and CoMP scenarios considering also different backhaul topology solutions [31, 32]. The authors have found out that optical fiber may greatly reduce operational power consumption; nevertheless, this technology suffer from topology constraints, which may limit its efficacy. In particular, Monti et al. have also proposed detailed power consumption models for both micro-wave and optical backhaul solutions [32]. In the case of the micro-wave, the power contribution of the backhaul network can be modelled as

$$P_{BH} = P_{sink} + \sum_{j=1}^{N_{BS}} P_j^{MW}, \tag{7}$$

where P_{sink} is the power consumption of the area sink node and P_j^{MW} represents the power consumption due to the micro-wave backhaul at the BS j. Then, these two terms can be calculated as

$$P_j^{MW} = P_{j,agg}(C_j) + P_{switch}(N_j^{ant}, C_j) \tag{8}$$

$$P_{sink} = P_{sink,agg}(C_{sink}) + P_{sink,switch}(N_{sink}^{ant}, C_{sink}) \tag{9}$$

where C_j and C_{sink} are the aggregated capacity that the BS j and the sink have to backhaul, N^{ant} is the number of micro-wave antennas, P_{agg} is the power consumption for transmitting and receiving the backhaul traffic, and P_{switch} takes into account the power consumption of the switches that are used at any BS/sink to aggregate traffic received from more that one site. Furthermore, P_{agg} can be modelled as a step function with respect to the total backhaul capacity C_j, and the number of used switches can be calculated as a function of C_j and maximum capacity of a switch C_{switch}^{MAX} [32]. On the contrary, for the fiber-based backhaul, the total power consumption is modelled as

$$P_{BH} = \left\lceil \frac{N_{BS}}{max_{dl}} \right\rceil P_s + N_{BS} P_{dl} + N_{ul} P_{ul} + \sum_{j=1}^{N_{BS}} c_j, \tag{10}$$

where max_{dl} is the maximum number of downlink interfaces available at one aggregation switch, P_s is the power consumption of a switch, P_{dl} is the power consumption due to one interface of a switch, and N_{ul} and P_{ul} are the total number of uplink interfaces, and the power consumption of one uplink interface, respectively. Finally, c_j represents the power consumption of a small form factor pluggable optical interface, which is used to connect a BS to the switch at the hub node.

In this section, we have presented the models proposed in literature to capture the economical and ecological characteristics of cellular networks. Most of these models are complementary, in the sense that they are related to different architectures and therefore it not worth to compare them. However, to summarize this section we describe in Table 3, the main advantages of drawbacks of these models. The first and the second column present the model and the related reference(s), respectively; the third and the fourth column indicate their main advantages and disadvantages.

4. Green metrics

The growth of interest concerning green communications has led to the development of a multitude of solutions to improve the cellular network EE. However, these strategies are different in nature; hence, it is necessary to have reliable and widely accepted instruments to evaluate energy saving techniques and their performance in practical systems. Chen et al. have defined the objectives of the green metrics as [33]:

Model	Ref.	Advantages	Drawbacks
Cellular network TCO	[22]	This model captures the impact of spectrum leasing, infrastructure costs, and operational costs	This model does not consider small cells
Annual average cell deployment cost	[24, 23]	This model permits to compare deployment costs of macro and micro BSs	It does not reflect the fact that the life-time of a M-BS is not the same as for a small cell; Cost parameters are based on technical reports as well as on the authors assumptions
RAN power consumption	[22]	This model describes the impact of the BSs, the backhaul, and the other network elements on the overall RAN power consumption	It has been used for a qualitative analysis and it does not describe how to calculate the power consumption components in details
BS power model	[3]	This model is based on measurements provided by vendors and mobile operators; It captures the relationship between the load and the input power of different type of BSs; It models the BS sleeping capabilities	It does not characterize relays and backhaul power consumption
DAS power model	[27]	This model describes the power consumption of an architecture where AEs are managed by a CU	It does not include the backhaul power consumption
Micro-wave link power model	[30]	This model describes the power consumption of micro-wave link	It does not capture the effect of the backhaul network topology/architecture
Micro-wave/Fiber backhaul network power model	[32]	This model captures the effect of the network topology and reflects the power consumption due to each component of the backhaul network	Parameters are based on technical reports as well as the authors assumptions

Table 3: Characteristics of the economical and power models proposed in literature.

1. compare the performance of components/systems, which belong to same class;
2. set research and development targets;
3. enable system adaptation towards a more sustainable configuration.

Moreover, they have defined three classes of EE metrics: component level, equipment level, and system/network level metrics. Component level metrics measure the performance of a specific equipment (such as antenna, PA, and power supply) of a wireless device. Equipment level metrics assess the EE of a given device (end-user terminal or BSs). Finally, system/network level metrics describe both the energy consumed by the wireless device and the performance measured at network level (such as coverage, capacity, and delay). Our goal is to investigate the energy efficiency of the overall cellular network; therefore, in the following, we discuss recent contributions on network level metrics.

The simplest metric to compare different network configuration is the Energy Consumption Gain (ECG) [%] [9], which measures the ratio of the energy consumption at the baseline system and at system under test. It is worth to mention that the ECG is often unfair and can drive to misleading conclusion when used to compare systems with different characteristics.

To solve this problem, more complex metrics are mostly used in literature. In particular, amongst the network level metrics, we can distinguish those metrics that are presented as Energy Consumption Index (ECI) and those that are described as Energy Efficiency Index (EEI) [34]. ECI metrics are computed as the ratio of the consumed energy and a given Key Performance Indicator (KPI), whereas EEI metrics are defined the other way around.

$$\left.\begin{aligned} ECI &= \tfrac{E}{KPI} \\ EEI &= \tfrac{KPI}{E} \end{aligned}\right\} \Rightarrow ECI = EEI^{-1} \tag{11}$$

Hence, representing a metric as an ECI or an EEI is equivalent, in the sense that in both cases the metric contains the same information; however, they can lead to different interpretations.

Consider for instance, the Energy Efficiency metric [bit/J or bit/s/W] [24], which is defined as the ratio of the total network throughput per unit bandwidth over the network energy consumption within a given period. Left side of Figure 4 shows the behaviour of such metric as a function of the power consumption. A small energy saving in the low power region (Δ P') results in high EEI gain (Δ EEI'); on the contrary, a high energy saving (Δ P") in the medium/high power region leads to a small EEI gain (Δ EEI"). However, by using an ECI metric, the gain linearly increases with the energy saving. Therefore, ECI metrics allow a more intuitive analysis of the system performance.

A well-known green metric is the Energy Consumption Rating (ECR), which is defined as the ratio between the peak power and the maximum data throughput that is successfully delivered by the network [J/bit or W/bit/s] [35]. However, this metric is appropriated only to describe the system behaviour at full load. In order to obtain a more general characterization, the EARTH project has proposed an energy per bit metric, which is defined as the network energy consumption during the observation period divided by the total number of bits successfully delivered in the network during the same period [34].

The ECR initiative have also proposed the variable-load ECR (ECR-VL), which is a weighted metric that is able to capture the degree of proportionality between the energy consumption and different levels of load [35]. This

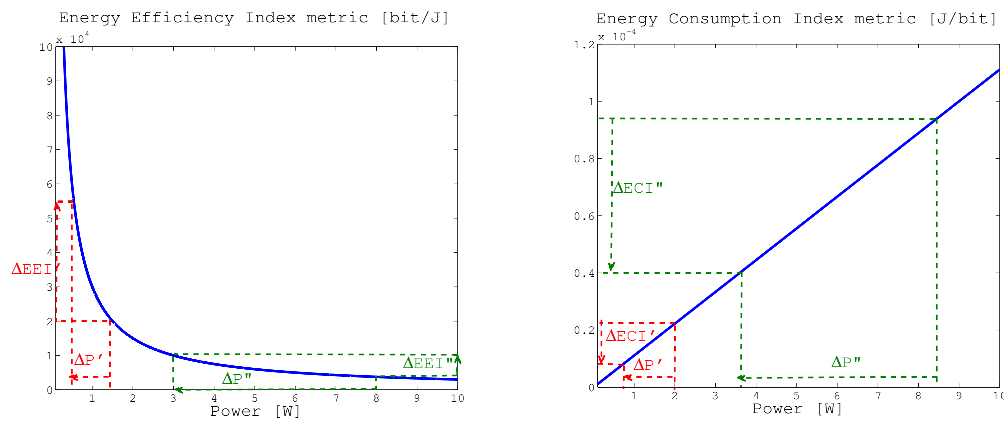

Figure 4: Energy Efficiency Index (left) vs Energy Consumption Index (right) [34].

metric is suitable to optimize systems in a particular operating point; in fact, weight coefficients are introduced to represent the relative importance of different modes of operation and are application-dependent. Extended-idle ECR (ECR-EX) further enhances ECR by describing the system energy saving introduced by terminals that enter in sleep mode during periods of low utilization [35].

