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A Survey on Cooperative Spectrum Sensing in Cognitive Radio Networks

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***Abstract* - In cognitive radio networks, spectrum sensing is a crucial component in the discovery of spectrum opportunities for secondary systems (or unlicensed systems). The performance of spectrum sensing is characterized by both accuracy and efficiency. Currently, significant research effort has been made on improving the sensing accuracy. Several exemplary techniques include energy detectors, feature detectors, and cooperative sensing. In these schemes, either one or multiple secondary users (SUs) perform sensing on a single and the same channel during each sensing period. This strategy on simultaneously sensing a single channel by several SUs may limit the sensing efficiency to a large extent. In this paper, we propose a new parallel spectrum sensing. In this scheme, several SUs are optimally selected to perform sensing. During a sensing period, each of the selected SUs senses a different channel. As a consequence, multiple channels can be simultaneously sensed in one sensing period, and the sensing efficiency is envisioned to improve significantly. To understand trade-off between the sensing overhead and communicative data some techniques proposed by researchers are investigated here.**

***Keywords* - Cognitive Radio Networks, Cooperative Sensing, Spectrum Sensing.**

I. Introduction

RADIO spectrum is usually considered as a scare resource while measurements show that the allocated spectrums are vastly under-utilized [1]. The cognitive radio (CR), which has received a considerable attention, is designed for the secondary users to opportunistically access to the unused primary (licensed) spectrums without causing interference to the primary users [2], [3]. For example, the Federal Communications Commission (FCC) has released a Notice of Proposed Rule Making (NPRM) to allow the unlicensed CR devices to operate in the unused broadcast channels [4], and the IEEE 802.22 Working Group is now building a CR-based air interface over the Broadcast bands [5]. Both of these activities dramatically improve the spectral efficiency of the existing communication networks. In CR, the secondary users need to opportunistically sense the idle channels. Once an idle channel is sensed, the secondary system will access this channel.

Spectrum sensing is an essential component in CR networks to discover spectrum opportunities. The performance of a CR network is highly dependent on the accuracy and efficiency of the discovered spectrum opportunities. The sensing accuracy refers to the precision in detecting a PU signal such that the PU’s communications are not interfered with. The sensing efficiency refers to the number of sensed spectrum opportunities within a sensing period and the resulting overall system performance with respect to throughput and delay. Recent research has spent considerable effort on the sensing accuracy. In the literature, several techniques have been proposed to enhance the sensing accuracy [6]–[12], including energy detectors, feature detectors, and cyclostationary detectors [3]. A very promising technique is cooperative spectrum sensing, which has been extensively investigated by exploiting the spatial diversity to combat the unpredictable dynamics in wireless environments [15]–[17]. The study in [9] reports a cooperative sensing approach through multiuser cooperation and evaluated the sensing accuracy. The frequently cited works [14] and [15] propose a cooperation technique in which one of the users acts as a relay for the others, leading to a significant decrease in detection time and an

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increase in overall agility. The study in [16] presents a new cooperative wideband spectrum-sensing scheme that exploits the spatial diversity among multiple SUs to improve the sensing reliability. The study in [17] investigates the sensing throughput trade-off in CR networks. It is observed that the prior schemes use either one or multiple SUs to perform sensing on a single or the same channel in one sensing period. During each sensing period, only one channel could be detected, and the detection of other channels is not allowed. The cooperation among several SUs is expected to improve the sensing accuracy of the sensed single channel. However, the strategy on sensing a single channel by one SU or several SUs simultaneously may largely limit the sensing efficiency. The conventional schemes decrease the chance in finding spectrum opportunities and may lead to low sensing efficiency [8]. A study in [10] introduced two novel cooperative sensing mechanisms, i.e., random sensing policy and negotiation-based sensing policy. The latter strategy assigns SUs to collaboratively sense different channels to improve the sensing efficiency. However, the sensing overhead is not considered.

