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Spectrum sensing using distributed sequential detection via noisy reporting MAC ☆

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ABSTRACT

This paper considers cooperative spectrum sensing algorithms for Cognitive Radios which focus on reducing the number of samples to make a reliable detection. We propose algorithms based on decentralized sequential hypothesis testing in which the Cognitive Radios sequentially collect the observations, make local decisions and send them to the fusion center for further processing to make a final decision on spectrum usage. The reporting channel between the Cognitive Radios and the fusion center is assumed more realistically as a Multiple Access Channel (MAC) with receiver noise. Furthermore the communication for reporting is limited, thereby reducing the communication cost. We start with an algorithm where the fusion center uses an SPRT-like (Sequential Probability Ratio Test) procedure and theoretically analyze its performance. Asymptotically, its performance is close to the optimal centralized test without fusion center noise. We further modify this algorithm to improve its performance at practical operating points. Later we generalize these algorithms to handle uncertainties in SNR and fading.

1. Introduction

Presently there is a scarcity of spectrum due to the proliferation of wireless services. Cognitive Radios (CRs) are proposed as a solution to this problem. They access the spectrum licensed to existing communication services (primary users) opportunistically and dynamically without causing much interference to the primary users. This is made possible via spectrum sensing by the Cognitive Radios (secondary users), to gain knowledge about the spectrum usage by the primary devices. However due to the strict spectrum sensing requirements [1] and the various inherent wireless channel impairments, spectrum sensing has become one of the main challenges faced by the Cognitive Radios.

Multipath fading, shadowing and hidden node problem cause serious problems in spectrum sensing. Cooperative (decentralized or distributed) spectrum sensing in which different cognitive radios interact with each other exploiting spatial diversity [1,2] is proposed as an answer to these problems. It also reduces the probability of false alarm and the probability of miss-detection. Cooperative spectrum sensing can be either centralized or distributed [1]. In the centralized algorithm a central unit gathers sensing data from the Cognitive Radios and identifies the spectrum usage [3]. On the other hand, in the distributed case each secondary user (SU) collects observations, makes a local decision and sends it to a fusion center (FC) to make the final decision. Centralized algorithms provide better performance but also have more communication overhead in transmitting all the data to the fusion node. In the distributed case, the information that is

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exchanged between the secondary users and the fusion node can be a soft decision (summary statistic) or a hard decision. Soft decisions can give better gains at the fusion center but also consume higher bandwidth at the control channels (used for sharing information among secondary users). However hard decisions provide as good a performance as soft decisions when the number of cooperative users increases [3].

Spectrum sensing problem can be formulated in different ways, two of them being Neyman–Pearson framework (fixed sample size detection) and sequential detection framework which reduces the average number of samples taken for deciding if a primary is transmitting or not [4]. Also, there are two types of sequential detection: one can consider detecting when a primary turns ON (or OFF) (change detection, see [5,6] and the references therein) or just testing the hypothesis whether the primary is ON or OFF ([7–9] and references therein). In [5], cooperative spectrum sensing under sequential change detection framework with no coordination between the secondary users is considered, and random broadcast policies and several improvements are proposed. In [6] a nonparametric framework is considered and performance is studied theoretically also. In sequential hypothesis testing one considers the case where the status of the primary channel is known to change very slowly, e.g., detecting occupancy of a TV transmission. Usage of idle TV bands by the Cognitive network is being targeted as the first application for cognitive radio. In this setup (minimising the expected sensing time with constraints on probability of errors) Walds' SPRT (Sequential Probability Ratio Test) provides the optimal performance for a single Cognitive Radio [4]. But the optimal solutions for cooperative setup are not available [10].

In this paper, we consider sequential hypothesis testing in cooperative setup. Feedback from the fusion node to the CRs can possibly improve the performance. However that also requires an extra signaling channel which may not be available and has its own cost. Therefore we do not consider feedback in our system. In sequential decentralized detection framework, optimization needs to be performed jointly over sensors and fusion center policies as well as over time. Unfortunately, this problem is intractable for most of the sensor configurations [10,11], specifically when there is no feedback from the fusion center and there is limited local memory, which is more relevant in practical situations. Recently [11] and [12] proposed asymptotically optimal (order 1 (Bayes) and order 2 respectively) decentralized sequential hypothesis tests for such systems with full local memory. But these models do not consider noise at the fusion center and assume a perfect communication channel between the CR nodes and the fusion center. Also, often asymptotically optimal tests do not perform well at a finite number of observations. Zou et al. and Yilmaz et al. [7,8] also proposed cooperative sequential algorithms for spectrum sensing, but neither of them deal with the fusion center noise and SNR uncertainty case.

Noisy channels between local nodes and fusion center are considered in [13] in the decentralized sequential detection framework. But optimality of the tests is not discussed and the paper is more focused on finding the best signalling schemes at the local nodes with the assumption of parallel channels between local nodes and the fusion center and perfect knowledge of local node probabilities of error.

We first propose a decentralized algorithm DualSPRT which uses SPRT at the local nodes and a SPRT-like test at the fusion center. Furthermore, we consider the receiver noise at the fusion center and allow multiple local nodes to transmit simultaneously their decisions to the fusion center to reduce the transmission time. This of course means that the fusion center does not know explicitly how many local nodes are transmitting at a time and certain fusion center decision rules, e.g., AND/OR/Majority [1,3] are ruled out in our setup. Moreover unlike some of the previous works on cooperative spectrum sensing using sequential testing (see [9,13] and references therein) we analyze this algorithm theoretically also.

We study asymptotic performance of DualSPRT, with fusion center noise. It is particularly important in the CR context because of detection in wireless channels at low SNR [14]. It can approach the optimal centralized sequential solution (in Bayes and frequentist sense), which does not consider noise at FC. We assume a MAC (Multiple Access Channel) as the reporting channel at the fusion center and the test is not based on the local node probability of error. Later we modify DualSPRT to improve its performance. The parameters of the modified algorithm are easier to fine tune also. Furthermore we introduce a new way of quantizing SPRT decisions of local nodes and extend this algorithm to cover SNR uncertainties and fading channels. We have seen via simulations that our algorithm works better than the algorithm in [11] and almost as well as the algorithm in [12] even when the fusion center noise is not considered and MAC layer transmission delays are ignored in [12,11]. Li and Evans [15] and Li et al. [16] consider distributed detection with MAC, but not in sequential detection framework. Banavar et al. [17,18] take into account MAC in the distributed estimation setup.

In addition, we generalize our algorithm to include uncertainty in the received Signal to Noise Ratio (SNR) at the CRs and fading channels between primary and CR. This requires a composite hypothesis testing extension to the decentralized sequential detection problem and is not considered in any of the above references (although [13] considers SNR uncertainty and fading between the CRs and the fusion center).

This paper is organized as follows. Section 2 presents the model. Section 3 provides the DualSPRT algorithm. An approximate theoretical performance of the algorithm is also provided. Section 4 studies the asymptotic performance of DualSPRT. In Section 5 we improve over DualSPRT. We compare the different versions so obtained and also compare them with existing asymptotically optimal decentralized sequential algorithms. Section 6 extends these algorithms to consider the effect of fading and SNR uncertainty. Section 7 concludes the paper.

2. System model

We consider a Cognitive Radio system with one primary transmitter and L secondary users. The L nodes sense the channel to detect the spectral holes. The decisions made by the secondary users are transmitted to a fusion node via a reporting MAC for it to make a final decision. This is the most common architecture for distributed detection and distributed