Censor-Based Multi-Antenna Cooperative Spectrum Sensing over Erroneous Feedback Channels

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***Abstract*—We propose a spectrally efficient censor-based cooperative spectrum sensing (C-CSS) approach for a sustainable cognitive radio network that consists of multiple antenna nodes and experiences imperfect sensing and reporting channels. First, analytic expressions are derived for the corresponding probabilities of detection and false alarm, assuming that each secondary user sends its detection outcome to a fusion center *only* when it believes to have detected a primary user's signal. Second, we derive lower bounds for the probability of false alarm, where we show that a sensing tail problem, which exist in the conventional (non-censor-based) scheme, can be effectively mitigated with the aid of the proposed C-CSS scheme. Simulation results are presented to corroborate the derived analytic results, and to provide theoretical and technical insights that are useful for the design of cognitive radio networks.**

I. INTRODUCTION

The radio spectrum has become a very precious commodity due to the ever-increasing number of connected devices which are estimated to reach 50 billion by year 2020. In light of this, there has been a radical shift in the way spectrum is managed by moving from rigid and tightly regulated spectrum policies to a more spectrally efficient and dynamic environment.

Cognitive radio networks (CRNs) emerged as an effective paradigm to increase the spectral efficiency, particularly in collaborative configurations. CRNs consist of two types of users. The first type are primary users (PUs) which are typically assigned licensed frequency bands with often guaranteed access and performance, and are often assumed oblivious to the existence of SUs. The second type are secondary users (SUs) which attempt to share the spectrum by harnessing the underutilized frequency bands without interfering with the operation of the PUs. Spectrum sharing can be realized by means of three different approaches, namely through overlay, underlay, and interweave [1]. In this paper, we are concerned with the third approach, in which SUs attempt to access the spectrum opportunistically, i.e., when PUs are considered to be idle. Therefore, there is a need for a highly accurate and efficient spectrum sensing technique that will ensure sufficient interference avoidance to PUs.

Several spectrum sensing (SS) techniques that mainly focus on achieving an improved sensing performance and/or a reduction of the overall system complexity have been proposed [2]. Energy detection (ED) is widely considered among the most common detection methods, and has received considerable attention owing to its relatively low computational and implementation complexity. Nevertheless, the non-cooperative ED-based approach has been shown to be susceptible to the so-called hidden terminal problem. Such phenomenon occurs when the SU is subject to non-negligible fading or path-loss effects while the PU is still in operation, thereby hindering an efficient detection of the PU. Therefore, cooperative spectrum sensing (CSS) has been proposed as an effective method to mitigate the hidden terminal problem and improve the sensing performance by exploiting the spatial diversity among SUs.

CSS consists of two successive phases, namely sensing phase and reporting phase. During the reporting phase, time division multiple access (TDMA) scheme is often used, where multiple SUs report their local sensing observations to a fusion center (FC) in different time slots. Longer sensing duration results in an improved sensing performance at the expense of increased waiting time for SUs to access the channel which can lead to lower spectrum utilization. One way to resolve such issue is to allow SUs to send their decisions on orthogonal frequency bands. However, more secondary users require larger bandwidth for the reporting channels, which requires effective optimization of the resource consumption of systems, while guaranteeing an acceptable sensing detection performance [2].

The majority of CSS schemes in the open literature rely on a conventional decision collection approach, in which SUs report all their decisions to the FC under the assumption of TDMA scheme in the reporting phase. Hereafter, we will refer to such an approach as traditional (non-censor-based) CSS (T-CSS). For instance, the authors in [3]–[7] analyzed the crucial relationship between sensing time, secondary throughput, and spectrum utilization. Optimal sensing duration was investigated [8]–[11] in an attempt to improve the overall system throughput, taking into account that a smaller number of SUs leads to a reduced sensing duration at the expense of reduced sensing diversity. T-CSS based schemes increase the detection performance and resolve the hidden terminal problem which is present in non-cooperative schemes. However, they incur extra signaling overhead, and can be unnecessarily detrimental to the detection performance, especially under imperfect sensing and reporting channels [12]–[18].