Another relevant metric is the power per subscriber that is defined as the ratio of the average network power consumption and the number of *satisfied users* [W/UE] [34]. The measurement of the satisfied users gives an intuitive description of the network Quality of Service (QoS) and also provides a reliable information on the unitary costs per users, which is a powerful information for MNOs. Such metric is likely to be used to evaluate the efficiency of the system in dense urban areas where the traffic demand is often larger than the network capacity. On the contrary, the Area Power Consumption (APC) $[W/m^2$ or $m^2/W]$ is a useful metric to describe system performance in scenarios where the network works below its capacity (e.g., in rural scenarios) and the coverage is the main KPI [26, 36]. The main advantage of the APC is that it does not use ratio of variables (the coverage area is often a system parameter), which can avoid misleading conclusions. In general, when combining different variables it is often difficult to understand which is the variable that leads to a variation of the metric.

Metrics	Units	Type	Calculation	Advantages	Drawbacks
ECG [9]	[%]	N/A	$\frac{E_{System\ 1}}{E_{System\ 2}}$, where $E_{System\ 1}$ and $E_{System\ 2}$ are the energy consumptions at the systems under test	Easy to calculate and understand	Useful only to compare systems/elements with same characteristics
EE [24]	[bit/J]	EEI	$\frac{R}{P}$, where P is the average power and R the average rate	It increases when energy consumption is reduced	It is not proportional with the power consumption
ECR [35]	[J/bit]	ECI	$\frac{P_f}{R_f}$, where P_f and R_f are the peak power and the maximum rate	It is proportional with the power consumption	It fits only for full load systems
E_b [34]	[J/bit]	ECI	$\frac{P}{R}$, where P is the average power and R the average rate	It reflects data rate improvements; Its captures loads variations	It diverges when traffic load approaches zero
ECR-VL [35]	[J/bit]	ECI	$\frac{\alpha P_{100}+\beta P_{50}+\gamma P_{30}+\delta P_{10}+\epsilon P_0}{\alpha R_{100}+\beta R_{50}+\delta R_{30}+\gamma R_{10}}$, P_x and R_x represent the power and the rate experienced when the network is at the x% of the load	It enables optimization at different operating points	Calculation is not simple
ECR-EX [35]	[J/bit]	ECI	$\frac{\alpha P_{100}+\beta P_{50}+\gamma P_{30}+\delta P_{10}}{\alpha R_{100}+\beta R_{50}+\delta R_{30}+\gamma R_{10}}$, P_x and R_x represent the power and the rate experienced when the network is at the x% of the load	It models networks with energy saving capabilities	Power in sleep mode may be greater than 0; Calculation is not simple
P/subscriber [34]	[W/UE]	ECI	$\frac{P}{N_{UE}}$, where P is the average power and N_{UE} the number of satisfied UEs	Suitable for evolutionary comparisons between systems with different rate targets	It does not have specific drawbacks
APC [26, 36]	[W/m^2]	ECI	$\frac{P}{A}$, where P is the average power and A the covered area	Easy to calculate and understand; It reflects service area aspects; It allows to compare networks of different cell sizes	It is not relevant for capacity limited systems; In real network measurements, it can be complex to assess the coverage area
DE [24]	[bits/$]	N/A	$\frac{I}{C}$, where I is the number of bits transferred and C the yearly deployment cost	It jointly reflects CAPEX and OPEX	CAPEX can be complex to calculate due to the lack of available information

Table 4: Summary of Green Metrics.

The Deployment Efficiency (DE) [bits/$] is used to characterize the EE of heterogeneous architectures [24]. DE is defined as the ratio of the network throughput per unit bandwidth over the network deployment cost within a year of operation. The network deployment cost includes both OPEX and CAPEX related to the network under test.

Finally, Table 4 synthesizes the main features of the analysed green metrics. The first column indicates the metric names and references; the second column indicates the units of measurement. The third column shows how to calculate the selected metric. The fourth and the fifth columns respectively describe the main advantages and drawbacks of each metric presented in this survey.

5. Fundamental trade-offs

In this section, we aim to present the fundamental trade-offs that are the theoretical basis for optimizing the wireless system configuration with respect to the energy consumption. These guidelines are important as they offer a holistic vision of the issues that characterize the system optimization. Furthermore, they capture aspects related with different network layers, such as the radio resource allocation, the network topology, coverage, and QoS constraints.

5.1. Energy per bit versus Spectral Efficiency

SE has been classically considered as the main criterion to optimize performance in wireless communication systems. More, recently, energy consumption has risen as an important design metric for future cellular networks. Preliminary results on the relation between Energy per information bit (E_b) and SE are based on seminal work of Shannon in [37], from which Golay [38] derived the minimum amount of received energy per bit of information (E_b^r) to reliably communicate over AWGN channels:

$$E_b^r = N_0 \cdot log_e 2 \tag{12}$$

where N_0 is the one-sided noise spectral level. This result can be obtained only at cost of infinite bandwidth and therefore null SE. However, in realistic scenarios, required E_b^r is strictly greater than the value achieved when Shannon capacity is considered [39].

Moreover, it is important to note that, considering only the RF power [39, 40], irradiated energy per bit monotonically increases with the SE (see the star-marked curves in Figure 5). Therefore, using the lowest order of Modulation and Coding Scheme (MCS), which limits the SE, may be assumed as the best strategy to minimize energy consumption [40].

On the contrary, when a more realistic model, which includes the energy consumption due the various components of the BS transceiver, is considered, the relation between E_b and SE is given by

$$E_b = \frac{P_0}{W \cdot SE} + \frac{\Delta_p \cdot (2^{SE} - 1)}{\gamma \cdot W \cdot SE} \tag{13}$$

where

$$SE = \frac{R}{W} = \log_2(1 + \gamma \cdot P_{out}) \tag{14}$$

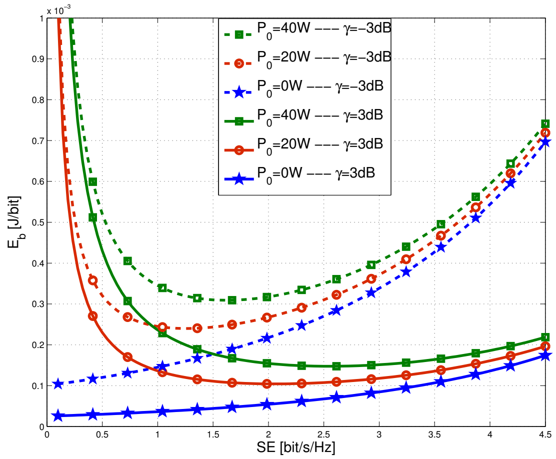

Figure 5: Energy per bit versus Spectral Efficiency trade-off. Star-marked, circle-marked, and square-marked curves respectively correspond to scenarios in which the BS minimum power consumption is equal to 0W, 20W, and 40W. Dashed and solid curves respectively correspond to results obtained for scenarios with normalized SINR equal to -3dB and 3dB.

Moreover, P_0, P_{out}, and Δ_p are parameters defined in Eq. (4), W is the channel bandwidth, R is the data rate, and γ is the normalized SINR experienced at the receiver. Therefore, a joint optimization of SE and energy consumption can allow more efficient communication [41]. In particular, assigning higher orders of MCS to those UEs that experience high SINR (such as the UEs that are close to the serving BS) may enable notable energy savings (compare dashed and solid curves in Figure 5). Moreover, when P_0 increases, it is important to limit the transmitter duty cycle; thus, in this case, improving SE also introduces energy saving (compare circle- and square-marked curves in Figure 5) [42].

Researchers have also observed that, in flat fading channels, increasing the number of allocated sub-channels reduces the energy consumption; however, in frequency selective channels, it is necessary to adjust channel allocation and transmission parameters for enabling energy-efficient transmissions [41].

However, to implement fast link adaptation mechanisms and exploit high data modulation mode (such as 64-QAM), a complete and dynamic knowledge of the wireless channel characteristics is required at the transmitter. In current cellular transmission standards, this issue is solved by continuously sending pilot symbols in the transmission frame. Depending on the channel bandwidth, from 10% to 20% of the available power at the BS is used to broadcast system information and these pilot symbols [43]. Therefore, from an energy efficient perspective, it is desirable to reduce the feedback traffic. To limit signalling and complexity, slow link adaptation, can be used to adapt transmission parameters to slow channel variations (i.e., neglecting the effect of fast fading). This approach is characterized by reduced SE with respect to fast adaptation schemes; however, it can introduce notable energy saving in wireless networks [44].

