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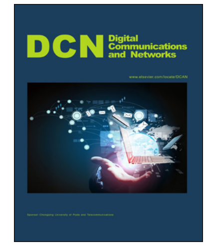

Joint optimization of spectrum and energy efficiency in cognitive radio networks

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Abstract
In this paper, we discuss the joint improvement of the energy efficiency (EE) and the spectrum efficiency (SE) in OFDM-based cognitive radio (CR) networks. A multi-objective resource allocation task is formulated to optimize the EE and the SE of the CR system simultaneously with the consideration of the mutual interference and the spectrum sensing errors. We first exploit the EE–SE relations and demonstrate that the EE is a quasiconcave function of the SE, based on which the Pareto optimal set of the multi-objective optimization problem is characterized. To find a unique globally optimal solution, we propose a unified EE–SE tradeoff metric to transform the multi-objective optimization problem into a single-objective one which has a D.C. (difference of two convex functions/sets) structure and yields a standard convex optimization problem. We derive a fast method to speed up the time-consuming computation by exploiting the structure of the convex problem. Simulation results validate the effectiveness and efficiency of the proposed algorithms, which can produce the unique globally optimal solution of the original multi-objective optimization problem.

1. Introduction

Spectrum scarcity crisis exists for many wireless applications, especially in the band below 6 GHz. On the other hand, investigations show that large portions of spectrum are highly underutilized due to inefficient conventional regulatory policies [1]. Cognitive Radio (CR) is deemed as a highly promising technology to improve the spectrum usage efficiency and has gained more and more attentions in recent years [2-4]. CR technology has been proposed as a solution to the underutilization problem by allowing Secondary Users (SUs) to sense radio spectrum environment and opportunistically access licensed frequency, as long as the interference to the Primary Users (PUs) can be kept under their tolerances, such as interference temperature. In order to meet the requirements of opportunistic access, the physical layer of a CR system should be very flexible, which

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necessitates multicarrier methods to operate in CR networks. Orthogonal Frequency Division Multiplexing (OFDM) has been widely recognized as a fascinating air interface for CR systems due to its flexibility in adapting spectral environments and allocating radio spectrum among SUs, which is the prerequisite for the CR system to acquire high performance [5].

Resource Allocation (RA) is one of the most important problems in OFDM-based wireless networks and has been studied extensively for more than a decade. A survey can be found in [6]. Spectral efficiency (SE), defined as the system throughput per unit of bandwidth, is a widely accepted criterion for wireless network optimization. For OFDM-based CR networks, there are many research results on how to improve the system performance from the SE perspective in the literature.

In [7], a balanced strategy for OFDMA radio resource allocation based on game theory concepts is presented. The proposed approach, explicitly addressing users perceived quality, ensures high balance between efficiency and fairness. In [8], an efficient algorithm is proposed to allocate bits among all OFDM subchannels in CR systems. The proposed algorithm can obtain the optimal solution with low computational complexity in most cases. In [9], both real-time and non-real-time services are considered, and fast RA algorithms are developed. However, fairness among users is ignored in [9], as well as spectrum sensing issue. In [10], a general RA framework in CR networks is developed, as well as efficient algorithms, which hint that RA in OFDM-based CR networks can be tackled effectively and efficiently by exploiting the structure of the considered problem.

On the other hand, the energy consumption of information and communications technology (ICT) has recently become an economic issue for operators as well as a big challenge for sustainable development [11]. With vast and rapid deployment of fourth generation (4G) networks, as well as the 5G vision of a totally connected world, the energy consumption is also growing at a staggering rate nowadays, which results in a large amount of greenhouse gas and high operation expenditure for wireless service providers. Green communication, which emphasizes on incorporating energy awareness in communication systems, is becoming more and more important [12]. Thus, energy-efficient RA has attracted much attention in both industry and academia, especially for the OFDM-based system which is the most promising modulation technique for the future wireless networks. Different from the throughput-oriented RA targets, energy efficient RA aims at maximizing the energy efficiency of wireless networks. An adequate energy-efficient metric should be given primary importance in overall energy-efficient network design, since it is related to the optimized decisions directly. The most popular one is called '*bits-per-Joule*', which is defined as the system throughput for unit-energy consumption. Recently, more and more researches have been carried out in the literature on energy-efficient wireless networks, and diverse technologies have been proposed in all aspects, trying to close the gap between practice and expectations.

In [13], an energy saving algorithm for spectrum sensing stage in cognitive radio networks is proposed and the detection accuracy over the desirable bound is maintained. In [14], green cellular operation is discussed. Using real data traces, [14] derived a first-order approximation of the percentage of power saving one can expect by turning off base stations during low traffic periods while maintaining coverage. In [15], the problem of non-cooperative resource allocation in multi-cell uplink OFDMA systems with multiple base station antennas is considered. In [16], a greedy energy-efficient BS deployment framework is developed for HetNets. The proposed algorithm deploys micro-BSs iteratively and maximizes the energy efficiency of the network. Ref. [17] analyzed three geographical adaptive fidelity models to optimize energy consumption in vehicular ad hoc networks. The relationship between the number of network grids and energy consumption is derived.

Both EE and SE are important for RA design. While it is noteworthy that there is only limited work on the joint optimization of EE and SE for wireless communication networks. The problem is that EE and SE do not always coincide and may even conflict sometimes [18]. The traditional approach to increase SE by trading off the transmit power for limited bandwidth results in reduced EE. Moreover, when the circuitry power factors are incorporated, the tradeoff relationship achieved between SE and EE is not quite straightforward. In fact, to develop a systematic way to find the remaining gaps for further optimization, a unified framework is needed. This is the fundamental framework of the EE and SE trade-off, which has long been pointed out by Shannon's ground-breaking theory but has yet to be fully utilized. The EE–SE trade-off analysis offers a balanced view to the nature of a communication system and provides guidelines for wireless system design and optimization. In [19], four selected green transmission technologies solutions are introduced, focusing on how to utilize the degrees of freedom in different resource domains, as well as how to balance the tradeoff between energy and spectrum efficiency. In [20], the EE–SE trade off optimization problem in downlink orthogonal frequency division multiple access (OFDMA) networks is formulated to maximize EE with a minimal SE requirement. In [21], a multi-criteria optimization problem is proposed to investigate the relationship between EE and SE in distributed antenna systems. The multi-criteria optimization problem is solved by using the weighted sum method. In [22], the EE and SE is simultaneously optimized and a unified metric for EE-SE tradeoff design in point-to-point wireless networks is proposed. However, EE–SE relation for OFDM-based CR networks is more complicated. In addition to the constraint that the interference to the PUs should be restricted, spectrum sensing errors should also be taken into consideration. In fact, perfect spectrum sensing is too difficult to acquire in practical wireless scenarios, and thus, RA with imperfect spectrum sensing is worth noting. How to allocate system resource to tradeoff EE and SE efficiently in OFDM-based CR networks is a nontrivial question.

In this paper, we formulate a multi-objective optimization problem to optimize EE and SE simultaneously. The mutual interference and the spectrum sensing errors are taken into consideration in our system model. We first prove that EE is quasiconcave in SE in the proposed system model. The Pareto optimal set of the multi-objective optimization problem is then characterized. To find a unique globally optimal solution, we proposed a unified EE–SE trade off metric to transform the multi-objective optimization