More recently, censor-based CSS (C-CSS) was proposed as an effective method that can reduce the sensing duration and signaling overhead. In doing so, the collaborative SUs report their decisions based on certain conditions rather than periodically [19]. In [20]–[22], the performance of C-CSS based schemes are investigated in terms of probabilities of detection and false alarm for wireless sensor networks under perfect sensing and reporting channels. Sun *et al.* [23] investigated the detection performance of a censoring method with quantization to decrease the average number of transmitted bits, where only reliable information (bits) are considered in the FC over perfect and imperfect reporting channels. In [23], both binary results of 0 (not present) and 1 (present) are transmitted to the FC, where the quantization is subject to optimization.

The present work considers a multi-antenna based C-CSS scheme under imperfect sensing and reporting channels. We consider that each SU sends its detection outcome to an FC only when it believes to have detected the primary users signal. We quantify the performance of both the C-CSS scheme (and it's respective T-CSS scheme) under imperfect sensing and reporting channels, and derive simple analytic expressions for the corresponding probabilities of detection and false alarm. In addition, we derive lower bounds for the probability of false alarm, and show that a sensing tail problem, which exist in T-CSS, can be effectively mitigated with the aid of the proposed C-CSS approach.

II. CSS System Model

We consider the CSS network configuration in Fig. 1, which consists of one PU and N SU nodes, each of which equipped with L antennas. The considered C-CSS process can be described in the following three steps:

Step 1: Let SU_i^j represent the ith SU node equipped with the jth antenna. Each SU node determines a local decision D_i by combining the results of L antennas, and then decides on the presence of a PU signal.

Step 2: Each SU node forwards its binary decision to the FC via a reporting channel *only* if the corresponding local decision is equal to unity, i.e., if $D_i = 1$. The set of transmitted decisions are denoted by $\hat{\mathbf{D}} = \{D_1, D_2, \ldots, D_{MC}\}$, where M_C represents the number of transmitted decisions. Similarly, the transmitted decisions in T-CSS are denoted by $\mathbf{D} = \{D_1, D_2, ..., D_N\}$, where $M_C \leq N$. Furthermore, the local results for all SUs are transmitted to the FC using orthogonal frequency division multiple-access (OFDMA), as illustrated in Fig. 2, where W and B resemble the total bandwidth and the control channel bandwidth used by each SU to report its local decision, respectively.

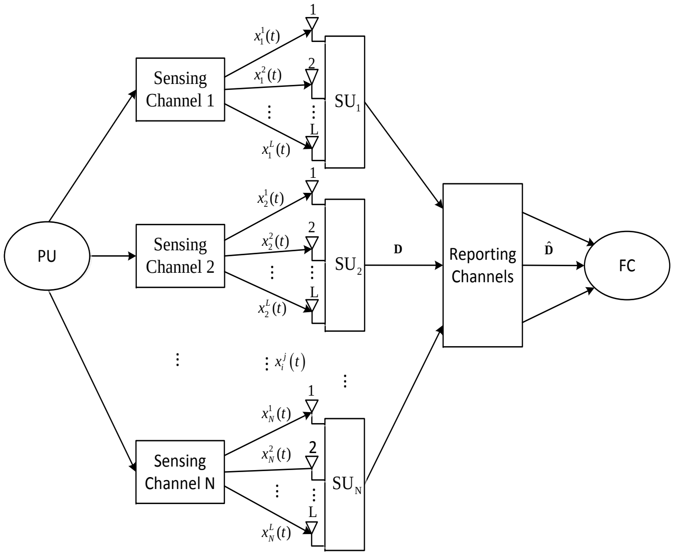


Fig. 1: Multiple antenna sensing network configuration.

Step 3: At the FC, all binary decisions are fused together, and a final decision is made based on the hard k-out-of-n fusion rule.