Another element that has a relevant impact on the discussed trade-off is co-channel interference [45]. In noisy-limited systems, increasing SE is always beneficial; however, when the user performance is interference-limited, adapting the SE is necessary to avoid outage events and energy wastage. Consider a system in which two neighbouring BSs communicate with mobile terminals as depicted in the left side of Figure 6. Therefore, the system E_b can be described as

$$\begin{aligned} E_b &= \frac{P_{in}^1 + P_{in}^2}{W \cdot (SE^1 + SE^2)} = \\ &= \frac{2P_0}{W \cdot (SE^1 + SE^2)} + \frac{\Delta_p P_{out}}{W \cdot (SE^1 + SE^2)} \left(\frac{2^{SE^1} - 1}{\alpha} + \frac{2^{SE^2} - 1}{\beta} \right), \end{aligned}$$

where we have assumed that the BS1 and BS2 transmit with the same RF power P_{out} and use the same bandwidth W. Moreover, $\alpha = \frac{h11}{h21}$ and $\beta = \frac{h22}{h12}$ are the network coupling factors, which describe the inter-cell interference. As shown in the right side of Figure 6, the pair (SE^1, SE^2) that minimizes the overall E_b strongly depends on (α, β). For instance, when the BSs are located far from each other (i.e., $\alpha, \beta \to \infty$), both cells should use the highest possible MCS (see the red surface). However, when inter-cell interference increases, lower MCSs are necessary to improve the system performance. Eventually, when one of the network coupling factor is greater the other ($\beta \gg \alpha$, see the light blue surface) the corresponding cell can operate with high SE, while the interfered cell should increase its transmission robustness.

5.2. *Energy Efficiency versus Coverage*

The explosion of data traffic, driven by smart-phones and video applications, has shown the limitations of the classic macro-based deployment in

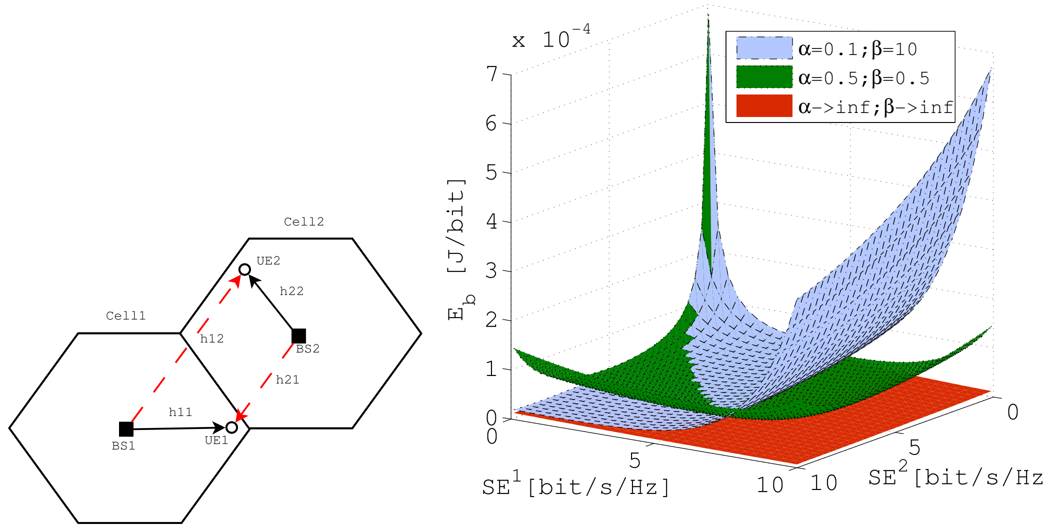

Figure 6: The two cell-system under investigation (left) and the E_b vs SE trade-off in interference-limited scenarios (right). $\alpha = \frac{h11}{h21}$ and $\beta = \frac{h22}{h12}$ are the network coupling factors.

cellular networks. Currently, about 50% of traffic is carried on by only the 15% of deployed BSs [46]: 70% of the overall traffic is generated by indoor users [47], and in average, cell load is below 10% of its peak from 30 to 45 % of the time [21]. State of the art M-BSs have not any energy saving capabilities, and at low traffic scenarios consume nearly the 90% of the maximum power consumption [21]. Furthermore, by implementing solutions that aim to guarantee continuous coverage by using few BSs characterized by high radiated power, cell-edge and indoor users are experiencing very poor performance due to propagation losses and interference.

Small cell network deployment has sparked tremendous interest in recent years and nowadays represent the major solution to achieve the capacity requirements of 3GPP LTE. Deployment of low-cost short-range BSs permits to extend the cellular network coverage and improve performance experienced at end-users by shortening the distance between mobile terminals and access points. Furthermore, recent studies claim that the small cell solution may reduce both OPEX and CAPEX for cellular operators, in particular when they are deployed ad-hoc to boost the system capacity in dense urban areas

[48, 49]. However, embodied energy does not scale with the cell size [50], and the aggregate cellular network energy consumption might increase due to the massive and uncoordinated roll out of additional BSs and backhaul.

Moreover, EE improvement due to macrocell offloading is constrained by the M-BS power consumption, which depends only partially on the cell load, and by the small cell access mode [51]. In open access mode, local APs allow access to all subscribers; however, in closed access mode, only a restricted set of users can access to the small cell. Open access small cells may have a higher impact on saving energy at cellular networks, due to the increase offloading and reduced interference [48]. On the contrary, cross-tier interference strongly affects macro user performance in closed access deployment.

Researchers have compared different size cells in terms of energy consumption, TCO, and DE [50, 52]. However, a unique optimal solution likely does not exist, and further studies should focus on the optimal balance amongst different type of BSs for a given traffic scenario. Furthermore, a fair analysis should also include the backhaul energy consumption and adaptive mechanisms that enable to introduce energy saving in lightly load scenarios.

Eventually, cooperative transmissions through relay deployment and/or CoMP is a promising technique, which exploits diversity schemes, to jointly improve coverage, capacity, and EE in cellular networks [27, 53]. However, in order to limit the impact of co-channel interference and achieve performance close to the theoretical bounds, these systems are characterized by complex signal processing and need to share (at least) CSI. Therefore, future investigations need to evaluate the burden that can be carried by the radio and backhaul networks while maintaining the system sustainability. These studies will enable to select the optimal backhaul medium and topology and also to efficiently configure the size of cooperative clusters.

5.3. Energy Efficiency versus end-user performance

Although in the previous sections we have mainly discussed of system level trade-offs, here we analyse a trade-off that mainly concerns the QoS experienced at the end-user. Up to the 3G mobile communication systems, services and traffic types have been very limited, and voice, which is characterized by low data rate and tight delay constraint, has been the major source of traffic. However, as shown in Figure 7, the trend is radically changing; this evolution is creating the opportunity to improve the cellular network sustainability by trading off service latency for energy consumption. Delay tolerant

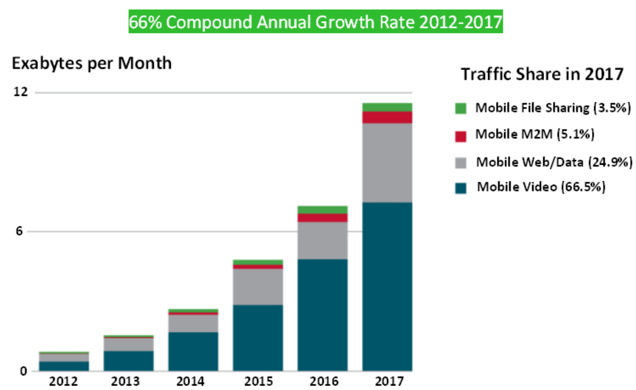

Figure 7: Mobile traffic trend according to Cisco VNI Mobile [1].

service demands can be accommodated when channel/network conditions are beneficial; moreover, broadcast transmissions enable energy saving by simultaneously serving multiple users that request the same data content.

Earlier studies have indicated that is desirable to transmit packets over a longer period of time to save irradiated power [40]. However, when load-independent energy consumption is taken into account, this approach may lead to poor performance, since circuit power consumption increases linearly with the transmission time [10]. In fact, E_b can be expressed as

$$E_b = \frac{P_0 T}{R} + \frac{\Delta_p T}{\gamma R}\left(2^{\frac{R}{WT}} - 1\right), \tag{15}$$

where T is the transmission time duration and R the user-rate target.

