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Full Length Article

On the performance of single ring law based sensing approaches for opportunistic spectrum access

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ABSTRACT

Multiple antenna systems are becoming increaingly prominent startig from 4G systems to the evolving 5G systems. During the course of these system deployments, spectrum scarcity has been a well prevailing problem. In this regard, opportunistic spectrum access schemes have been developed, which adopt periodic sensing approaches to detect the presence of the primary user and thereby allow efficient spectrum utilization by secondary users. Extension of spectrum sensing approaches to multiple antenna systems require a proper detection framework. The recent formulations of large random matrices and associated single ring law (SRL) for signal detection have been validated only for massive antenna systems. Further, its detection performance with respect to existing sensing approaches has not been studied so far. In this paper, first we present a detection framework suitable for any multiple antenna system. Introducing modifications to this framework so as to reduce the number of computations, we explore the suitability of single ring law (SRL) based spectrum sensing in comparison to other approaches. Finally, we propose a hybrid dual-stage sensing approach, which renders better detection performance than the existing ones. Using system simulations, under two different cases of sparse channel environments, namely multiple channels having exact common support and approximate common support, the efficacy of the proposed approach is demonstarted using detection probability versus signal to noise ratio (SNR) plots.

1. Introduction

From the dawn of 4G systems to the currently evolving 5G wireless communication systems, multiple input multiple output (MIMO) technology has been utilized for improved communication services. Few systems have been utilizing the advantages of MIMO combined with orthogonal frequency division multiplexing (OFDM) technology for further enhanced services. At the inception, MIMO systems with few antennas have been popular, while at present massive MIMO systems are slowly taking over [1]. In this regard, coexistence of fewer antenna systems and massive systems is very essential to avoid user dissatisfaction.

Though service qualities have been improving owing to the two frontiers MIMO and OFDM, the endless demand for wireless services and applications has put a lot of limitations on the usage of available radio spectrum. A survey on spectrum utilization shows that entire spectrum is not used at all the times, and that most of the radio spectrum is unutilized [2]. Specifically, some of the frequency bands in the spectrum are unoccupied, some are less occupied and few other bands are over utilized. To overcome the problem of spectrum underutilization, opportunistic spectrum access has been conjured.

Opportunistic spectrum access is performed by a device that acts as a radio with the ability to acquire, measure, sense, learn and be aware of its operating environment, which is termed as cognitive radio. Sensing techniques are based on the detection of primary user independently through continuous spectrum sensing. The presence or absence of primary user is identified periodically to locate the unused spectrum bands in targeted spectrum pool. Thereby, these bands can be used for secondary user transmissions optimally without causing harmful interference to the licensed primary users.

Various spectrum sensing techniques are available in the literature that sense the unused spectrum bands. The conventional sensing technique is based on energy detection, which requires the a priori knowledge of noise power and is optimal for independent and identically distributed signals and not for correlated signals [3]. Matched-filtering detection requires primary user signal patterns to be known by the secondary user and involves different matched filters for different signal patterns [4]. Feature detection

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also known as cyclo-stationary detection exploits the periodicity of the modulation scheme employed by the primary user signal and requires the knowledge of cyclic frequencies [5].

To sense the spectrum without prior knowledge of the primary signal, covariance based detectors or eigenvalue based detectors can be employed. For a predefined probability of false alarm value, a covariance absolute value (CAV) based detector performs better than energy detection, without any prior knowledge of the primary signal or noise power [6]. Information theoretic criterion like Akaike information criterion (AIC) or minimum description length (MDL) can be computed and used for primary signal detection, without fixing any probability of false alarm value [7]. A weighted covariance detection (WCD) can be performed for a fixed value of false alarm probability [8]. In practice, the choice of a specific sensing approach is a tradeoff between detection probability and computational complexity. Spectrum sensing can also be performed in a cognitive radio network (CRN) using cooperative sensing techniques [9,10]. Soft detection can be employed for cooperative spectrum sensing in a CRN [11,12]. Further, a combination of hard and soft combining based spectrum sensing [13] can also be employed. Energy efficient detection schemes [14,15] in a CRN can also be devised in a distributed manner [16,17].

Recently, with regard to massive MIMO systems [18,19], data received at a massive base station is modeled as a large random matrix and the corresponding asymptotic eigen spectral density has been shown to be in accordance with Marchenko Pastur (MP) law and single ring law (SRL) [20]. Further, MP law and SRL have been shown to have signal detection capabilities, for massive MIMO systems with large number of antennas [24,26] but not for fewer antenna systems. Further, the applicability of such a detection approach has not been studied with respect to the other existing sensing approaches.