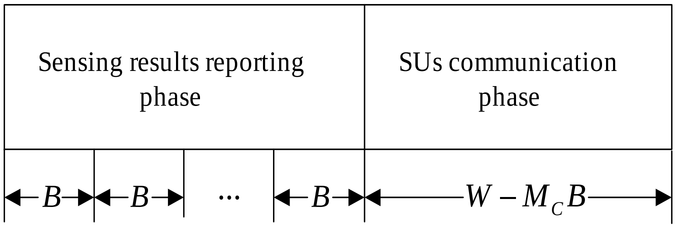


Fig. 2: The bandwidth allocation in C-CSS.

III. Proposed Censor-based Spectrum Sensing

A. Non-cooperative Detection

We commence by analyzing the single user performance. Let $x_i^j(t)$ represent the observed signal at the jth antenna of the ith node at time t, and $\mathcal{H}_0$ and $\mathcal{H}_1$ denote the hypotheses for the absence and presence of a PU signal, respectively. Thus, the observed signal can be represented as

$$x_i^j(t) = \begin{cases} n_i^j(t), & \mathcal{H}_0 \\ h_i^j s(t) + n_i^j(t), & \mathcal{H}_1 \end{cases} \tag{1}$$

where $n_i^j(t)$ is $\mathcal{CN}(0,\sigma_n^2)$ denoting the circularly symmetric complex white additive Gaussian noise (AWGN) in the secondary user channel SU_i^j, $s(t)$ is the information signal transmitted by the PU with energy $E_s = \mathbb{E}\{|s(t)^2|\}$, and h_i^j is the complex Gaussian channel gain of the sensing channel between the PU and SU_i^j, with $\mathbb{E}\{\cdot\}$ denoting statistical expectation.

To this effect, when SU_i makes a decision based on the local observations, the corresponding energy Y_i can be statistically represented as follows [2]

$$Y_i = \begin{cases} \chi_{2u}^2, & \mathcal{H}_0 \\ \chi_{2u}^2(2\gamma_i), & \mathcal{H}_1 \end{cases} \tag{2}$$

where u denotes the time bandwidth product, γ_i represents the instantaneous SNR of the received signal at the SU_i, χ_{2u}^2 denotes a central Chi-square distribution with $2u$ degrees of freedom, and $\chi_{2u}^2(2\gamma_i)$ represents a non-central Chi-square distribution with $2u$ degrees of freedom. Hence, the detection of PU signals can be realized by comparing Y_i with a predetermined energy threshold λ_i, which is represented as

$$\begin{cases} D_i = 1, & Y_i \geq \lambda_i \\ D_i = 0, & Y_i < \lambda_i \end{cases} \tag{3}$$

Based on the above, the probability density function (PDF) of Y_i under the two considered hypotheses is given by

$$f_{Y_i}(y) = \begin{cases} \frac{1}{2^u\Gamma(u)} y^{u-1}\exp(-\frac{y}{2}), & \mathcal{H}_0 \\ \frac{1}{2}(\frac{y}{2\gamma_i})^{\frac{u-1}{2}}\exp(-\frac{2\gamma_i+y}{2}) I_{u-1}(\sqrt{2\gamma_i y}), & \mathcal{H}_1 \end{cases} \tag{4}$$

which yields the corresponding conditional probability of false-alarm and probability of detection:

$$\hat{P}_{f_i} = \Pr\{Y_i > \lambda_i | \mathcal{H}_0\} \tag{5}$$

and

$$P_{d_i} = \Pr\{Y_i > \lambda_i | \mathcal{H}_1\} \tag{6}$$

respectively, which yield

$$\hat{P}_{f_i} = \int_{\lambda}^{\infty} f_{Y_i|\mathcal{H}_0}(y)\,\mathrm{d}y = \frac{\Gamma\left(u, \frac{\lambda_i}{2}\right)}{\Gamma(u)} \tag{7}$$

and

$$\hat{P}_{d_i} = \int_{\lambda}^{\infty} f_{Y_i|\mathcal{H}_1}(y)\,\mathrm{d}y = Q_u\left(\sqrt{2\gamma_i}, \sqrt{\lambda_i}\right) \tag{8}$$

respectively, where $\Gamma(a)$ and $\Gamma(a,x)$ denote the Euler gamma function and the upper incomplete gamma function, respectively, $I_n(x)$ is the n^{th} order modified Bessel function of the first kind, and $Q_m(a,b)$ is the generalized Marcum $Q-$function [24].

