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Cooperative game-theoretic approach to spectrum sharing in cognitive radios

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ABSTRACT

In this paper, a framework for modeling multi-user, multi-band, spectrum sensing and sharing problem in cognitive radios as a cooperative game (CG) in a characteristic form is proposed. Secondary users (SUs) jointly sense the spectrum and cooperatively detect primary user (PU) activity for identifying unoccupied spectrum bands. A CG is formulated to quantify and share the benefits of cooperation by accessing identified idle channels in a fair manner. The characteristic function describing the CG is based on the worth of SUs, which is calculated according to amount of work done for coalition by increasing awareness about state of spectrum that may also be seen as reduction in uncertainty about PU activity. Such CGs are balanced and super-additive, making resource allocation possible and providing SUs with an incentive to cooperate and form the grand coalition. Based on their worth, SUs get payoffs that are computed using singleton solutions. SUs use payoffs earned from sensing to bid for idle channels through a scheduling mechanism, in particular, the socially optimal Vickrey–Clarke–Groves auction. Simulation results show that, in comparison with other resource allocation models, the proposed CG model provides the best balance among fairness, cooperation and performance in terms of data rates obtained by SUs.

1. Introduction

Current wireless networks are characterized by static spectrum allocation policy, where spectrum is assigned to license holders on a long term basis. Due to continuous increase in spectrum demand, certain bands face severe scarcity and yet, a large portion of spectrum is often under-utilized across time and space [1]. Apparent scarcity in spectrum arises from rigid frequency allocations rather than actual physical shortage of spectrum. Techniques facilitating flexible spectrum usage have been developed in order to solve these inefficiency problems. The key enabler of dynamic spectrum access is cognitive radio (CR) technology [2,3], which provides the capability for unlicensed secondary users (SUs) to opportunistically access unused licensed bands (spectrum overlay approach) without causing harmful interference to primary users (PUs).

In a CR network, SUs may collaboratively sense the spectrum based on commonly used sensing methods such as energy detection [4,5], cyclostationary-based detection [6], and matched filter to identify idle sub-bands of spectrum referred to as *spectrum holes*. By combining information about the state of spectrum occupancy in terms of local log likelihood ratios (LLRs) and side information such as observed interference levels and signal to noise ratios (SNRs), SUs are able to improve detection performance and network coverage [7]. After sensing, SUs share the available spectrum amongst themselves and coordinate access to idle channels based on a access policy. A Fusion Center (FC) manages the coalition's sensing and

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access policy. Since spectrum access is entirely dependent on sensing results, both policies are closely related and hence, a joint spectrum sensing and access policy must be modeled to optimize the utilization of spectral resources. Thus, there is a need to normatively model the spectrum sensing and sharing problem jointly in CRs to design, regulate, optimize and evaluate system performance.

Sharing the benefits of cooperative sensing is a non-trivial problem of great interest. In order to arrive at an access policy that is acceptable to all SUs, competition over spectral resources between the SUs must be resolved in a fair manner. This calls for a game-theoretic approach to modeling the problem at hand. A cooperative game (CG) is ideally suited to model this scenario where all SUs benefit from cooperation and share the benefits amongst themselves fairly. For example, if identification of unoccupied spectrum bands and improving the state of awareness of spectrum by the SUs can be construed as *benefit* in a quantitative and/or qualitative sense, the problem of accessing unoccupied spectrum bands reduces to allocating this *benefit* fairly among SUs by means of a CG. Thus, participating in the CG guarantees benefits for all SUs and provides them with an incentive to cooperate in the future. The main assumption in CGs is that the grand coalition of all SUs within a certain local area (since spectrum opportunities and propagation characteristics are local in nature) will form and hence, the aim of the CG is to allocate overall *benefit* created by cooperating SUs in a fair and stable manner. A cooperative game in coalitional form focuses on what SUs in a coalition can jointly achieve while maximizing each SU's payoff. In a non-cooperative game, each SU may have a large number of available actions/strategies to choose from and with a large number of SUs, the analysis may become computationally complex and intractable with a lot of communication overhead and information exchange. Thus, modeling spectrum sensing and sharing in CRs as a CG is both intuitively and logically appealing. A brief introduction to CG theory has been provided in [8] that is relevant in this context. For a more general setting, see [9,10].