Figure 8 shows that limiting the BSs duty cycle improves the system EE. Nevertheless, the optimal value of the service latency also depends on the heterogeneous requirements of the traffic generated in the cell. Furthermore, limiting the BS activity and related power consumption introduces several technical challenges from both hardware and RRM perspectives. First, enabling dynamic BS operations requires Self Organizing Network capabilities and agile transmission chains to flexibly react to changes in the network load [54]; second, current 3GPP standard constrains continuous transmission of pilot channels to guarantee coverage [55]; third, BS cooperation is necessary to avoid outage events whenever the number of activated BSs changes [56]. Moreover, hardware components, which remain active during sleep mode,

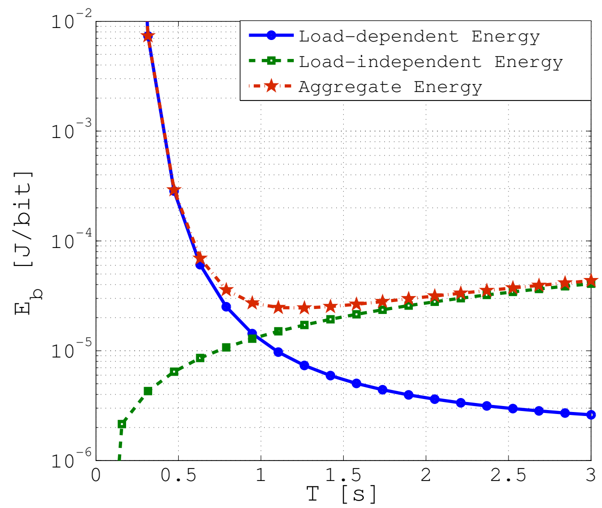

Figure 8: Energy per bit vs service latency trade-off (R=1 Mbit/s, γ=3dB) [10].

should be characterized by a very limited power consumption to avoid energy wastage. However, the number of deactivated components impacts also on the time necessary to reactivate the BS, which further increases end-to-end experienced latency.

6. Energy-Aware Management Strategies

Future wireless networks require enabling mechanisms/hardware, which exploit the green trade-offs to improve the network sustainability. These approaches enable the cellular network to adapt its characteristics to load variations and avoid energy wastage while ensuring end-users QoS. Then, a first classification of such enabling technologies can be made by observing the time-scale, in which they operate.

Fast adaptation mechanisms are implemented in short-time scale (from milliseconds to seconds) to reply to fast changes due to mobility, cell load, and wireless channel conditions. Slower schemes operate on a per hours-basis in order to adapt the network characteristics to the traffic daily variations. In fact, load presents a regular pattern during the day [57], which can be used to predict average capacity request in a given geographical region. Moreover, additional flexible hardware/software can be integrated in the system in a longer time scale (weeks to months) to improve the network capacity in a more sustainable way. Finally, each network energy saving technique can also be analysed with respect the domain in which it runs. Basically, we can identify mechanisms, which change the network configuration and parameters in time, frequency, or space domain. For instance, bandwidth adaptation operates in the frequency domain while small cell switch-off creates geographical hotspots. Figure 9 presents a general classification of the energy-efficiency enablers proposed in literature.

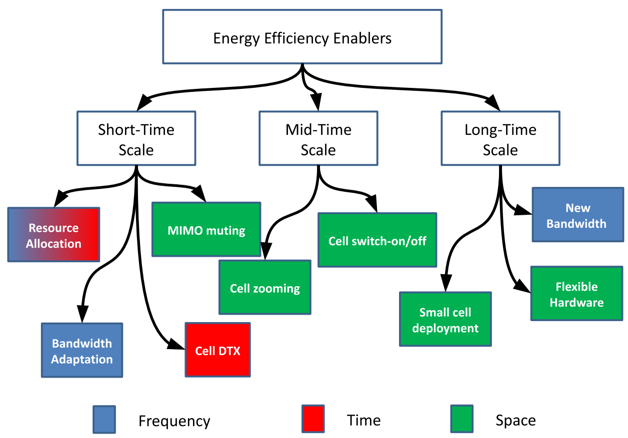

Figure 9: Energy Efficiency Enablers classification.

6.1. Short time-scale

The cell data rate is characterized by short term variations, which depend on several factors such as the number of active UEs, the traffic types, and mobility. Therefore, fast adaptation mechanisms, which operate in the transmission time interval, are required to dynamically match the actual traffic demand and the cell available capacity. Cognitive Radio-based algorithms can be used to measure and predict cell load variations and adapt network parameters accordingly [58].

An intuitive approach consists in limiting the usage of transmission resources in the frequency, time, and spatial domains. 3GPP/LTE downlink implements an OFDMA air interface where OFDM symbols are organized into a number of physical Resource Blocks (RBs) consisting of 12 contiguous sub-carriers for 7 consecutive OFDM symbols (see Figure 10). With a bandwidth of 10 MHz, 50 RBs are available for data transmission; however, LTE defines a set of transmission bandwidths (from approximately 1.25 MHz up to nearly 20 MHz) that can be selected according to the cell load.

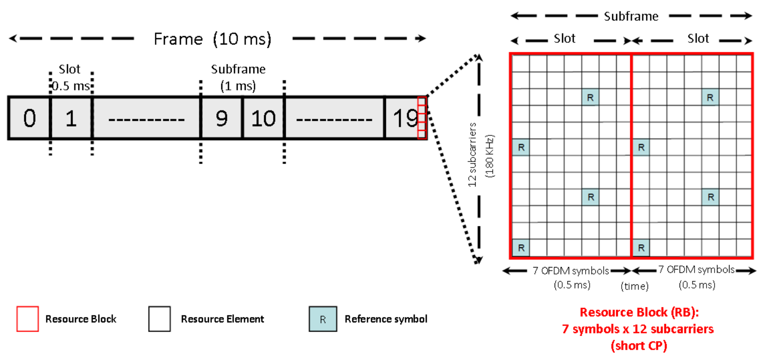

Figure 10: LTE air interface.

Using less frequency resources reduces the irradiated power and also limits the number of reference symbols: switching from 10 to 5 MHz can enable up to 3 dB of energy saving [59]. A step forward scheme exploits an energy-aware resource scheduler that concentrates the allocated RBs on a fraction of the available bandwidth [6]. Then, additional energy saving can be achieved by avoiding transmissions of reference symbols in data-free sub-carriers and also by adapting the operational point of the PA to the new output power. However, this Bandwidth Adaptation approach is characterized by two main drawbacks: first, it reduces the benefits of frequency diversity, second it requires modifications in the standards to fast switch amongst different bandwidth configurations.

In order to solve this issues, the EARTH project has proposed a Capacity Adaptation scheme [6], which, on the contrary, constrains the maximum number of RBs to allocate on the entire available bandwidth (see Figure 11). This approach is transparent for the end-user and is able to exploit the frequency diversity; however, reference symbol transmission can not be limited.

Energy saving in time-domain can be achieved by dynamically deactivating hardware components (such as the PA), when transmission is absent in a given frame [55]. The benefits of the discontinuous transmission (DTX) ap-

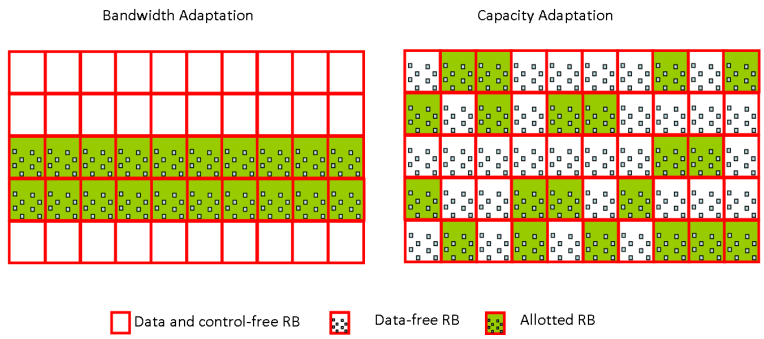

Figure 11: Scheduling pattern with Bandwidth Adaptation (left) and Capacity Adaptation (right) with 40% of cell load [6].

proach are limited by the transmission of control signal, which is required by the 3GPP standard even in absence of downlink traffic. However, this basic scheme can already achieve nearly the 50% of energy saying at the BS [59]. In a more advanced approach, the Multicast-Broadcast Single Frequency Network (MBSFN) frame, which is a new feature introduced in LTE to enable mobile TV broadcasting, is used to introduce longer sleep periods, since less signalling is transmitted in this frame. Finally, a more radical approach named as extended DTX proposes to completely remove reference symbols to enable further energy savings [6]. Hence, only synchronization signals and the broadcast signal are used in idle scenarios, and mobility measurements are performed on the synchronization signals. However, this approach requires standard modifications and it is not transparent for the UE, which may lose synchronization and also be unable to enter in discontinuous reception mode, which preserves the battery life [59].

MIMO muting introduces energy saving in the spatial domain by dynamically adapting the number of active antennas in each cell [59]. As for the solutions that operate in the time/frequency domains, the main issue is to fast implement this adaptation mechanism (i.e., avoiding signalling exchange with UEs) while satisfying coverage and data rate constraints. Two main approaches are discussed in the EARTH framework to implement MIMO muting in a transparent way [6]: in the first case, the control signal for muted antennas are not transmitted, accordingly, neighbouring UEs will perceive these signals as in deep fade. In the second scheme, the signal corresponding to active and muted antennas are added together and transmitted by only a physical antenna. Then, these signal will be seen as correlated at the end-users.