Since the $\hat{P}_{f_i}$ is independent of γ_i and the present signal in the $\mathcal{H}_1$ hypothesis is typically subject to non-negligible fading effects that affect the corresponding probability of detection, the unconditional probabilities of false alarm and detection are given by

$$\begin{cases} P_{f_i} = \hat{P}_{f_i} \\ P_{d_i} = \int_{\gamma} \hat{P}_{d_i}(\gamma) f(\gamma_i)\mathrm{d}\gamma \end{cases} \tag{9}$$

where $f(\gamma_i)$ denotes the SNR PDF of the statistics of the SU_i sensing channel [25]. To this effect, by specifically assuming Rayleigh distributed multipath fading and that SU_i performs local sensing independently, it follows that the average probability of detection and probability of false alarm of each antenna are expressed as [2]:

$$\begin{aligned} P_d =& e^{-\frac{\lambda}{2}} \sum_{n=0}^{u-2} \frac{\lambda^n}{n!2^n} + \left(\frac{1+\bar{\gamma}}{\bar{\gamma}}\right)^{u-1} \\ & \times \left\{ e^{-\frac{\lambda}{2(1+\bar{\gamma})}} - e^{-\frac{\lambda}{2}} \sum_{n=0}^{u-2} \frac{\lambda^n \bar{\gamma}^n}{n!2^n(1+\bar{\gamma})^n} \right\} \end{aligned} \tag{10}$$

and

$$P_f = \frac{\Gamma(u, \lambda/2)}{\Gamma(u)} \tag{11}$$

respectively, where $\bar{\gamma}$ denotes the corresponding average SNR.

B. Square-Law Selection

It is widely known that diversity receivers can significantly improve the performance of CRNs, particularly in the presence of multipath fading and shadowing effects. Based on this, square-law combining and square-law selection (SLS) techniques have been employed extensively in numerous spectrum sensing scenarios. Although the SLS combining technique is sub-optimal when compared to the former combining scheme, it is adopted in our C-CSS due to its tractability and low complexity that renders its realization straightforward. To this end, it is first recalled that SLS is based on the selection of the branch with the maximum $\gamma^{(j)}$ for each SU, namely

$$\gamma_{\mathrm{SLS}} = \max_{j=1,2,\ldots,L} \gamma^{(j)} \tag{12}$$

where L denotes the number of antennas at each SU node. Therefore, the probability of false alarm of each SU can be expressed as

$$P_{f,\mathrm{SLS}} = 1 - \Pr(\gamma_{\mathrm{SLS}} < \lambda | \mathcal{H}_0) \tag{13}$$

which upon use of (12) can be written as follows:

$$P_{f,\mathrm{SLS}} = 1 - \Pr(\max(\gamma^{(1)}, \gamma^{(2)}, \ldots, \gamma^{(L)}) < \lambda | \mathcal{H}_0) \tag{14}$$

which can be alternatively re-written as

$$P_{f,\mathrm{SLS}} = 1 - [1 - P_f]^L. \tag{15}$$

Likewise, the average probability of detection of each SU for the SLS scheme is expressed as

$$P_{d,\mathrm{SLS}} = 1 - [1 - P_d]^L. \tag{16}$$

C. Multi-User Detection

In multi-user sensing, local decisions are reported to the FC through dedicated reporting channels which are also subject to detrimental fading effects and additive noise. By letting $P_{e,i}$ denote the reporting error between the i^{th} SU and the FC and, without loss of generality, assuming that all reporting channels are independent and identically distributed, for a given γ with binary phase shift keying (BPSK), the probability of reporting error under AWGN can be expressed as