It is possible that the number of idle sub-bands is quite limited in order to be allocated to all SUs or SUs might not want to access idle channels immediately after sensing but at a later time. This can occur when SU–SU channels quality is bad and/or if a SU wants to conserve power or if she does not want to interfere with PU receiver. Hence, it would be useful to have a procedure where SUs can translate payoffs to some form of common currency and use it to bid at an appropriate time depending upon their data rate requirements for transmission, power constraints, estimated channel quality, etc., or simply save payoffs for later use. A suitable scheduling mechanism is needed to facilitate the process of coordinating bids and allocating idle channels. Vickrey–Clarke–Groves (VCG) auction [11] is used as an example to demonstrate that a socially optimal and feasible scheduling mechanism exists that can allocate idle channels to SUs. However, devising an optimal bidding strategy for SUs is a complex combinatorial problem that entails a separate study in mechanism design and is beyond the scope of this paper.

Non-cooperative game theory has been used to study, design, and evaluate performance of CRs in [12]. A detailed tutorial on coalitional game theory for communication networks can be found in [13]. CGs have been applied in higher layers such as network and transportation layers to study routing protocols in [14], packet forwarding in [15], dynamic spectrum access in [16] and resource allocation in [17]. CGs have been used to model cooperation in wireless networks [18] and coalition formation games have been studied with respect to cooperative spectrum sharing in interference channels [19]. Auctioning has been studied in detail with respect to spectrum sharing in [20], whereas cooperative and competitive spectrum bidding and pricing have been studied in [21]. A joint spectrum sensing and sharing model based on a coalitional game in partition form is proposed in [22], where the payoffs are dependent on externalities, i.e, the way network is partitioned. However, in a typical CR setting, worth of a coalition does not depend on SUs who are not a part of the coalition (except when SUs have malicious intent), thereby rendering CGs in a characteristic form more suited to modeling scenarios where each SU is looking to solely maximize her utility in the coalition without considering the action of other SUs outside the coalition.

In this paper, we propose a framework for jointly modeling spectrum sensing and sharing in CRs as a CG in a characteristic form. The characteristic function captures the essence of cooperation by quantifying what each SU brings to the coalition by sensing the channels. The resulting CGs have an inherent structure with desirable properties such as balancedness and super-additivity. Balanced CGs have non-empty cores which make resource allocation possible and stable. Super-additivity provides SUs with an incentive to form the grand coalition so that SUs prefer to cooperate rather than compete with each other. Since the core could be very large, one-point solutions that lie within the core are used to calculate singleton solutions, i.e., SUs receive mutually agreeable payoffs for cooperatively sensing the spectrum. Depending upon their rate requirements, SUs bid using payoffs earned from increasing awareness about state of spectrum occupancy to gain access to idle channels. A VCG auction is used to demonstrate that a socially optimal and feasible scheduling mechanism exists that can allocate idle channels to SUs based on their bids and data rate requirements. The proposed cooperative game-theoretic joint spectrum sensing and access model (CG-JSJA) provides the best balance between fairness, cooperation and performance in terms of data rates obtained by each SU as well as data sum rates of all SUs among other considered models such as individual sensing and probabilistic access model (ISPA), joint sensing and probabilistic access model (JSPA), joint sensing and round robin access model (JSRR) and joint sensing and rate maximization access model (JSRM).The contributions of this paper are as follows:

- A novel and comprehensive framework for jointly modeling spectrum sensing and sharing in CRs as a CG in a characteristic form is proposed.
- The characteristic function of the CG is derived based on the worth of SUs, calculated according to the amount of