An alternative approach to MIMO muting is to use a very large number of antennas at BSs to operate in a limited energy per bit region. This idea, named as massive MIMO, originates from the linear relation between the ergodic capacity and the minimum value between the number of antennas at transmission/reception sides [60]. However, the benefits of MIMO systems strongly depend on the availability and robustness of CSI of all transmission links. In practical scenarios, CSI is affected by interference, delay, and user mobility, and it is hardly *perfect*. Ng et al. have investigated the resource allocation problem (in terms of number of antenna, power, frequency resources, and data rate) at cellular BSs characterized by a large number of antennas and they have also considered the effect of imperfect CSI [61]. The authors have showed that this optimization problem is non-convex, and to limit the complexity and latency, they have found and equivalent problem that can be solved with an iterative algorithm. Hence, based on shadowing and path loss information, BSs adapt the resource allocation scheduling according to a policy that maximizes the cell EE. The authors have considered a single cell scenario, however, intra-cell interference, due to the sub-carrier reuse, affects the end user performance. Simulation results have showed that high number of antennas is always beneficial from a capacity perspective, even with imperfect CSI; however, an exceedingly number of active antennas strongly increases the circuit power consumption, which may limit sustainability.

Another relevant resource allocation problem addressed in literature, is the energy-aware scheduling in cooperative cellular networks. Devarajan et al. have considered the scenario where amplify-and-forward relays are deployed by MNOs to enhance performance of cell-edge users [62] (see Figure 12). In this context, the authors have proposed a user selection and power allocation algorithm, which enhances the network EE while ensuring user QoS. The macro cell is divided in several clusters, each served by a different relay. Then, at a given time slot, each relay is responsible to serve one of the users located in its cluster, while simultaneous transmissions are operated in different cluster on orthogonal channels. Hence, in the scenario under test, interference issue is neglected. The user selection is normally managed to jointly limit RF power at both source and relay; moreover, a fairness algorithm is introduced to avoid starvation of users that experience high propagation losses. Simulation results have showed that the proposed algorithm optimally balances energy consumption and throughput.

To summarize this section, we show in Table 5 the main characteristics of the energy efficient RRM algorithms operating in a short-time scale. The first and the second column present respectively the algorithm name and the related reference(s); the third column indicates in which load scenario the algorithm performs the best. The fourth column underlines whether the algorithm requires inter-cell cooperation. The fifth and the sixth columns respectively describe the main advantages and drawbacks of the algorithms presented in this section. Finally, the seventh column indicates the impact of the presented algorithm with respect to the 3GPP standard.

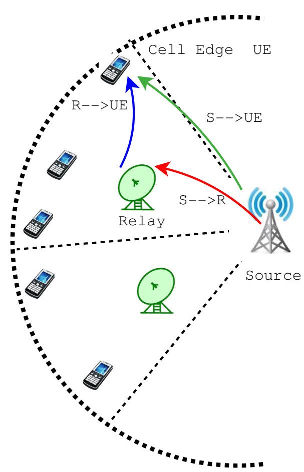

Figure 12: Energy-aware resource allocation in cooperative cellular networks [62].

6.2. Medium time-scale

In this section, we aim to discuss technologies that operate in mid-time scale and enable energy saving by adapting system characteristics to the slow variations of the network load. Traffic daily profile shows a regular pattern during the day with low load periods early in the morning, medium loads during work-time, and high data rate in the late evening (see Figure 13); this profile holds also on a weekly time scale, however, weekends are characterized by lower traffic demands with respect to workdays [43].

Nevertheless, mobile networks are normally dimensioned to deal with peak time traffic and are under-utilized during the rest of the day. As previously discussed, BSs are characterized by high power consumption even at very low load scenarios, and in these cases, limiting the number of simultaneously activated BSs can result in notable energy saving. This energy saving

Algorithm	Ref.	Scenario of interest	Inter-Cell Cooperation	Advantages	Drawbacks	Standard impact
Bandwidth Adaptation	[6, 43, 59]	Low loads	Not required	It reduces the signalling overhead	It reduces the benefits of frequency diversity	It requires modifications in the standards to fast switch amongst different configurations
Capacity Adaptation	[6]	High loads	Not required	Transparent to the mobile terminals; Enable a fine adaptation to the traffic load	Reference symbol transmission can not be limited	No restrictions
Cell DTX	[55, 59, 6]	Low loads	No	It limits the power consumption when there is no data traffic	Advanced hardware is required to fast switch on the AP	No restrictions
MBSFN based DTX	[59, 6, 55]	Low loads	No	It further limits the reference symbol transmission	MBSFN result in limited capacity; Switching from MBSFN to classic unicast frame is a slow procedure	MBSFN was defined in LTE Rel-8
Extended DTX	[59, 6, 55]	Low loads	No	It avoids the transmission of cell specific reference symbols	Not compatible with current standard	It may be introduced in LTE-Rel 12
MIMO muting	[59, 6]	Low loads	Can be beneficial	It reduce the number of active PAs	It may lead to coverage issue; Cell edge UEs may perceive poor SINR	No restrictions
Massive MIMO	[61, 63]	Medium/High Loads	No	Radiated power can be greatly reduced	Early stage technology	No restrictions
Cooperative RRM	[62]	Medium/High Loads	Required	This scheme limits the system radiated power	Poor spectrum reuse	No restrictions

Table 5: Characteristics of the Energy-Aware Management Strategies operating in short-time scale.

approach can be implemented in three different uses cases [64]:

- Inter-eNB energy saving;

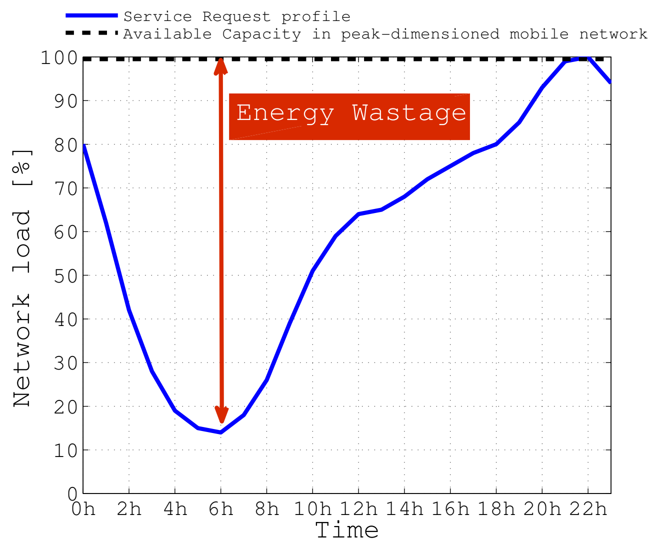

Figure 13: Average data daily traffic profile in Europe [57].

- HetNet energy saving;
- Inter-Radio Access Technique (RAT) energy saving.

In the first case, when the mobile network is working in off-peak, load is concentrated in a small number of cells that remain active while a given set of BSs can deactivate transmission functionalities. This mechanism, also named as cell zooming [65], requires that BSs, which stay active react to changes in the network layout to compensate the coverage losses (see Figure 14). This constraint presents different challenges in terms of inter-cell interference and coverage holes, which can be experienced in the area where deactivated BSs are located.

The general problem of which base station to activate based on the traffic profile is introduced and analyzed in [66], where mathematical programming models that address the key capacity and coverage constraints are presented. The degrees of freedom available for adapting the active set of BSs to the traffic profile obviously depend on the network layout. In [67, 68] the problem of designing an optimal network layout for exploiting at best the adaptation mechanisms to traffic profile is introduced for the cases with and without

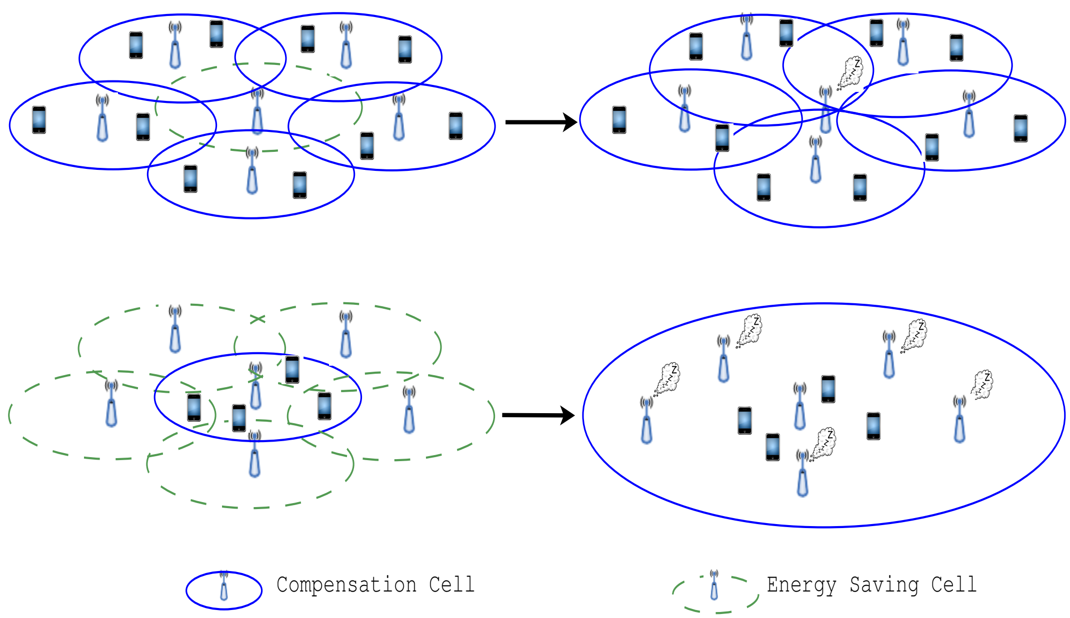

Figure 14: Cell zooming operations in mobile networks.

relay nodes. It is shown that there is a trade-off between network deployment cost and level of efficiency in energy management and that full coverage constraints limit the energy savings when traffic levels are low.