$$P_{\mathrm{e,AWGN}} = Q(\sqrt{2\gamma}) \tag{17}$$

where $Q(\cdot)$ denotes the one dimensional Gaussian $Q-$function [24]. Hence, for the case of Rayleigh distributed multipath fading, the average error rate, P_e, is given by

$$P_e = \int_{\gamma} Q(\sqrt{2\gamma}) f(\gamma) \mathrm{d}\gamma = \frac{1}{\overline{\gamma}} \int_0^{\infty} Q(\sqrt{2\gamma}) e^{-\frac{\gamma}{\overline{\gamma}}} \mathrm{d}\gamma \tag{18}$$

which can be expressed in closed-form as follows:

$$P_e = \frac{1}{2}\left(1 - \sqrt{\frac{\overline{\gamma}}{1+\overline{\gamma}}}\right). \tag{19}$$

Since in T-CSS, both types of decisions are sent to the FC, the false-alarm probability and detection probability subject to erroneous feedback channels can be expressed as

$$P'_{f,\mathrm{SLS,T-CSS}} = \Pr\{\mathcal{H}_1 | \mathcal{H}_0\}(1-P_e) + \Pr\{\mathcal{H}_0 | \mathcal{H}_0\} P_e \tag{20}$$

and

$$P'_{d,\mathrm{SLS,T-CSS}} = \Pr\{\mathcal{H}_1 | \mathcal{H}_1\}(1-P_e) + \Pr\{\mathcal{H}_0 | \mathcal{H}_1\} P_e \tag{21}$$

respectively, which yields

$$P'_{f,\mathrm{SLS,T-CSS}} = (1-P_e) P_{f,\mathrm{SLS}} + (1 - P_{f,\mathrm{SLS}}) P_e \tag{22}$$

and

$$P'_{d,\mathrm{SLS,T-CSS}} = (1-P_e) P_{d,\mathrm{SLS}} + (1 - P_{d,\mathrm{SLS}}) P_e \tag{23}$$

respectively.

Here, the FC combines all decisions and makes the final decision according to the hard k-out-of-n fusion rule. That is, the FC infers the presence of the PU when there exist at least k SUs that either (i) correctly claim $\mathcal{H}_1$ without an error in reporting phase (i.e., $(1-P_e)P_{d,\mathrm{SLS}}$), or (ii) falsely claim $\mathcal{H}_0$ with an error in reporting phase ($(1-P_{d,\mathrm{SLS}})P_e$). Therefore, it follows that for the case of T-CSS, the total probability of false alarm ($Q_{f,\mathrm{T-CSS}}$) and probability of detection ($Q_{d,\mathrm{T-CSS}}$) are

$$Q_{f,\mathrm{T-CSS}} = \sum_{i=k}^{N} \binom{N}{i} \frac{(P'_{f,\mathrm{SLS,T-CSS}})^i}{(1-P'_{f,\mathrm{SLS,T-CSS}})^{-(N-i)}} \tag{24}$$

and

$$Q_{d,\mathrm{T-CSS}} = \sum_{i=k}^{N} \binom{N}{i} \frac{(P'_{d,\mathrm{SLS,T-CSS}})^i}{(1-P'_{d,\mathrm{SLS,T-CSS}})^{-(N-i)}}, \tag{25}$$

where $k \in \{1, 2, \ldots, N\}$ and $\binom{b}{a}$ is the binomial coefficient.

On the contrary, in C-CSS, due to the fact that SUs only report their decisions *only* when they claim $\mathcal{H}_1$, the corresponding false-alarm and detection probabilities become

$$\begin{aligned} P'_{f,\mathrm{SLS,C-CSS}} &= \Pr\{\mathcal{H}_1 | \mathcal{H}_0\}(1-P_e) \\ &= (1-P_e) P_{f,\mathrm{SLS}} \end{aligned} \tag{26}$$

and

$$\begin{aligned} P'_{d,\mathrm{SLS,C-CSS}} &= \Pr\{\mathcal{H}_1 | \mathcal{H}_1\}(1-P_e) \\ &= (1-P_e) P_{d,\mathrm{SLS}} \end{aligned} \tag{27}$$

respectively. Thanks to the censoring technique, the unfavorable error terms due to erroneous reporting channels in (22) and (23) was filtered out in (26) and (27).

