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Optimisation of censoring-based cooperative spectrum sensing approach with multiple antennas and imperfect reporting channel scenarios for cognitive radio network

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Abstract: In this article, we have employed an energy detector (ED)-based cooperative spectrum sensing (CSS) with multi-antenna for cognitive radio network (CRN). The spectrum sensing error and energy efficiency (EE) are the key performance parameters in CRN which are affected by the threshold selection method, number of antennas employed at each cognitive user (CU), reporting error probability and cooperative fusion-rule applied at fusion center (FC). Therefore, we have derived the expression for sensing error by considering the effect of all these parameters and have optimized the cooperative fusion-rule at FC by formulating mathematical expression for optimal *K in k-out-of-M rule* to minimize the sensing error. Since CSS improves the sensing performance of CRN at the cost of increased overhead bits due to more CUs reporting to FC, results reduced EE. We have employed censoring approach to reduce the energy consumption and hence increase the EE of CSS technique. Further, we have illustrated the sensing error and EE improvement achieved under the censoring approach when different threshold selection approaches are employed at each CU. The percentage EE enhancement in censoring approach are 19.53% and 19.9% with constant false-alarm rate (CFAR) and minimized-error probability (MEP) approaches, respectively in comparison to that of the non-censoring approach.

1 Introduction

In the next generation of wireless communication, various services, e.g. Internet-of-Things, machine-to-machine communication and seamless connectivity of a large number of devices etc., increase the demand for new frequency spectrums [1, 2]. However, the current static spectrum allocation scheme is inappropriate to fulfil the demand of the new frequency spectrum and one of the most popular solutions to this problem is the cognitive radio network (CRN) [3]. CRN employs the cognitive user (CU) who identify the unutilised/underutilised licensed band in time/frequency/space domain and can transmit its information to the licensed user or primary user (PU) is not being detected in the licensed frequency band [4]. In order to avoid the interference of the CU information with PU, continuous monitoring and accurate sensing of the frequency spectrum is required [5, 6]. Therefore, the spectrum sensing (SS) is an essential step in a CRN to identify the free licensed frequency band and different SS approaches are explored by various researchers [7, 8]. The energy detector SS (EDSS) is one of the commonly used SS methods, which is mostly employed by researchers to date due to its easy implementation, less computational complexity and semi-blind nature [7, 8]. Moreover, the performance of EDSS degrades drastically under the multipath fading scenario [9]. Further, in order to overcome this problem, cooperative SS (CSS) technique is employed in which the sensing decision of multiple CUs is sent to the one central device named, fusion centre (FC) to take a global decision about the free or busy state of the licensed channel [10].

However, the performance of the SS is improved with CSS, but simultaneously the energy consumption also increases in CRN, which is a critical issue for limited battery-powered CUs [11]. In this context, to reduce energy consumption, the censoring approach is commonly employed in which the sensing decision of some particular CUs is sent to FC [12, 13]. The sensing decision of CUs is measured in terms of false-alarm and detection probability where the false-alarm probability (P_f) is defined as the wrong predicted free licensed channels as busy, while the detection probability (P_d) is defined as the correctly predicted busy licensed channels [14]. Generally, in CRN, it is required to have low false-alarm and high detection probability in order to maximise the utilisation of idle licensed channels and minimise the interference at PUs by CUs, respectively [15]. As in IEEE 802.22 wireless regional area network cognitive radio (CR) standard, the false-alarm probability is limited to 0.1 and detection probability minimum requirement is set to be 0.9, i.e. $P_\mathrm{f} \leq 0.1$ and $P_\mathrm{d} \geq 0.9$ [16]. Moreover, the false-alarm and detection probabilities are mainly affected by the selection of threshold (λ) and both probabilities decrease with an increase in threshold value [17]. Therefore, the proper threshold selection approach is required in order to achieve less sensing error or good sensing performance of CU. Further, the related work section presented further gives an insight into the different performance parameters of CRN in CSS.

