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Review

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 enable 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.

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.

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 user cases.

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

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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 overcome 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 tradeoffs 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, the base station and the 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 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