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Time-efficient cooperative spectrum sensing via analog computation over multiple-access channel

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ABSTRACT

Conventional cooperative spectrum sensing (CSS) schemes in cognitive radio networks (CRNs) require that the secondary users (SUs) report their sensing data separately in the time domain to the fusion center, which yields long reporting delay especially in the case of large number of cooperative SUs. By exploiting the computation over multiple-access channel (CoMAC) method, this paper proposes a novel CoMAC-based CSS scheme that allows the cooperative SUs to encode their local statistics in transmit power and to transmit simultaneously the modulated symbols sequence carrying transmit power information to the fusion center. The fusion center then makes the final decision on the presence of primary users by recovering the overall test statistic of energy detection from the energy of the received signal. Performance metrics of the CoMAC-based CSS scheme, i.e., detection probability and false alarm probability, are further derived based on the central limit theorem. Finally, based on the derived detection and false alarm probabilities, both energy detection threshold and spectrum sensing time are optimized to improve the average throughput of the CRN. Simulations demonstrate the efficiency of this work.

1. Introduction

With the proliferation of wireless technologies, spectrum scarcity problem hinders the further development of nowadays wireless communication systems. However, it was reported that most of the currently allocated spectrums were mainly underuitlized by licensed primary users (PUs) [2]. For this, an emerging technology-cognitive radio (CR), with which the secondary users (SUs) are able to detect the spectrum opportunity and access the vacant spectrum in an opportunistic way, has received much attention recently [3–6].

Spectrum sensing functions have been frequently considered as important components in existing CR approaches, such as [7–10]. However, due to the presence of noise and fading of wireless channels, hidden terminals, obstacles and so on, spectrum sensing of individual nodes cannot achieve high detection accuracies. In contrast, cooperative spectrum sensing (CSS) exploits a parallel fusion sensing architecture in which independent SUs transmit their sensing data to a fusion center. The fusion center then makes a final soft or hard decision regarding the presence or absence of PUs [11,12]. The cooperative gains in spectrum sensing performance have been extensively demonstrated in existing works [13–25].

In conventional CSS schemes, the local statistic of each SU basically has to be sent to the fusion center in different time slots based on a time division multiple access (TDMA) scheme [13–23] or a random access scheme [24,25], due to the extremely limited bandwidth of the common control channel.[2] Correspondingly, the fusion center decodes each received local statistic separately and finally computes the overall test statistic which in this paper turns out the weighted arithmetic mean of the collected local statistics. The drawback of conventional CSS schemes [26,27] is the large reporting delay, especially when the CRN scales. Code division multiple access (CDMA) and orthogonal frequency division multiple access (OFDMA) can allow SUs to transmit concurrently in the same time slot their local statistics to the fusion center. How-

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[2] Notice that, in some cases, e.g. [12], a dedicated control channel is not mandatory for reporting the sensing results in the conventional CSS schemes.

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ever, either CDMA or OFDMA requires a reporting control channel with large bandwidth, which is impractical in the CRN scenario.

Motivated by the recent robust analog function computation scheme–computation over multiple-access channel (CoMAC) [28], this paper proposes a novel CoMAC-based CSS scheme, in which each SU first transmits a distinct complex-valued sequence at a transmit power depending on the SU reading and consequently the received energy at the fusion center equals the sum of all transmit energies corrupted by background Gaussian noise. The fusion center then takes advantage of the collected energy information to estimate the desired weighted arithmetic mean of the local statistics from SUs, based on which the spectrum availability is determined. This paper then establishes an analytical framework on the performance of the proposed CoMAC-based CSS scheme. The major contributions of this paper are summarized as follows:

- We develop a CoMAC-based CSS scheme to accelerate the spectrum sensing in CRNs with guaranteed sensing accuracy. The proposed CSS scheme allows each SU to concurrently transmit a large sequence of modulated symbols to the fusion center, with the magnitude of each symbol carrying the information of its weighted local statistic and the pre-compensation for the reporting channel magnitude. With the superposition property of wireless channels, the fusion center could recover the global statistic from the received signal energy. In contrast to conventional CSS schemes, the CoMAC-based CSS scheme needs only *one reporting time unit* to collect all of the local statistics.
- Based on the central limit theorem, we prove that the distribution of the received signal energy at the fusion center can be approximated by a Gaussian distribution. Then, we derive the detection probability and the false alarm probability, two primary performance metrics of the proposed CSS scheme, and show their asymptotic trends.
- We further optimize the throughput performance of the CoMAC-based CSS scheme via formulating an optimization problem in terms of spectrum sensing time and detection threshold.
- Simulation results demonstrate the high approximation accuracy of the CoMAC-based CSS scheme and show that the proposed CSS scheme could yield much higher average throughput than conventional CSS schemes while guaranteeing almost the same sensing performance.

