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Performance evaluation of improved double-threshold energy detector over Rayleigh-faded sensing and imperfect reporting channels ☆

Ramtin Rabiee *, Kwok Hung Li

Department of Electrical and Electronic Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore

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A B S T R A C T

Cognitive radio (CR) has been viewed as a promising solution to spectrum scarcity. In order to design a reliable CR system, many improvements have been proposed to enhance spectrum sensing performance of secondary users (SUs) in a CR network (CRN). Sensing reliability and transmission throughput of SUs are two important performance criteria, which should be optimized to enhance signal protection of primary user (PU) as well as spectrum utilization rate. In this paper, we consider Rayleigh-faded sensing channels and SUs use improved energy detector (IED) to make their local decisions. The final decision is made in a fusion center (FC) through the cooperative spectrum sensing (CSS) scheme with erroneous reporting channels. We show that the improved double-threshold energy detector (IDED) outperforms the conventional energy detector (CED) in terms of the total error rate. Furthermore, we evaluate the transmission throughput of the CRN through various ED schemes with detection constraints over both perfect and imperfect reporting channels. We show that the IDED has the highest achievable throughput among different ED schemes over imperfect reporting channels.

1. Introduction

Nowadays, spectrum scarcity is a deterrent for the continuous growth of wireless communication, and cognitive radio (CR) [1,2] has been viewed as a promising solution to the problem. The idea behind of the CR network (CRN) is to increase the utilization rate of licensed frequency bands which has made it as significant as a key policy [3–5].

In a CRN, a secondary user (SU) attempts to find spectrum holes and occupy them opportunistically whenever the primary user (PU) is idle. There is also another scenario that SUs reuse occupied frequency bands coexisting with active PUs by imposing some constraints such as signal power and distance to avoid any excess interference to primary signals [2]. Since it is very important to design a communication system as reliable as possible, spectrum sensing by SUs is a key element in designing a practical CRN. There exist some challenging problems to have reliable spectrum sensing in a realistic channel. One of them is the *hidden terminal problem* in which an SU is shadowed or affected by severe multi-path fading, and cooperative spectrum sensing (CSS) is a practical solution to solve it [6–8], as SUs send their own local decisions to a fusion center (FC) through reporting channels to make a more reliable global decision. The other problem appears here when the SUs send their observations to the FC through noisy channels [9]. Hence, it is crucial to consider a suitable detection method involving a sufficient number of cooperative users

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* Corresponding author.
E-mail addresses: ramtin001@e.ntu.edu.sg (R. Rabiee), ekhli@ntu.edu.sg (K.H. Li).

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and an optimum fusion rule to minimize any decision error.

Usually, SUs need to obtain a blind estimate of primary signal due to the lack of information about the channel conditions and PU's waveform. Hence, energy detection (ED) [10–13] has been considered as a suitable method to sense the presence of PU. Furthermore, many improvements have been suggested to enhance the power of ED in terms of detection performance and reliability. In [14], the authors showed that the optimum power operator of received signal amplitudes, p, is not necessarily two. Note that an exponent of two is used in the conventional energy detector (CED), and we can find an optimum exponent with respect to the desired performance criteria. It is called the improved energy detector (IED). The authors in [15–17] applied CSS to the one-sample based IED, where SUs just use one sample of the received signal for sensing. They began their studies in [15] over additive white Gaussian noise (AWGN) sensing channels (the PU–SU channel) and perfect reporting channels, and extended it to Rayleigh-faded sensing and imperfect reporting channels in [16]. Finally, they completed their job by equipping SUs with multiple antennas to have a more reliable local decision [17].

Using double thresholds, which has been suggested in recent studies, is another way to increase the performance of ED [18]. Each SU compares the measured energy with two thresholds. If it falls between the two thresholds, the SU either avoids transmitting any decision to FC [18,19] or just sends the observed energy value to avoid the sensing failure problem (the situation in which all SUs do not send any decision to the FC) at the cost of increased overhead [20–22]. In [23], a two-stage detection improvement was considered by using the IED besides the double-threshold method to achieve more reliable detection as compared with the conventional double-threshold energy detector (CDED). They used the approximate probability density function (PDF) of the N-sample based IED over the AWGN sensing channels, which has been derived in [14] to analyze the detection performance of the improved double-threshold energy detector (IDED). However, the effect of the number of sensing samples (N) is not analyzed. Since the sensing time is related to N, the throughput should also be considered and evaluated. Another two-stage method was proposed in [24]. If the single-threshold detector of the first stage decides on idleness of the PU, a double-threshold detector checks it again in the second stage to increase the reliability of the final decision. They have claimed that the sensing time is improved, albeit the required time to find the idle channel is higher due to the double checking process, which degrades the transmission throughput. The authors in [25] improved detection performance at the expense of sensing time, in which SUs do another sensing when observed energy level falls between two thresholds.

Although reliable sensing is vital to protect the primary signal, it also takes a longer sensing time to have a more accurate decision about PU's status. On the other hand, longer sensing time results in shorter transmission time for the secondary network, which degrades the throughput of SUs. The authors in [26] published a comprehensive study of sensing-throughput trade-off. Nonetheless, they just analyzed the CSS scheme over perfect reporting channels which is also analyzed for AWGN and Rayleigh-faded sensing channel in [27,28], respectively. The joint optimization of the threshold and the number of sensing samples was formulated in [29] to improve system performance in terms of the mean detection time and also the aggregate throughput of both PU and SU over a non-CSS scheme. In [30], the throughput of CSS networks over imperfect reporting channels has been evaluated. They showed that the maximum throughput is achievable by jointly optimizing sensing time and the number of SUs. However, they just considered a constraint on the probability of detection while the probability of false alarm is more effective on the throughput and should be also limited. The authors in [31,32] proposed methods which do sensing and transmission simultaneously to increase the throughput. Whereas they have focused on the utilization rate, it might increase the interference as well. Moreover, the effect of different ED methods on throughput was investigated over both perfect and imperfect reporting channels under required constraints in [33] when adopting the IDED over AWGN sensing channels. They just focused on the throughput over AWGN channels using the approximate PDF of [14], without any analysis of detection performance.

In this paper, we focus on a Rayleigh-faded sensing channel which is more likely in a wireless communication area, and use the CSS through imperfect reporting channels to consider a more practical channel model. Although the CSS can enhance the sensing efficiency, the quality of reporting channels is a challenging issue which can affect the detection performance, while it has been considered to be ideal in many works. We aim to propose an efficient ED based method in terms of both detection performance and transmission throughput over Rayleigh-faded channels when it is suffered from imperfect reporting channels. In the most of the previous works, one of these performance criteria is to evaluate the efficiency of the suggested method. We will first derive expressions of the IED for Rayleigh-faded sensing channels. By analyzing the detection reliability of one-sample based IED (the minimum sensing time) using single- and double-threshold methods, we show that there is no gain in the single-threshold based IED while the IDED outperforms the CED in terms of total error rate. Next, we introduce the sensing-throughput trade-off of SUs and extend our previous work in [33] to Rayleigh fading, using the derived PDF in the first part of this paper. We show that the IDED enhances throughput, in addition to the desired detection accuracy in the case of imperfect reporting channels. By introducing the system model and the IED scheme in Section 2, we find detection probabilities under both single- and double-threshold methods in Section 3. We then analyze the detection performance and throughput in Sections 4 and 5, respectively. Finally, we present numerical results in Section 6 and conclude them in Section 7.

2. The system model

Suppose a CRN with K SUs and one FC. We consider a signal model which has been used in [34,35]. The