Key Issues and Research Directions in Green Wireless Networking

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INTRODUCTION

Wireless communications have experienced an explosive growth in the last two decades and they have become a necessity for most of us. With the rapid development of wireless communications, applications and services which demand high data rates and increased quality of service (QoS) emerge. At the same time, high mobility and global connectivity are usually required. A direct result of the extensive growth of the wireless communications market is the rapid increase in energy consumption. Therefore, the limited energy resources and the increase in carbon (CO2) emissions have resulted in a keen interest from scientists and engineers to provide energy-efficient solutions including green wireless networks.

The rest of the article is organized as follows: First, we provide a short theoretical background and discuss the motivation behind green information and communications technology (ICT) in general and green wireless networking in detail. In its main part, we present and evaluate current trends in the area. Next, future research directions are highlighted, and finally, conclusions are drawn. The article outlines key concepts of energy-efficient networking and serves as an accessible introduction in green wireless networks that is suitable not only for researchers and practitioners in the field but also for non-experts.

BACKGROUND

In the previous decades, energy efficiency has not been seriously considered in the design and deployment of communication systems and networks, except for the battery-operated units. Gupta and Singh (2003) were among the first who posed the problem of energy-efficient networking by addressing issues related to the energy consumption of networking devices and the impact of network protocols on it. In the years that followed, the rapid development of telecommunications has resulted in a noticeable increase in energy consumption and carbon emissions. As an outcome, energy efficiency has nowadays emerged as a significant concern in ICT industry. Within this context, we discuss the "green" approach in modern communication systems focusing on wireless networks.

MOTIVATIONS FOR GREEN ICT: THE WIRELESS NETWORKS CASE

The increase in energy consumption and CO2 emissions of the ICT sector are serious issues for world economy and environmental pollution. Nowadays, the ICT market consumes 3% of worldwide energy and contributes 2% of global carbon emissions. Only in the United States, the amount of CO2 emissions due to the ICT industry was 151 MtCO2 in 2002, where 43% was due to cellular networks, while the forecast for 2020 is 350 MtCO2 with half of the emissions from the cellular infrastructure (Han et al., 2011; Suarez, Nuaymi, & Bonnin, 2012). These numbers by themselves, show the significance of the design, development and operation of energy-efficient wireless communication systems and networks.

The main objective of green wireless networking is the development of methods and techniques for the reduction of energy consumption in wireless networks. Apart from the reduced carbon emissions, the decrease

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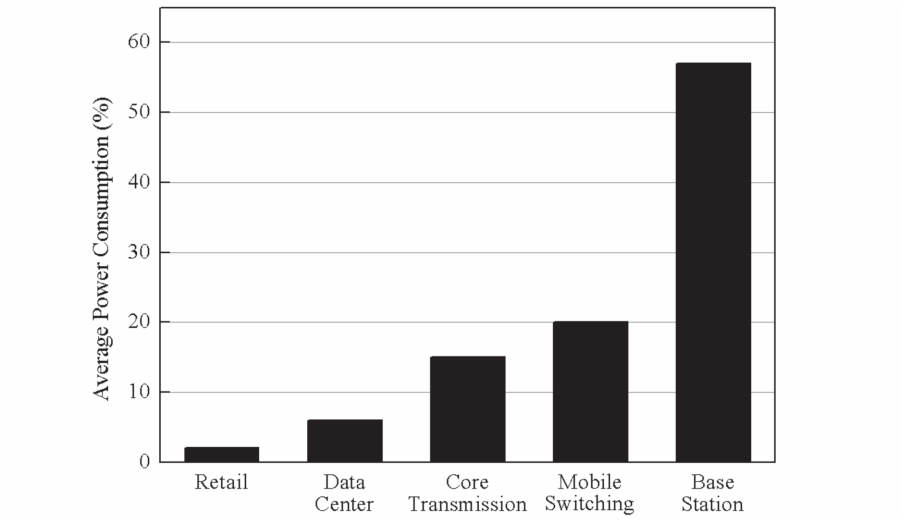
Figure 1. Power consumption of a traditional cellular network (Adapted from Han et al., 2011)



in energy consumption is translated to lower operating costs in the ICT industry. Moreover, issues such as electromagnetic pollution, spectral efficiency, radio interference, and battery lifetime of mobile devices are further "green" motivations.

In order to obtain a better idea of the motivation behind the current research and future challenges in the area, it is worth mentioning to note that more than half of the energy consumption in wireless networks is due to base stations (BSs), see Figure 1; however, less than one tenth of this consumption is accounted for signal transmission, see Figure 2. Moreover, empirical data, e.g. Micallef (2010), show a slight dependence of energy consumption on traffic load.

DEFINING "GREEN" METRICS

The design and deployment of traditional cellular networks mainly focus on throughput increase. On the other hand, the priority for the designers and developers of green wireless networks is energy efficiency. In order to meet both criteria and evaluate green wireless networks properly, we define energy efficiency metrics, the so-called "green" metrics, which provide information for the comparison and assessment of energy consumption of individual components and the network and help us to set research goals for energy reduction. These metrics refer to high-level systems, e.g. data centers, or to individual equipment where parameters related to traffic load and network coverage may also be considered. A list of the most popular "green" metrics (Hasan, Boostanimehr, & Bhargava, 2011; He, Srikanteswara, Bae, Reed, & Tranter, 2010; Wang, Vasilakos, Chen, Liu, & Kwon, 2012) follows:

- The power usage efficiency (PUE) and the data center efficiency (DCE) measure the energy efficiency of data centers. PUE is defined as the ratio of the power consumption of the data center to the power used by the servers, the storage systems and the network equipment; DCE is the reciprocal of PUE.
- The data center productivity (DCP) is the data center workload divided by its power consumption.
- The telecommunications energy efficiency ratio (TEER) quantifies the energy efficiency of network devices. It is given by the ratio of the useful work (data rate, throughput, capacity, etc.) to a weighted sum of the device energy consumption at full load, half load and idle modes.
- The telecommunications equipment energy efficiency ratio (TEEER) also quantifies the