Cooperation amongst neighbouring cells can reduce the impact of these issues, however, introduces further complexity and overhead.

Samdanis et al. have introduced the energy partition concept, in which a set of neighbouring BSs share information on the momentary load and cooperatively re-configure the network layout by changing their transmission characteristics [56]. The authors have compared centralised and distributed versions of the proposed approach in terms of overhead, complexity, and EE. Furthermore, a simpler BS-awakening algorithm is investigated to enable energy saving when cooperative mechanisms are inefficient. However, the impact of the inter-cell interference is not considered in this work.

A different approach proposed by Niu et al. introduces inter-cell cooperative transmissions to guarantee coverage and traffic requirements when cell zooming is implemented [69]. The selection of the set of active BSs is modelled as a mixed integer programming problem, and hence, a suboptimal solution with limited complexity is proposed. The authors have showed that the proposed scheme gains up to 20% in terms of energy saving in light loaded scenarios; however, this result does not take into account the backhaul energy consumption, which is required for inter-cell cooperation.

Cell wilting and blossoming processes have been investigated to design reliable and efficient BSs sleep and wake-up transients [70]. BS wilting enables a soft reduction of cell coverage by slowly reducing the power in the control channel. This approach permits to carefully manage those mechanisms (such as handover and coverage extension) required to avoid call drops. Furthermore, if a UE experiences performance degradation, it may send an alert message that suspends/reverts the cell zooming process. On the contrary, when the capacity of active BSs goes to saturation, cell blossoming is activated in sleeping cells. Therefore, their pilot channel power is slowly increased up to the target value. Accordingly, strong inter-cell interference is avoided and user performance is not affected by the network re-configuration. Although the proposed mechanisms avoid service degradation to end-users, a static transient duration may lead to limited energy saving. Higher performance can be achieved by dynamically optimizing the transient duration with respect to the network layout and the average inter-cell interference. The selection of the load threshold that initiates the re-configuration process is a further relevant challenge in the cell zooming mechanism. In fact, when this threshold is set equal to a very low load level, cell zooming is rarely implement and energy saving is limited; on the contrary, higher load threshold can lead to frequent zooming process, which results in excessive overhead and handover failure.

In the HetNet scenario, small cells overlay the macrocell region to locally provide high data rate services. Therefore, in lightly loaded periods, energy saving schemes can be implemented to dynamically switch-off unnecessary low power nodes. To enable fast and reliable HetNet activity management, Ashraf et al. have investigated three different strategies that allow to control the status of small cells [54]. In the small cell driven algorithm, the AP is equipped with an energy detector that enables to *sense* the presence of a nearby M-UEs . An indoor UE, which is served by the M-BS, likely transmits with high power; hence it is easy to detect. Detection threshold is computed at small cell by estimating the path loss to the M-BS, such that UEs located at its cell edge can be correctly detected (see Figure 15). Henceforth, when a UE is detected, the AP switches in active mode and whether the UE has the right to access the small cell, the handover process is initiated. Otherwise, the AP reverts to the deactivated mode. This approach is characterized by limited complexity but required additional hardware (*the sniffer*) at the

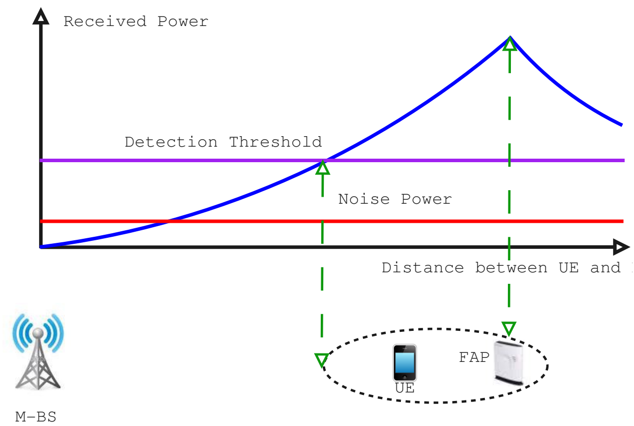

Figure 15: UE detection at a Femtocell Access Point (FAP) [54].

small cell; moreover, in high density scenarios, the aggregate energy received from different M-UEs can cause false alarm events that affect the detection reliability.

A more reliable solution assumes that small cells are controlled by the core network through the backbone. In highly loaded scenarios, the mobile network exploits the knowledge on the UE positioning, the cell locations, and the cell transmit powers to dynamically select the set of cells to activate. The optimization policy, which selects the set of APs to activate, depends on the completeness of this information, and partial or delayed feedback affects the system performance [71]. Alternatively, when location information is not available, the network may require to dormant hotspots to temporary switch-on and transmit the pilot signal [64]; UE measurements from the small cells are reported to the network (i.e., through the M-BS) and then used to decide which APs have to be activated.

Different from the propositions above, the small cell activity can be controlled directly by the UE, which can periodically broadcast a wake-up message to find idle APs in its range. Alternatively, a reactive scheme is feasible to save the UE battery consumption: in this case, the UE sends the wake-up message either when it experiences poor performance from the M-BS or when it requires higher data rate. A specific short range radio interface, like Bluetooth Low Power can be used to transmit the control message [72], however, such a blind wake-up algorithm is not supported in the current 3GPP standard.

All the previous schemes aim to dynamically manage the activity of small cell to create, ad-hoc hotspots in the macrocell region. However, an opposite, more flexible energy saving approach could be implemented if coverage constraints could relaxed at low loads; in this case, high-power M-BSs could also be switched-off and small cells kept activated, where required, to satisfy local user service requests [73].

The last uses case considers inter-RAT energy saving mechanisms. Nowadays, different wireless networks offer a variety of access options in a given geographical region. Legacy systems, such as GSM and UMTS, coexist with WiFi, LTE, and WiMAX, and in each of these network the APs are denoted by different coverage, capacity, and EE characteristics. When network cooperation is possible great energy saving is achievable by dynamically selecting those RATs and related APs that can satisfy local service requests with the minimum energy consumption [74, 75]. However, the overall network optimization is even more complex in this case, and it is fundamental to guarantee that vertical handover can be implemented amongst the selected RATs. To deal with these challenges, Bennis et al. have recently investigated a system with multi-mode small cells, which are able to simoultaneously operate on both the WiFi and licensed bands [76]. In this scenario, the authors have proposed a distributed traffic offloading mechanism, in which small cells steer data flows between cellular and WiFi RATs, according to the traffic type, users QoS constraints, network load, and interference levels. In particular, in this framework, delay-tolerant applications can be offloaded to WiFi, while LTE is used to manage delay-stringent applications. Although this approach reduces the complexities in the inter-RAT offloading process, different wireless networks (like WiFi and LTE) may be handled by different providers; hence, new issues arise to balance energy saving and costs amongst different operators, which accept traffic originated from competitor subscribers.

In Table 6 we summarize the main characteristics of the analysed management algorithms operating in a medium-time scale. The first and the second column show the algorithm name and the related reference(s), respectively; the third column indicates the load scenario where the algorithm should be used. The fourth column underlines whether the algorithm requires intercell cooperation. The fifth and the sixth columns show the main advantages and drawbacks of the algorithms, respectively. Finally, the seventh column indicates the constraint of 3GPP standard with respect to the algorithm.