II. Parallel Sensing: System Models And Mechanisms

The infrastructure-based primary network has a centralized base station. The BS monitors and allocates the available spectrum in a central manner. PUs communicates with the primary BS based on a synchronous slot structure. In the primary system under consideration, there is a licensed spectrum band that consists of Q channels. In the CR network, all SUs are allowed to opportunistically access the temporarily unoccupied licensed channels without interfering with the PU transmissions. We consider the operation of the CR network on a frame-by-frame basis. Each frame has a time duration T, within which the SUs first sense the channel for the duration of Ts. If none of the PUs is sensed in the detected channel, the SUs will use the remaining duration of the frame Tr = T − Ts for data transmission. Normally, the sensing period Ts is predetermined by the physical layer, and it is relatively very short, as compared with Tr. For instance, in the standard IEEE 802.22, the sensing period Ts is 0.5 s, and the frame length T is 30 s.

III. Parallel Cooperative Sensing

The main focus of our scheme is to significantly improve the efficiency of spectrum discovery. In practice, each SU has a single antenna and is not capable of simultaneously monitoring multiple spectrum bands due to the hardware constraint. In this case, it becomes necessary to propose a new spectrum sensing to circumvent the inherent hardware constraint in an individual SU. In this paper, a parallel cooperative sensing scheme is proposed. The main motivation is the spectrum sensing on multiple channels by multiple SUs at the same time. Each SU is able to sense a different channel. The parallel manner is able to increase the sensing efficiency and lower the sensing duration. For the sake of presentation, we define the term appropriate channels. The set of appropriate channels denotes the subset of spectrum opportunities whose channel rate is no lower than the CRT. Hereby, the CRT is defined as the CRT for the BS to select a channel.

In particular, the strategy includes the following phases. 1) Each SU performs spectrum sensing of its own channel for the duration of the sensing period Ts. If the SU does not detect a signal from any PU over its channel, the SU will send out data in the transmission period for duration Tr. In case PU appearance is detected, the SU will deliver the message MSG-PARALLEL-SENSING-REQ to the BS, indicating a parallel sensing requirement. 2) Upon receiving the message MSG-PARALLELSENSING-REQ, the BS will deliberately select a subset of SUs to perform parallel spectrum sensing through an optimal cooperative sensing scheme (the detail is described in Section III). Each of these selected SUs is assigned to sense a different channel at the same time during the sensing period. Thereby, these SUs perform spectrum sensing in a parallel manner. After the sensing, the SUs will send back the message MSG-PARALLELSENSING-ACK with the sensing results to the BS, including the elements of the channel availability (“1” for busy and “0” for idle) and the achievable channel rate. 3) After receiving the message MSG-PARALLELSENSING-ACK and collecting all information on the channels, the BS will allocate the specific channel with the highest rate to the SU provided that there are idle channels. The BS then delivers the message MSG-SUCHANNEL to the SU with the index of the allocated channel. 4) The SU continues data transmission over the allocated channel. For the SUs that helped sensing, they have temporarily stopped their own data transmission to help the SU perform sensing. After the parallel sensing, these SUs will continue their own transmission over their own channel.

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IV. Using History For Prediction

For minimizing interference to primary users while making the most out of the opportunities, cognitive radios should keep track of variations in spectrum availability and should make predictions. Stemming from the fact that a cognitive radio senses the spectrum steadily and has the ability of learning, the history of the spectrum usage information can be used for predicting the future profile of the spectrum. Towards this goal, knowledge about currently active devices or prediction algorithms based on statistical analysis can be used [19]. Channel access patterns of primary users are identified and used for predicting spectrum usage in [20]. Assuming a TDMA transmission, the periodic pattern of channel occupancy is extracted using cyclostationary detection. This parameter is then used to forecast the channel idle probability for a given channel. In order to model the channel usage patterns of primary users, HMMs are proposed in [21]. A multivariate time series approach is taken in [115] to be able to learn the primary user characteristics and predict the future occupancy of neighboring channels. A binary scheme (empty or occupied) is used to reduce the complexity and storage requirements. It is noted in [22], [23] that the statistical model of a primary user's behavior should be kept simple enough to be able to design optimal higher order protocols. On the other hand, the model would be useless if the primary user's behavior could not be predicted well. In order to strike a balance between complexity and effectiveness, a continuous time semi-Markov process model is used to describe the statistical characteristics of WLAN channels that can be used by cognitive radio to predict transmission opportunities. The investigation of voice over Internet protocol (VoIP) and file transfer protocol (FTP) traffic scenarios for a semi-Markov model is performed in [24], [25]. Pareto, phase-type (hyperErlang) and mixture distributions are used for fitting to the empirical data. Statistics of spectrum availability is employed in [26] for dynamically selecting the operating frequency, i.e. for identifying the spectrum holes. Statistics of the spectral occupancy of an FFT output bin are assumed to be at least piecewise stationary over the time at which they are observed in order to guarantee that these statistics are still reliable when a spectrum access request is received. Using the statistics, the likelihood that a spectral opportunity will remain available for at least the requested time duration is calculated for each bin. Then, these likelihood values are used to identify the range of frequencies which can be used for transmission. When observation history is used optimally, the throughput of the secondary user can be increased approximately 40% [27], [28]. A predictive model is proposed in [29] which is based on long and short-term usage statistics of TV channels. The usability characteristics of a channel are based on these statistics and it is used for selection of a channel for transmission. Channels with frequent and heavy appearance of primary users are filtered out using a threshold mechanism.

