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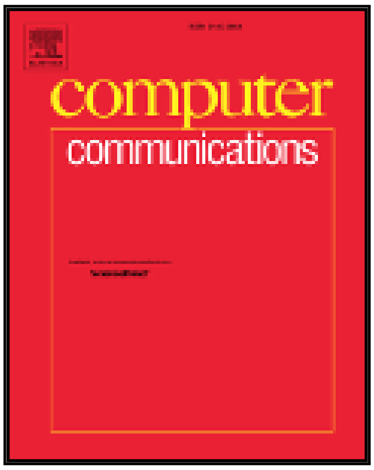

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Energy Sustainable Paradigms and Methods for Future Mobile Networks: a Survey

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***Abstract*—In this survey, we discuss the role of energy in the design of future mobile networks and, in particular, we advocate and elaborate on the use of energy harvesting (EH) hardware as a means to decrease the environmental footprint of 5G technology. To take full advantage of the harvested (renewable) energy, while still meeting the quality of service required by dense 5G deployments, suitable management techniques are here reviewed, highlighting the open issues that are still to be solved to provide eco-friendly and cost-effective mobile architectures. Several solutions have recently been proposed to tackle capacity, coverage and efficiency problems, including: C-RAN, Software Defined Networking (SDN) and fog computing, among others. However, these are not explicitly tailored to increase the energy efficiency of networks featuring renewable energy sources, and have the following limitations: (i) their energy savings are in many cases still insufficient and (ii) they do not consider network elements possessing energy harvesting capabilities. In this paper, we systematically review existing *energy sustainable paradigms and methods* to address points (i) and (ii), discussing how these can be exploited to obtain highly efficient, energy self-sufficient and high capacity networks. Several open issues have emerged from our review, ranging from the need for accurate energy, transmission and consumption models, to the lack of accurate data traffic profiles, to the use of power transfer, energy cooperation and energy trading techniques. These challenges are here discussed along with some research directions to follow for achieving sustainable 5G systems.**

***Index Terms*—Mobile Networks, Energy Sustainability, Renewable Energy, Energy Trading, Energy Cooperation, Smart Grid, Wireless Power Transfer.**

I. Introduction

We live in the digital era. Dematerialization is becoming a reality, humans and machines alike are globally connected through the Internet. ITU estimated that 750 million households are online and that there exist almost as many mobile subscribers as people in the world (around 6.8 billions) [1]. The trend is of a further increase in the traffic demand, in the number of offered and connected devices, especially mobile. The forecast in [2] is of an annual traffic growth rate of 53%, for the mobile traffic alone. This new era is undoubtedly opening up new possibilities for individuals as well as new opportunities for businesses and organizations. However, the massive use of ICT is also increasing the level of energy consumed by the telecommunication infrastructure and its footprint on the environment. In a report of 2013, the Digital Power Group [3] has calculated that 10% of the worldwide electricity generation is due to the ICT industry, which surpasses of more than 50% that of the avionic one. The report also highlights that the ICT energy consumption Compound Annual Growth Rate is of around 10%. In fact, forecasts for 2030 are that 51% of the electricity consumption and 23% of the carbon footprint by human activity will be due to ICT [4]. Hence, any future development in the ICT technology and in its infrastructure has definitely to cope with their environmental sustainability.

Besides such increment in the demand, the ICT industry has to solve an economical problem, since operators' Average Revenue Per Unit (ARPU) is decreasing every year. The case of Vodafone Germany is particularly striking: its ARPU has been shrinking annually by 6% on average in the period 2000-2009 [5]. One of the reasons of this is the annual increase of the OPerational EXpenditure (OPEX) of its network. Energy has been dominating these costs: it has been calculated that the energy bill equals the cost of the personnel required to run and maintain the network, for a western Europe company in 2007 [5]. Considering the rise in the energy price during the last few years, we conclude that energy saving is key for the economical sustainability of ICT.

In this survey, we discuss the crucial role of energy in the design of future networks, paying special attention to *mobile networks*, which are growing the most, among all ICT sectors, in terms of number of subscribers, traffic demand, connected devices and offered services [2]. Several survey papers, e.g., [6], [7], have recently appeared on these subjects, offering a thorough review of existing techniques and open issues. Nevertheless, existing solutions still have the following limitations: their energy savings are still insufficient and most of the research is still in a preliminary stage, they do not discuss the integration of energy harvesting capabilities into future networks and, in turn, energy self-sustainability is marginally addressed. The aim of the present survey is to fill these gaps, especially focusing and elaborating on the use of energy harvesting technology (including renewables) as a means to decrease the environmental footprint and OPEX of future mobile networks. We advocate that environmental energy can be scavenged through dedicated harvesting hardware, so as to power mobile system elements like base stations, mobile terminals and sensors. New network design paradigms, along with scenarios for future mobile networks and suitable network