Algorithm	Ref.	Scenario of interest	Inter-Cell Cooperation	Advantages	Drawbacks	Standard impact
Cell zooming	[65]	Low load regions	Not required	It reduces the number of active BSs in a given region	It may result in coverage holes and cell edge UEs may perceive higher interference	It does not require modifications in the standard
Cooperative cell zooming	[56, 68, 69]	Low/medium load regions	Required	It avoids coverage holes and throughput losses	It increases the system complexity and overhead	It does not require modifications in the standard
Cell wilting and blossoming	[70]	Low load regions	Not required	It avoids losses due to reconfiguration of the network layout	Low activation threshold results in poor energy saving; High activation threshold results in poor QoS	It does not require modifications in the standard
Small cell activation	[54]	Low load regions	Not required	This study introduces procedures to manage the small cell activation	Excessive handover and related overhead may limit the system performance	It may require modifications in the standard
Vertical handover	[74, 75, 76]	Low load regions	Not required	Inter-RATs cooperation enables to serve a UE through the most energy efficient solution	Increased system complexity and overhead	3GPP/WiFi interworking is under study in 3GPP Rel-12

Table 6: Characteristics of the Energy-Aware Management Strategies operating in medium-time scale.

6.3. Long time-scale

The previous sections have discussed strategies that improve the sustainability of wireless networks by dynamically adapting the system capacity to the load variations and avoiding energy wastage. Here, we aim to analyse the recent advances in wireless technologies that ameliorate the system EE on a longer time-scale. Accordingly, we have identified three areas of improvement:

- Hardware components and technology innovation;

- Deployment optimization;

- Integration of renewable energy sources in small cells.

A complete analysis of BS power consumption is the fundamental starting point for identifying future research axes for greener radio access network.

Source of Energy Consumption	Percentage
PA Feeder	50∼80%
Power Supply	5∼10%
Signal Processing	5∼15%
Air Conditioning	10∼25%

Table 7: Sources of energy consumption in radio access equipments [77].

Table 7 shows that the PA represents by far the main contribution to energy consumption in BSs. This is mainly due to the high power consumption required to serve cell edge and indoor UEs, which experience high propagation losses. However, non-linear effects and modulation schemes with non-constant envelope signals (such those used in current wireless technologies) required PAs to operate well below saturation [57]. This prevents adjacent channel interference due to non-linear distortions, and therefore avoids performance degradation at the receiver. However, this high operating back-off limits the amplifier efficiency and further increases power consumption. Digital pre-distortion jointly with Doherty PAs can be integrated to improve the power efficiency and linearise the PA while keeping interference under control, but require an extra feedback for pre-distortion and additional signal processing [78].

Moreover, standard PAs operate on high power supply independently of the traffic load, which results in high energy wastage. In the framework of the EARTH project, two main solutions are proposed for designing flexible and energy efficient PAs [6]: in the first approach, the operating point of PAs is tuned for minimizing the power consumption at arbitrary signal levels, so that the power efficiency is optimized also for low and medium traffic loads. The second approach enables the fast deactivation/activation of PA stages during time slots without signal transmission. In variable load situations, the joint application of both concepts can enhance the EE of mobile networks.

In current BSs, radio equipment is connected to antennas through coaxial cables which are characterized by several meters of length and introduce few decibel of attenuation, hence limiting the system efficiency. A first step forward has been the integration of RRHs [79]. RRHs are compact-size, high-power, and low-weight units, which are mounted outside the conventional macro BS and connected to it through fiber. This solution creates a a distributed antenna systems, where a Central Unit (CU) is in charge of control and baseband signal processing. In this architecture, active cooling, which characterizes standard M-BSs, is obsolete and replaced by natural air circulation; moreover, feeder loss is strongly reduced by installing the PA at the same location as the antenna. A recent investigation has estimated that more than 40% of energy saving can be achieved by replacing classic M-BSs with RRHs [3]. RRHs also affect CAPEX: in fact, they enhance flexibility of network deployments by limiting site acquisition challenges and/or physical constraints.

Further optimization of the RAN can be achieved by using active antennas, where signal conversion, filtering, active RF parts, and the radiating elements are integrated and fed to the central unit by optical fibres [6]. In this architecture, a number of traditional antenna elements forms an array and allows to remotely control the radiation pattern in order to concentrate RF power on a per-cell or per-user basis.

Locally deploying heterogeneous low-power nodes is another major solution to optimize the network deployment. Such nodes can be either deployed in outdoor or in indoor environment. Moreover, they can act as network APs or relaying the message generated by the M-BS towards cell-edge users. Complementing the macro networks with low power nodes, such as Micro and Pico BSs, has been considered a way to increase capacity for nearly 3 decades [80]. This approach offers very high capacity and data rates in areas covered by the low-power nodes. However, due to their reduced range a dense deployment of local APs may be required. Therefore, in such a novel heterogeneous architecture, a high number of cells of different characteristics may share the same spectrum in a given geographical area, increasing the inter-cell interference. Moreover, due to the limited capacity of the backhaul, inter-cell coordination for interference mitigation purpose is a challenge. Hence, completely replacing the current architecture with small cell APs is unaffordable. Therefore, for a given traffic scenario, the challenges from an EE perspective are, first, to find the optimal balance amongst heterogeneous nodes and second, to optimally locate related cell sites.

Koutitas et al. have investigated the network planning problem that enable to optimally select deployment sites and associated BS type with respect to a given objective function [81]. The authors have considered QoS, coverage, and capacity constraints; moreover, a 3D ray tracing algorithm is used to characterize the propagation channel. Three different objective functions are considered (minimum radiated power, minimum system power consumption, and a hybrid strategy) and a genetic algorithm is used to solve the modelled NP-hard problem. Simulation results have showed that a network mainly composed by a large number of optimally placed low-power APs is the most energy efficient topology in both uplink and downlink. However, the impact of backhaul deployment and related energy consumption is neglected in the analysis.

Le et al. have proposed a different deployment approach, where common macro-based cellular network is completely replaced by small cells to reduce power consumption. The authors have first evaluated the reduction in terms of RF power due to the novel deployment [82], second they have investigated different cooperative beamforming techniques, which enable to mitigate inter-cell interference [83]. The authors have discussed the architecture design and backhaul requirements to implement the inter-cell cooperation. The impact of the backhaul characteristics, in terms of protocol, latency, capacity, and RF-related energy consumption, is investigated. Therefore, a multicell beamforming schemes which exploits information on user position is proposed to limit complexity and overhead with respect to classical schemes.

An additional advantage of small cell deployment is the possibility to use renewable sources of energy to fully or partially enable operations of low power nodes. In this regard, Han and Ansari have proposed a network management algorithm that aims to satisfy user request by maximizing the usage of *green* energy [84]. In fact, the energy generated by renewable sources directly connected to low power nodes is intermittent in nature, and also the energy storage capacity is limited. Therefore, the authors have proposed to dynamically balance the cell load (i.e., by cell zooming) to limit the usage of supplementary energy generated with classical sources. The problem of adapting the pilot channel to change the cell coverage and to determinate user-AP association is modelled and showed to be as NP-hard. Hence, a heuristic algorithm is proposed to solve it with limited overhead and complexity.

The step forward in this research topic has been the integration of smart grids in COMP-based mobile networks [85]. In this scenario, Bu et al. have

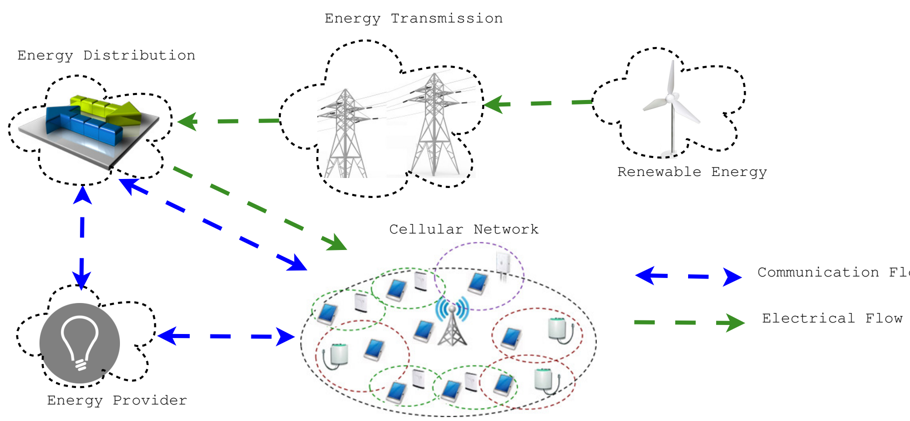

Figure 16: A cellular network powered by smart grids [85].

investigated the mechanisms to reduce costs at MNOs while optimizing the choice of the energy sources to power the cellular network (see Figure 16). This problem is modelled as a Stackelberg game with two levels: the mobile network and the smart grid. The MNO aims at maximizing an objective function that depends on offered QoS, real-time price, and pollutant level associated with used energy. In cellular networks, superfluous BSs are deactivated in lightly loaded scenarios, when the energy costs increases, or the pollution level is unacceptable. Then, cooperative transmissions can be used to maintain coverage and QoS requirements in location with a limited number of active BSs. Moreover, a MNO selects how much energy requiring from each provider to limit the economical and ecological impacts of wireless services. On the other side, the goal of an energy retailer is to maximize its profits by optimally balancing the energy price according to concurrent choices and the pollutant level of its energy sources. The authors have demonstrated the existence and the uniqueness of the equilibrium in the investigated Stackelberg game and they have discussed related system performance. Simulation results have underlined as smart grid operations have a significant impact on mobile networks and that a jointly optimization can strongly reduce wireless network OPEX and also CO_2 emissions.