V. Spectrum Sensing In Current Wireless Standards

Recently developed wireless standards have started to include cognitive features. Even though it is difficult to expect a wireless standard that is based on wideband spectrum sensing and opportunistic exploitation of the spectrum, the trend is in this direction. In this section, wireless technologies that require some sort of spectrum sensing for adaptation or for dynamic frequency access (DFA) are discussed. However, the spectrum knowledge can be used to initiate advanced receiver algorithms as well as adaptive interference cancellation [30].

VI. IEEE 802.11k

A proposed extension to IEEE 802.11 specification is IEEE 802.11k which defines several types of measurements [31]. Some of the measurements include channel load report, noise histogram report and station statistic report. The noise histogram report provides methods to measure interference levels that display all non-802.11 energy on a channel as received by the subscriber unit. AP collects channel information from each mobile unit and makes its own measurements. This data is then used by the AP to regulate access to a given channel. The sensing (or measurement) information is used to improve the traffic distribution within a network as well. WLAN devices usually connect to the AP that has the strongest signal level. Sometimes, such an arrangement might not be optimum and can cause overloading on one AP and underutilization of others. In 802.11k, when an AP with the strongest signal power is loaded to its full capacity, new subscriber units are assigned to one of the underutilized APs. Despite the fact that the received signal level is weaker, the overall system throughput is better thanks to more efficient utilization of network resources.

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VII. Limitation Of Cooperative Spectrum Sensing

In practice, the reporting channels between the CRs and the common receiver will also experience fading and. This will typically deteriorate the transmission reliability of the sensing results reported from the CRs to the common receiver. For example, when one CR reports a sensing result f1g (denoting the presence of the PU) to the common receiver through a realistic fading channel, the common receiver will likely detect it to be the opposite result f0g (denoting the absence of the PU) because of the disturbance from the random complex channel coefficient and random noise. Eventually, the performance of cooperative spectrum sensing will be degraded by the imperfect reporting channels. Let $P_e^{(i)}$ denote the error probability of signal transmission over the reporting channels between the i^{th} CR and the common receiver. We shall refer to $P_e^{(i)}$as the probability of reporting errors. Then, the cooperative spectrum sensing performance can be given by [18].

VIII. Conclusions

Spectrum is a very valuable resource in wireless communication systems, and it has been a focal point for research and development efforts over the last several decades. Cognitive radio, which is one of the efforts to utilize the available spectrum more efficiently through opportunistic spectrum usage, has become an exciting and promising concept. One of the important elements of cognitive radio is sensing the available spectrum opportunities. In this paper, the spectrum opportunity and spectrum sensing concepts are re-evaluated by considering different dimensions of the spectrum space. The new interpretation of spectrum space creates new opportunities and challenges for spectrum sensing while solving some of the traditional problems. Various aspects of the spectrum sensing task are explained in detail. Several sensing methods are studied and collaborative sensing is considered as a solution to some common problems in spectrum sensing. Pro-active approaches are given and sensing methods employed in current wireless systems are discussed. Estimation of spectrum usage in multiple dimensions including time, frequency, space, angle, and code; identifying opportunities in these dimensions; and developing algorithms for prediction into the future using past information can be considered as some of the open research areas.

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