The number of transmitted decisions in the C-CSS scheme is not necessarily equal to the number of the sensing users, and the actual transmitted sensing decisions are based on two possible outcomes: i) the SUs detected falsely the presence of PU signals with probability $P_{f,\mathrm{SLS}}$, while the corresponding frequency band is idle; ii) the SUs detected correctly the presence of PU signals with probability $P_{d,\mathrm{SLS}}$, while the spectrum is actually being utilized. Therefore according to Bayes theory, the expected number of transmitted decisions in the C-CSS scheme can be determined as [23]:

$$M_C = \lceil N(P_0 P_{f,\mathrm{SLS}} + (1-P_0) P_{d,\mathrm{SLS}}) \rceil \tag{28}$$

where P_0 accounts for the probability of idle channel, and $\lceil . \rceil$ denotes the ceiling function. In this context, with C-CSS scheme, when utilizing the hard k-out-of-N fusion rule, for the total probability of detection, we need at least k users that correctly claim $\mathcal{H}_1$ without an error in reporting phase, i.e.,

$$Q_{d,\mathrm{C-CSS}} = \sum_{i=k_c}^{M_C} \binom{M_C}{i} \frac{(P'_{d,\mathrm{SLS,C-CSS}})^i}{(1-P'_{d,\mathrm{SLS,C-CSS}})^{-(M_C-i)}} \tag{29}$$

and for the total false-alarm probability, we need at least k users that falsely claim $\mathcal{H}_1$ without an error in the reporting phase, i.e.,

$$Q_{f,\mathrm{C-CSS}} = \sum_{i=k_c}^{M_C} \binom{M_C}{i} \frac{(P'_{f,\mathrm{SLS,C-CSS}})^i}{(1-P'_{f,\mathrm{SLS,C-CSS}})^{-(M_C-i)}} \tag{30}$$

where $k_c = 1, 2, ..., M_C$.

D. The False Alarm Bound

In this subsection, we determine the false alarm bound for the T-CSS and C-CSS schemes. It is noted here that the former sensing technique experiences a considerable sensing tail issue when the reporting channels are erroneous (subject to fading effects). However, with the aid of the aforementioned C-CSS setup, the sensing tail is ultimately eliminated. We demonstrate such phenomenon by considering 1-out-of-n fusion rule, *i.e.*, $k = k_c = 1$.

Proposition 1. *When the reporting channel is subjected to Rayleigh fading with an average error rate of P_e, and as $P_f \to 0$, the false alarm for the considered T-CSS and C-CSS schemes are:*

$$Q_{f,\mathrm{T-CSS,min}} \approx N P_e + \mathcal{O}(P_e^2) \tag{31}$$

and

$$Q_{f,\mathrm{C-CSS,min}} = 0 \tag{32}$$

where $Q_{f,\mathrm{T-CSS,min}}$ and $Q_{f,\mathrm{C-CSS,min}}$ denote the minimum value of $Q_{f,\mathrm{T-CSS}}$ and $Q_{f,\mathrm{C-CSS}}$, respectively.

Proof. By substituting (15) and (22) into (24), differentiating (24), and after some algebraic manipulation, one obtains

$$\begin{aligned}\frac{\partial Q_{f,\mathrm{T-CSS}}}{\partial P_f} =& LN(1-2P_e)[1-P_f]^{L-1} \times [1-P_e \\ & -(1-2P_e)(1-[1-P_f]^{L})^{N-1}].\end{aligned} \tag{33}$$