In Table 8, we describe the main features of the energy efficient management algorithms operating in a long-time scale. The first and the second column indicate the algorithm name and the related reference(s), respectively; the third column underlines the load scenario where the algorithm leads to higher improvements. The fourth column indicates whether the algorithm needs inter-cell cooperation. The fifth and the sixth columns describe the main advantages and disadvantages of the algorithms, respectively. Finally, the seventh column indicates the constraint of the 3GPP standard with respect to the algorithm.

Algorithm	Ref.	Scenario of interest	Inter-Cell Cooperation	Advantages	Drawbacks	Standard impact
HetNet deployment	[81]	High load regions	Can be beneficial	It optimizes the network deployment with respect to the energy efficiency and QoS constraints	Backhaul requirements are neglected	HetNet has been introduced in 3GPP Rel-10
Replace Macro with small cells	[82, 83]	High load regions	Required	This approach strongly limit path losses experienced at the UEs	Static power independent by the radio transmission is not considered; At low loads this architecture can be inefficient	HetNet has been introduced in 3GPP Rel-10
Energy harvesting small cell	[84]	This approach can be always beneficial	Not required	This approach improves the environmental impact of mobile communications	The overall energy consumption can increase with this scheme	No restrictions
Mobile network and smart grid	[85]	This approach can be always beneficial	Required	This approach jointly improves economical and ecological impacts of mobile communications	Early stage technology	No restrictions

Table 8: Characteristics of the Energy Efficient Algorithms operating in long-time scale.

7. Conclusions and future lines of research

A comprehensive overview on the challenges for achieving sustainable cellular networks was presented. Energy consumption models, fundamental trade-offs, green metrics, and energy-aware management strategies were introduced and critically discussed.

While green communications has produced great expectation, improving the wireless network EE is still an open research field. Hereafter, we aim to underline some of the novel research axes in the domain:

- Currently, LTE commercial solutions are not available for every type of architecture/BS. Therefore, provided power models are often derived from existing solutions and may diverge each others. The relay case is emblematic in this sense: these low power nodes are characterized by a smaller coverage region than the macrocells, thus they may significantly lower irradiated power with respect to the M-BS. Furthermore, they are expected to have a simpler architecture than the M-BS resulting in lower aggregate power consumption. Researchers have mostly modelled the relay power consumption by separating the transceiver components whose power scales with the irradiated power and those components whose power consumption is independent to the RF power (such as in Eq. (4)). Recent studies are consistent claiming that relay deployment may introduce energy saving in the cellular network (see for instance [86, 87, 88]); however, they have arrived to misleading conclusions about the power model parameters. In some cases the authors have assumed that relay hardware components (especially the PA) are less efficient than the components in M-BSs [86, 88]. Therefore, they have pointed out that relay power consumption scales less with the load than the M-BS. However, other investigations have come out with a different conclusion [87]. Such ambiguity can obviously lead to different results and deductions.

- Due to the intrinsic difference of various architectures and scenarios under observation, it is questionable that only one green metric may be sufficient for analysing the system performance. Furthermore, in future, metrics should capture also the delay introduced by the system under test, Quality of Experience at the end-user, backhaul costs, and system reliability. Therefore, we believe that achieving a wide consensus on a small set of (simple, relevant, and accurate) metrics will permit to reliably compare different methodologies/systems and accelerate the research/standardization activities towards greener cellular networks.

- Very large MIMO array, also named as massive MIMO, indicates a system where eNBs are equipped with hundreds of antennas and serve a very few (i.e., ten) users [89, 63]. This paradigm has notable properties and it is attracting substantial interest in the wireless community. In particular, in this regime the effect of fast fading can be average out, intra-cell interference and uncorrelated noise disappear, and emitted RF power can be greatly reduced [90]. However, when the number of antennas per eNB grows, new challenges arise from the so-called pilot contamination which is related to the limited number of orthogonal pilots that can be used at neighbouring cells for acquiring CSI. Furthermore, it has pointed out that interaction amongst antenna elements may lead to notable losses in terms of channel orthogonality and system capacity. Finally, this technology is at its very early stage, and due to the lack of dedicated power consumption models, it is not clear if this technology may lead to an effective reduction of power consumption [61].

- Traditional RAN approaches, where each eNB act independently and allocate resource only according to feedback received from end users, cannot fulfill QoS requirements of future cellular networks. Recently, ICIC mechanisms and cooperative transmissions have been introduced, especially for enhancing performance at cell-edge users; however, complexity and overhead notably constrain the achievable gains. C-RAN is a novel framework, where centralized base-band pooling, software-defined radio, distributed antennas (i.e., RRH), and real-time cloud platform are jointly combined for a more efficient wireless networks [91, 92]. In particular, the main objectives of C-RAN are reducing CAPEX and OPEX, improving efficiency in resource usage, supporting of multiple standards, and enabling smooth evolution of wireless standards. Basically, in C-RAN, only the radio function is located at RRH, although baseband and higher layer functionalities (such as scheduling, load balancing, etc.) are managed by the CU. This approach enables high inter-cell coordination, better resource usage, and easy system upgrading. Nevertheless, these benefits come at cost of notable bandwidth requirement, which can be satisfied only with a massive deployment of optical fiber. To fully realize the cooperation paradigm in dense small cell deployment, where heterogeneous (in terms of latency, capacity, and topology) backhaul is available, more flexible solutions are required to trade-off advantages of centralized processing, complexity, and related costs. For instance, the FP7 UE project iJOIN is currently investigating a novel architecture where RAN functions are adaptively distributed at the CU and local APs according to current traffic demands and depending on the backhaul and access network constraints [93]. Furthermore, iJOIN aims to jointly optimize the RAN and the backhaul network, which improves the efficiency in resource usage and may avoid capacity bottleneck.

- The evolution of cellular networks has always been characterized by two fundamental concept, ubiquitous coverage and backward compatibility. One of the consequences is that, in current standard, BSs need to continuously transmit reference symbols, which limits the period in which hardware components can be switched off for energy saving purpose (see Section 6.1). Furthermore, even in very lightly loaded scenarios, when only reference symbols are transmitted, the PA activity results in high power consumption and system inefficiency. Due to the high number of small cells required in dense urban deployment, which is characterized by notable fluctuation in the traffic demand, a more flexible architecture is urged. A straightforward solution is to change the current 3GPP standard by separating signalling and data network [94, 95]. This approach introduces two main advantages: first, small cells, which are locally deployed to improve the network capacity, can be dynamically deactivated without affecting the network coverage. Second, signalling BSs can be efficiently designed for low-data rate and long-range transmissions. Researchers in the framework of GreenTouch [4] have started to investigate the technical challenges related to this novel architecture focussing in particular on the signalling, RRM, mobility and access functionalities. A first attempt to introduce this paradigm in cellular networks is current under study in 3GPP release 12 by exploiting the concept of New Carrier Type (NCT) [96]. In NCT data transmissions are enabled through UE specific signals introduced in 3GPP release 10 [97]. These signals, unlike cell-specific reference signals, are transmitted only when data transmission is active. Hence, this approach often results in data and control signalling originated from different points, in a transparent way for the end-user. Ericsson and NTT DOCOCO have recently presented technical solutions, indicated respectively as *lean carrier* [98] and *phantom cell* [99], which exploit NCT for achieving energy saving.

- Recently, the integration of the cloud computing paradigm in small cell networks has emerged as a cost-effective way for improving user QoS [100, 101]. Opposite to the C-RAN, researchers are investigating a scenario where distributed intelligence, processing, and storage capabilities are jointly managed through a cloud platform. In particular, local caching based either on pro-active or predictive schemes may notably improve the usage of backhaul resource and limit end-to-end latency [102, 103]. Hence, content- and context-aware mechanisms have to be developed to fully exploit the advantages of this architecture. For instance, distributed consensus is required to manage the available resources and prediction algorithms are required for anticipate user location, service request, and mobility.

- Research in green communications has focused on limiting energy consumption from a system perspective, often neglecting the impact on the RF radiated power. Nevertheless, some *green* solutions (such as cell zooming) may constraint few APs to operate at maximum radiated power. Recently, public concern has arisen on possible impact of electromagnetic fields (EMF) to human health, and the mobile community has to improve the acceptability of existing and future wireless systems by reducing the human exposure without compromising QoS. Thus, it is necessary to understand the trade-offs between fundamental green enablers and EMFs and then investigate novel approaches that jointly reduce energy consumption and exposure to electromagnetic radiations.

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