The rest of this paper is organized as follows. Section 2 reviews the related work of this paper. In Section 3, the system model and conventional CSS schemes are briefly introduced. In Section 4, the proposed CoMAC-based CSS scheme is particularly illustrated. In Section 5 sensing performance of the proposed CoMAC-based CSS scheme is approximated. In Section 6, both the energy detection threshold and the spectrum sensing time are optimized to improve the average throughput of the CRN. In Section 7, simulations are employed to validate the efficiency of the proposed CSS scheme. Finally, we draw conclusions in Section 8.

2. Related work

In the context of CSS in CRNs, the optimal voting rule and energy detection threshold for minimizing the total sensing error rate, and the least number of CRs fulfilling the targeted error rate constraints under hard decision were derived in [13]. The optimal number of SUs in CSS for lognormal shadowing channels, static additive white gaussian noise channels and Rayleigh fading channels when considering the efficiency of resources usage in the system design was derived in [14]. Unlike the works [13,14] optimizing the number of sensing SUs, reference [15] studied throughput optimization of the hard fusion based sensing using the "*K*-out-of-*N*" rule for energy-constrained CRNs. Reference [16] focused on the performance analysis and comparison of hard decision and soft decision based CSS schemes in the presence of reporting channel errors. Reference [17] proposed an algorithm for a quantization-based CSS scheme in CRNs, which simultaneously optimizes the number of sensing samples at a local node, the number of bits for quantizing local sensing data and the global threshold at a fusion center. Different from the fundamental topics in CSS schemes [13–17], reference [18] presented a cooperative sequential detection scheme to reduce the average reporting load that is required to reach a detection decision. Sequential CSS schemes in time varying channels were investigated in [19]. Based on the past local observations from previous sensing slots, a fixed or an adaptive number of past observations were combined with the current energy values to improve the detection performance of the energy detection. Censoring is another promising method to reduce the reporting SUs since one SU does not report its sensing report unless it lies outside the a specific range. A censoring-based CSS scheme for cognitive sensor networks was proposed in [20]. The censoring thresholds to minimize the energy consumption while considering the constraints on the detection accuracy were optimized. Reference [21] generalized [20] via combining censoring and truncated sequential sensing to further reduce the reporting time of the CSS scheme. A novel objection-based CSS scheme, which includes that one of the SUs broadcasts its local decision and other SUs agree or object with the announced decision, was presented in [22]. Each objecting SU sends an objection report to the fusion center, while the agreeing SUs stay silent on their time slots. Reference [23] formulated a generalized modeling approach for sensing data with an arbitrary abnormal component and proposed a robust spectrum sensing scheme by developing a data cleansing framework. Different from the above works [13–21,23] based on TDMA reporting, reference [24] applied quickest detection in spectrum sensing in CRNs when multiple SUs collaborate with limited communication time slots and proposed a threshold random broadcast scheme without an explicit coordination for the information exchange. A random access-based reporting order control scheme for cooperative sensing was proposed in [25]. By controlling the reporting order of local statistics, the global statistic at the fusion center accumulates faster than the case without order control. More related works can be found in the recent surveys on CSS [26,27].

We observe that the local statistic transmission and the overall test statistic computation in conventional CSS schemes (under both soft decision and hard decision) are separate in the time domain. Such separation-based computation schemes are generally inefficient as a complete reconstruction of individual local statistics at the fusion center is unnecessary to compute the overall test statistic. In contrast, this paper proposes to merge the process of local statistics transmission and test statistic computation via exploiting the CoMAC scheme, which takes only one time unit of the reporting phase. With the high bandwidth efficiency, the proposed CoMAC-based CSS scheme yields higher average network throughput in comparison to conventional CSS schemes.

Note that, there are recent works which also could reduce the reporting time of CSS schemes by OFDM subcarrier modulation [29] or BPSK modulation with the same carrier frequency [30,31]. On one hand, reference [29] suffered hardware limitations on OFDM physical layer and one extra half-duplex antenna with self-cancelation technique for each SU, whereas all of these hardware limitations can be avoided in this paper. On the other hand, the works [30,31] are hard decision-based CSS schemes whose spectrum sensing performances are degraded by quantization errors, while the proposed CoMAC-based CSS scheme is immune to quantization errors since CoMAC is an analog function computation scheme. We have shown that this work could guarantee almost the same sensing performance of conventional CSS schemes by choosing a sufficiently large sequence length.