In view of the above discussion, the following are the contributions of this paper. We first develop a generalized detection framework applicable to multiple antenna sensing systems. Second, by modifying the detection framework to reduce the computational complexity, we develop a sensing algorithm using SRL based detection that suits fewer antenna systems in practice. Specifically, we model the data received by a multiple antenna sensing system as a random matrix and extract the mean spectral radius (MSR) of the received data. Comparing MSR with a proposed pre-computed threshold, a decision criterion is devised for spectrum sensing. Further, we propose a dual-stage spectrum sensing approach to obtain improved detection probability.

Third, with the help of Monte Carlo trials, system simulations are carried out for two different cases of channel environments, namely sparse channels with exact common support and sparse channels with approximate common support. For both these cases, the detection performance of the proposed sensing approach is ascertained to be better than the existing ones, for both Rayleigh and Nakagami fading scenarios.

The rest of the paper is organized as follows. Section 2 illustrates the adopted multiple antenna sensing system model and the corresponding generalized detection framework. Section 3 presents the details of modified detection framework, SRL based sensing algorithm and the proposed dual-stage spectrum sensing approach. Section 4 provides a comparison on the detection performances and computational complexities of proposed and the existing approaches, with regard to system simulations and algorithm steps respectively. The paper is concluded in Section 5.

2. System model – spectrum sensing

Consider a single primary user scenario and a secondary user sensing system equipped with N_r sensing antennas. The discrete base band equivalent of the received signal at the mth sensing antenna is modeled as

$$x_m(n) = s(n) \otimes h_m(n) + w_m(n), \quad 1 \leqslant m \leqslant N_r \tag{1}$$

where $s(n)$ is the primary signal, $w_m(n)$ is the additive white Gaussian noise (AWGN) at the mth sensing antenna, $h_m(n)$ represents the multipath fading channel between the primary user and the mth sensing antenna and $\otimes$ represents convolution operation. The fading channel impulse response (CIR), $h_m(n)$ is considered as a L length vector, implying the CIR has taps at instants $0 \leqslant n \leqslant L-1$. Accordingly, CIR is expressed as

$$h_m(n) = \sum_{l=0}^{L-1} a_m(l)\delta(n-\tau_l) \tag{2}$$

where $a_m(l)$ represents path loss and fading component of the lth multipath, while τ_l represents the delay of the lth multipath. The path loss and the delay of each path, together termed as the power delay profile (PDP) can be of many types. In this work, PDP of Brazil-A type [22,23] is used. Typical fading behaviors in 3G and 4G are of Rayleigh type, however for the evolving 5G communications, owing to the higher frequency services, the channels are of Nakagami type [25]. Hence, in this paper both Rayleigh and Nakagami type fading behaviors are considered. The present work considers only single secondary user in the system, which is shown in Fig. 1. Systems with multiple secondary users have also been considered in [27–29] for spectrum sensing.

Frequently encountered wireless channels are sparse in nature, which implies only T out of L taps of the CIR $h_m(n)$ are non-zero. As the sensing system has N_r antennas, $s(n)$ passes through N_r different channel environments. Hence N_r different sparse CIRs are possible. In this paper two cases are considered, first case with exact common support, which implies τ_l are exactly same for all N_r CIRs and second case with approximate common support, which implies τ_l are different for different CIRs but are approximately close to each other.

2.1. Generalized detection framework for multiple antenna system

To perform spectrum sensing in a multiple antenna sensing system, the received data from each of the N_r sensing antennas is collected over an observation time window M, which implies data is collected for observation instants $0 \leqslant n \leqslant M$. At each instant n, the collected data from all the N_r antennas is represented as

$$X(n) = [x_1(n) \quad x_2(n) \quad \cdots \quad x_{N_r}(n)]^T \tag{3}$$

Further, using (1) $X(n)$ can be rewritten as

$$X(n) = \mathbf{H_{ch}}S(n) + W(n) \tag{4}$$

where $W(n) = [w_1(n)\ w_2(n)\ \cdots\ w_{N_r}(n)]^T$, $S(n) = [s(n)\ s(n-1)\ \cdots\ s(n-L+1)]^T$ are the noise vector and the primary signal vector respectively and $\mathbf{H_{ch}}$ is the channel matrix, given as

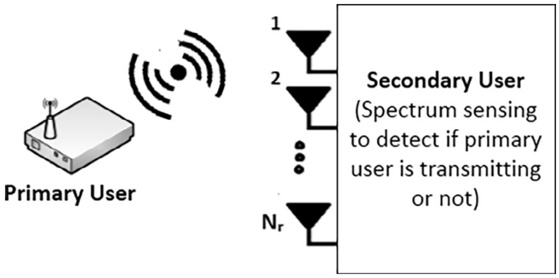

Fig. 1. System model.