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BEP walls for cooperative sensing in cognitive radios using K-out-of-N fusion rules ☆

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ABSTRACT

Cooperative spectrum sensing is used to identify idle spectrum in cognitive radio or co-existing wireless systems. This paper identifies a performance limitation for cooperative sensing (CS) involving distributed secondary users (SUs) and a fusion center (FC). The local binary decisions are fused at the FC using a K-out-of-N fusion rule. The performance limitation presented in this paper for CS is in the form of a *bit error probability* (*BEP*) *wall* and results from imperfect reporting channels between the SUs and the FC. That is, if the BEP of the reporting channel exceeds the BEP wall value, then irrespective of the received signal quality on the listening channel or the sensing time at the SUs, constraints on the detector performance cannot be met at the FC. The BEP wall is an important phenomenon and needs to be taken into account while designing communication protocol between the SUs and the FC. Expressions for the BEP walls are derived in terms of the error probabilities at the FC and the number of users cooperating. Further, important properties of the BEP walls are derived and discussed in detail for the K-out-of-N fusion rules under the assumption of independent and identically distributed reporting channel errors.

1. Introduction

Distributed detection involving multiple sensors in different locations and a fusion center (FC) has been a topic of great interest in the radar, sensor network and cognitive radio research communities [1–4]. Currently, there is considerable interest in its application to cooperative spectrum sensing in cognitive radios [5–8], in which secondary users (SUs) can cooperate to identify spectral holes and obtain awareness of the radio environment. Similarly, idle spectrum needs to be identified when there are co-existing and potentially heterogeneous wireless networks. There are several advantages of using cooperation for spectrum sensing. Cooperative detection provides diversity gains in the presence of multipath fading and shadowing. It also improves the detector performance, increases the coverage in a cognitive radio network, and facilitates simpler detectors.

Cooperative detection based on fusing local binary decisions reduces the communication cost at the expense of loss of information. Moreover, hard decision (HD)-based cooperative sensing (CS) schemes are easy to implement. In this paper, we consider the K-out-of-N fusion rules (also referred to the *counting rules*) for CS. The K-out-of-N fusion rules encompass a general class of fusion rules that includes widely used OR, AND, and MAJORITY Boolean fusion rules as special cases. In addition, the optimal fusion rule at the FC is of the form of a K-out-of-N fusion rule under the assumptions of conditional independence of observations at the SUs and the

☆ Some preliminary results were presented in [14] at the 36th IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP 2011), Prague, Czech Republic, May 2011.

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use of identical likelihood ratio test (LRT) detectors for hard decisions at all SUs [3].

Performance of HD-based CS in the presence of reporting channel errors has been well studied both in the distributed detection literature [9,10] and in the cognitive radio literature [11,12]. Most of the related work in the literature (see [9–11] and references therein) concentrates on how different reporting channel conditions affect the CS performance and on the design of optimal fusion rules to improve the performance. However, performance limitation issues due to imperfect reporting channels have not received sufficient attention. Establishing limitations of a detection scheme is an important topic as it helps in designing practical detectors. For example, the *SNR wall* is a performance limitation that needs to be taken into account if energy detection is employed [13]. Therefore, it is even more important to investigate the limitations of the widely used *K*-out-of-*N* fusion rules. The performance limitations for the *K*-out-of-*N* rules have been studied in [12,14–16]. In [12], the authors consider the application of cooperative communication techniques to spectrum sensing and spectrum sharing. In addition, the performance limitations of the OR rule are briefly studied in the presence of channel errors under a constraint on the false alarm probability.

In [14–16], the reporting-channel errors are modeled using the BEP (bit error probability) model, which is a very general and widely used method to model the end-to-end performance of the system including the transmitter, the channel and the receiver and wide varieties of communication techniques (modulation, coding, interleaving, relaying, etc.) in practical communication networks. Based on this model, a performance limitation in the form of a BEP wall phenomenon is established for CS in [14–16] resulting from the reporting channel errors: *If the reporting channel BEP is above the BEP wall value, it is impossible to satisfy the imposed performance constraints on the detector error probabilities at the FC irrespective of the SNR on the listening channel or the sensing time at the SUs.* Studying the BEP wall phenomenon is important as it helps designers to find feasible BEP values for the reporting channels used for transmitting the sensing information from the local detectors to the FC. Once feasible target BEP values are decided, appropriate modulation, coding, interleaving and relaying schemes can then be chosen without seriously affecting the cooperative sensing performance. In [15], the BEP walls are demonstrated for the '*K*-out-of-*N*' fusion rules with independent but non-identically distributed reporting channel errors while the BEP walls are demonstrated for the soft decision-based CS with independent and identically distributed (*i.i.d.*) reporting channel errors in [16]. In both the cases, the BEP wall phenomenon was only demonstrated and that too through simulations. *In this paper, detailed analytical derivations, properties and results corresponding to the BEP walls are presented for the K-out-of-N fusion rules under the assumption of i.i.d. reporting channel errors.*

Specific contributions of this paper are[1]

1. Existence of a BEP wall is shown for the *K*-out-of-*N* fusion rules in the presence of reporting channel errors with constraints on the global probabilities of missed detection and false alarm.
2. An analytical expression for the BEP wall value is derived for the *K*-out-of-*N* fusion rules in terms of the constraints on the false alarm probability and probability of missed detection at the FC. It is shown that the BEP wall exists even for BEP values as low as 10^{-3} and is therefore important to take into account.
3. *A symmetry property* of the BEP wall for the *K*-out-of-*N* fusion rules is established analytically: *the BEP wall value for the K-out-of-N fusion rule is the same as the BEP wall value for* $(N-K+1)$*-out-of-N fusion rule with the constraints on the error probabilities interchanged*. This halves the effort required for evaluating the BEP walls for different values of *K* and the constraints on the detector performance given the number of SUs is *N*.
4. The effects on the BEP wall of different parameters such as *K*, *N*, and the constraints on the global probabilities of false alarm and missed detection are studied. Different choices of *K* are shown to result in very different BEP wall values for the '*K*-out-of-*N*' fusion rules resulting in significant differences in the robustness of these fusion rules to the reporting channel errors.
5. It is shown that the cooperation may degrade the performance of the widely used OR and AND fusion rules in the presence of reporting channel errors.

This paper is organized as follows. In Section 2, we analyze the performance of CS using the *K*-out-of-*N* fusion rules with imperfect reporting channels under constraints on the global error probabilities at the FC. In Section 3, we demonstrate the concept of the BEP wall and derive the symmetry property. Section 4 present theoretical and simulation results along with discussion of the effects of various parameters on the BEP wall. Section 5 concludes the paper.

2. Cooperative detection with imperfect reporting channels

Consider the scenario shown in Fig. 1, in which *N* SUs are cooperating to detect the presence or absence of a primary user (PU) transmission. For convenience, we assume that each sensor experiences the same average SNR on the listening channel. Moreover, identical sensors are assumed. Let the corresponding probabilities of detection, false alarm, and missed detection at the SUs be denoted by P_d, P_f, and P_m, respectively. Note that $P_m = 1-P_d$. For HD-based CS, the *n*th SU makes a binary decision u_n and sends it to the FC on the possibly erroneous reporting channel. Let P_b denote the BEP of the reporting channel for each SU. We assume that the channel errors are independent and identically distributed for all SUs. Let the hard decision received by the FC from the *n*th SU be denoted by u'_n. Because of the channel errors, the effective error probabilities incurred by each SU change at the FC. If P'_d, P'_f, and P'_m denote the probabilities of detection, false alarm, and missed

[1] Some preliminary results were presented in [14] at ICASSP 2011.