Since the error probability is practically no more than $1/2$, eq. (31) satisfies the inequality $\frac{\partial Q_{f,\mathrm{T-CSS}}}{\partial P_f} \geq 0$. It is evident that $Q_{f,\mathrm{T-CSS}}$ is monotonically increasing with respect to P_f. Hence, the minimum value of $Q_{f,\mathrm{T-CSS}}$ is obtained when $P_f = 0$, i.e.,

$$Q_{f,\mathrm{T-CSS,min}} = \lim_{P_f \to 0} Q_{f,\mathrm{T-CSS}} = 1-(1-P_e)^N. \tag{34}$$

Using the binomial expansion of $(1+(-P_e))^N$, and truncating to the first term, we obtain

$$Q_{f,\mathrm{T-CSS,min}} \approx NP_e + \mathcal{O}(P_e^2). \tag{35}$$

For C-CSS, by first substituting (15) and (26) into (30), and then differentiating (30) with respect to P_f, we obtain

$$\begin{aligned}\frac{\partial Q_{f,\mathrm{C-CSS}}}{\partial P_f} \approx & LM_C(1-P_e)[1-P_f]^{L-1} \\ & \times \{(1-(1-P_e)(1-[1-P_f]^{L}))\}^{M_C}\end{aligned} \tag{36}$$

which leads to concluding that

$$\frac{\partial Q_{f,\mathrm{C-CSS}}}{\partial P_f} > 0 \tag{37}$$

and thus, the minimum value of $Q_{f,\mathrm{C-CSS}}$ is given by

$$Q_{f,\mathrm{C-CSS,min}} = 0 \tag{38}$$

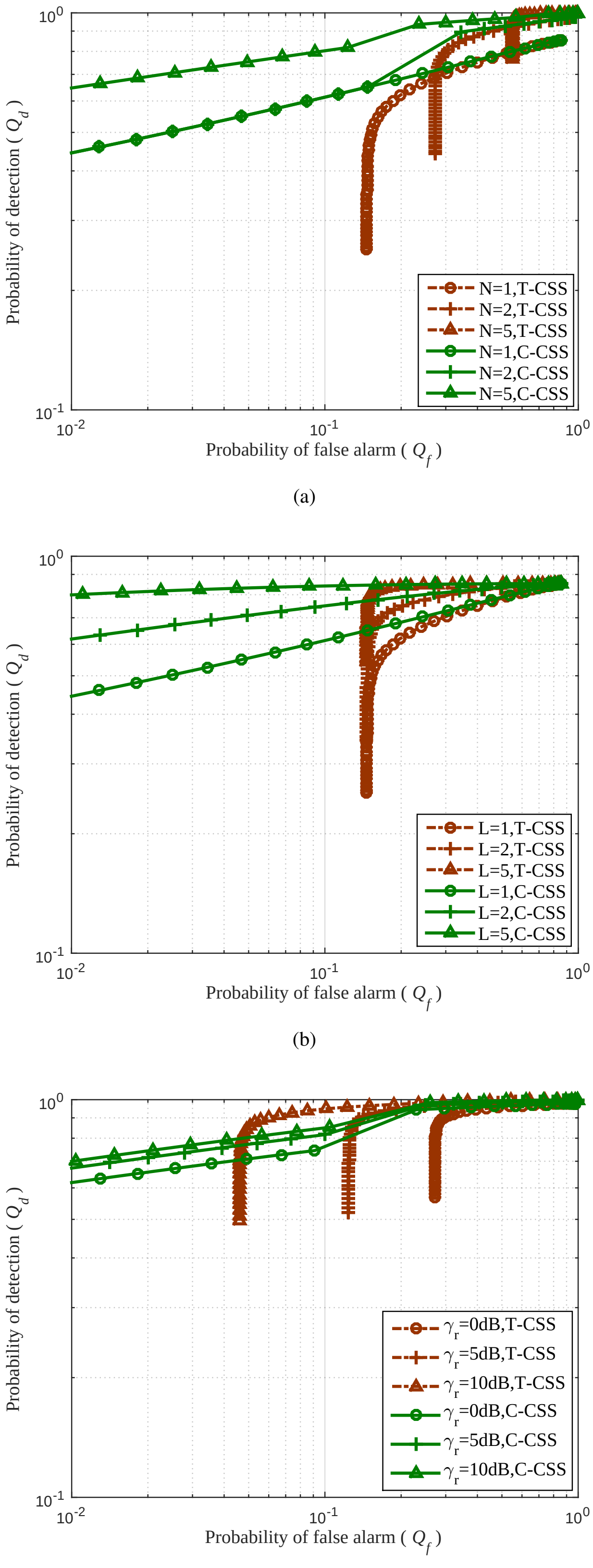
which completes the proof. ☐

There is a lower bound on the cooperative probability of false alarm $Q_{f,\mathrm{T-CSS}}$ in the T-CSS scheme, with a truncation error of the order $\mathcal{O}(P_e^2)$. Correspondingly, the cooperative probability of detection approaches zero when $Q_{f,\mathrm{T-CSS}} = Q_{f,\mathrm{T-CSS,min}}$. It merits to emphasize that $Q_{f,\mathrm{T-CSS,min}}$ increases proportionally with the number of SUs (N) and the fading severity (P_e) of the reporting channel. On the contrary, the lower bound on $Q_{f,\mathrm{C-CSS,min}}$ is practically *independent* of the number of SUs and the quality of the reporting channels. The above result is intuitive in the sense that when the characteristics of the reporting channel is severed from the perspective of the SU, refraining from voting is advantageous.

Investigating further performance metrics, such as the secondary throughput, and analyzing its relation with the derived analytic expressions and false alarm bound, under the T-CSS and C-CSS setups, is a topic for future research.

IV. NUMERICAL RESULTS

In this section, the offered analytic results are utilized in order to quantify the performance of the considered setup and develop meaningful theoretical and technical insights that will be useful in the design and deployment of CR systems. Respective results from computer simulations are



(a)

(b)

(c)

Fig. 3: Performance of C-CSS and T-CSS with: (a) Varying number of sensing users (N) with L=1 and $\gamma_r = 0$ dB; (b) Varying number of antennas (L) with N=1 and $\gamma_r = 0$ dB; (c) Varying SNR of reporting channels (γ_r) with L=1 and N=2.

also provided for verifying the validity of the offered analytic results.

Fig. 3 demonstrates the results from the analysis in Section III, where the performance of T-CSS and C-CSS is compared for different number of sensing users (N), number of antennas (L), and average SNR of the reporting channel (γ_r). Here, we assume that the average SNR of the sensing channel is (γ_s) is 10 dB, while $k = k_c = 1$, $\alpha = 0.1$, and $P_0 = 0.5$.

Recall that $Q_{f,\mathrm{T-CSS,min}} \approx NP_e$ in T-CSS. Therefore, when either N or the fading severity of the reporting channels increase, the sensing tail problem becomes more evident. The sensing tail problem is illustrated clearly in Fig. 3, where at low false alarm regions, the detection performance of the T-CSS scheme is acutely degraded, contrary to the C-CSS scheme which does not suffer from such degradation. Furthermore for the T-CSS scheme, it is shown that increasing N does not enhance the detection performance significantly, particularly in the low false alarm region, due to the dependence of the lower bound on N. Likewise, Fig. 4(b) shows that the lower bound of the probability of false alarm is independent of L, while Fig. 3(c) demonstrates the increase of the false alarm bound as γ_r decreases. Fig. 3 also shows that the detection probability in the T-CSS scheme reduces drastically to zero at the lower false alarm bound.

V. CONCLUSION

We introduced a censor-based cooperative spectrum sensing approach using multiple antenna nodes that operates in realistic communication scenarios with imperfect sensing and reporting channel conditions. Analytic expressions were derived for the probabilities of detection and false-alarm. Moreover, a lower bound for the cooperative false alarm was derived for the conventional (non-censor-based) sensing technique, showing that a critical sensing tail problem emerges when considering realistic erroneous feedback channels. To resolve such a phenomenon, we show that the considered C-CSS approach provides an effective solution to the sensing tail problem, thereby providing useful insight for the future designs and deployment of efficient cognitive radio networks.

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