2 Related work

In the literature, different threshold selection approaches are considered, namely, the constant detection rate [8, 18], constant false-alarm rate (CFAR), [19, 20] and minimised error probability (MEP) [21] to compute the sensing performance of CU. Further, various researchers have tried to improve the sensing performance of CU in terms of the throughput, sensing error and energy efficiency (EE) by employing different approaches, which are as follows. Firouzabadi and Rabiei [22] have optimised the sensing threshold (λ) along with sensing and reporting time in order to maximise the throughput. However, an improvement in the throughput under perfect reporting channels is achieved by Tuan and Koo [23] by performing the sensing and data transmission at the same time. In addition, Zhao *et al.* [24] have maximised the throughput under imperfect reporting channel by considering joint constraints on sensing overhead bits and the interference of CU with PU. In the context of the sensing error, Kumar *et al.* [14] have considered additive white Gaussian noise (AWGN) channel in the non-cooperative scenario and proposed an approach to opt the suitable threshold according to signal-to-noise ratio (SNR) for minimising the sensing error. However, in CSS, Atapattu *et al.* [25] have employed OR cooperative rule and minimised the sensing error under different fading channels. Further, an improvement in the sensing error is achieved by Kumar *et al.* in [26] while considering the majority cooperative fusion rule at FC under the perfect reporting channel.

Recently, Li *et al.* [27] have analysed the effect of multiple antennas, reporting error probability and number of CUs on the probability of false-alarm (P_f) and the probability of detection (P_d) individually at high SNR with OR cooperative rule for the predefined value of threshold (λ). However, the analysis in the context of total sensing error was missing in [27]. Further, Nallagonda *et al.* [13] have employed threshold-based censoring and analysed the performance of CSS under the fading channel. Moreover, in CSS, with an increase in the number of CUs the sensing error is reduced but at the cost of increased energy consumption [28]. To increase the lifetime of battery-powered CU in CRN, energy consumption should be minimised. In this context, Maleki *et al.* [29] have employed censoring and sleeping schemes simultaneously, Najimi *et al.* in [30] initiated best sensing CU nodes, and Eryigit *et al.* in [31] minimised the energy consumed in sensing. Further, in the multi-antenna and imperfect reporting environment, EE is maximised in [32] by properly selecting the duration of sensing time and afterwards selecting the best CUs to report to FC about sensing decision.

Moreover, Zhang *et al.* [33] have minimised the sensing error by adapting the cooperative rule at FC (i.e. finding the optimal value of K in k-out-of-M rule) according to a selected sensing threshold value. Further, their analysis is only limited to perfect reporting channels with a single antenna without considering the licensed channel's idle and busy probability. Banavathu and Khan in [34] have achieved an optimal value of K and M in the k-out-of-M rule for minimising the Bayes risk in a homogeneous CR environment with imperfect reporting channels. Further, the authors also derived the expressions for optimal M in k-out-of-M rule to maximise the throughput in [35, 36] with and without imposing the constraint on protection to PU from CUs. Moreover, Hu *et al.* in [37] have proposed the optimisation strategy to yield the optimal K value in the k-out-of-M rule to maximise the EE. Recently, in [38], the authors computed the optimal value of K in the k-out-of-M rule for the Bayesian test under a heterogeneous environment in the imperfect reporting channels. Further, Olawole *et al.* [39] have employed a new hard fusion rule that is known as cluster head with k-out-of-M fusion rule in the heterogeneous environment in which the SS threshold and distribution of CU location with respect to PU is employed for cluster head selection [39]. Variously reported literature with context to minimising the SS error, maximising the throughput and EE are presented in Table 1. Motivated by the above discussed related work performed by various researchers in the direction of minimising the SS error and maximising the EE, we have investigated the optimal value of K in k-out-of-M rule to minimise the sensing error by considering multiple antennas in censoring and non-censoring scenario. Afterwards, we have also maximised the EE by employing censoring on the computed optimal K value in different threshold selection approaches. The author's contributions in this paper are as follows:

- In this paper, we come across the expressions for SS error in CSS by considering the effect of multiple antennas, reporting error and idle/busy channel's probability by employing different threshold selection approaches. Further, we have derived the expressions for the optimal value of K in k-out-of-M fusion rule at FC to minimise the SS error.
- It is illustrated that by employing the optimal rule at FC, the SS error is minimised with respect to the majority fusion rule.
- Further, the censoring approach is employed to improve the EE, and the closed-form expression is derived for the optimal number of CUs at FC.
- Moreover, the EE comparison is also illustrated under the non-censoring and censoring scenarios for CFAR and MEP threshold selection approaches when the respective optimal value of K is employed at FC in order to reduce the SS error. Further, from the results, it is depicted that the EE is significantly higher in the censoring scenario as compared to that of the non-censoring scenario.

This paper is arranged as follows. The proposed system model is presented in Section 3. In Section 4, the performance analysis for the proposed CRN is described. The mathematical expressions for optimal K in the non-censoring and censoring approaches are computed in Section 5. Section 6 shows MATLAB simulation results for the proposed CRN system model and Section 7 finally concludes the work.

3 Proposed system model

In the proposed CRN system model, we have considered a single PU transmitter (PU-Tx), M CU nodes and one FC, as shown in Fig. 1. Each CU consists of L_a number of antennas and has employed the EDSS technique for SS. Here; the CUs act as a transceiver, therefore CU's can transmit and receive information/data. The CU will sense the licensed channel between the PU transmitter and itself while reporting their SS results through the reporting channels to the FC. Further, the SS decision of each CU is sent to the FC via censoring and non-censoring approaches. In the censoring approach, it is considered that only M_c ($\leq M$) CUs send their sensing results to FC via the imperfect reporting channels where the imperfect reporting error probability is given by P_e^r. The description of censoring and the method for computation of M_c is presented in Section 4.3. Moreover, in the non-censoring scenario, all M CUs report their sensing decision to the FC via imperfect reporting channels. Further, at FC, the optimal value of K is computed in the k-out-of-M rule to take the global final decision about the status of licensed/PU channels after reporting by CUs through the censoring or non-censoring approaches.

Further, the acronyms used in the system model are presented in Table 2. In addition, we have assumed that each CU has the same value of $P_{f_i}^{SLS}$ and $P_{d_i}^{SLS}$ and sensing decision of each CU is affected equally in reporting channels via censoring or non-censoring approaches. Therefore, we have removed the subscript i, e.g. $P_{f_i}^{SLS}$ and $P_{d_i}^{SLS}$ are demonstrate simply as P_f^{SLS} and P_d^{SLS} in further analysis and same for the other symbolic representations. Further, in EDSS, the status of the PU signal in the licensed channel is obtained with the help of a received signal $r(n) = \theta x(n) + w(n)$. We have considered binary hypotheses H_0 and H_1 to know the status of licensed channel, where H_0 represents the hypothesis that the licensed channel is free and H_1 represents the hypothesis for the licensed channel being busy. Hence when $\theta = 0$ means PU signal is absent and hypothesis H_0 is true while for $\theta = 1$, PU signal is present on the channel and hypothesis H_1 is true. In addition, $x(n)$ is the transmitted modulated PU signal, $w(n)$ is the noise in the channel. n represents the sample number of the signal and ranges from 1, 2, …, N. Moreover, the test statistics of the received signal, i.e. $T(r)$ (energy of the $r(n)$) of energy detector is given as [21]

$$T(r) = \frac{1}{N}\sum_{n=1}^{N}\left|r(n)\right|^2 \tag{1}$$

In the literature, it has been already reported that when N is sufficiently large ($N > 250$), the probability density function of $T(r)$ can be considered as a normal distribution. In this case, for hypothesis H_0, $T(r)$ has the mean $N\sigma_n^2$ and variance $N\sigma_n^4$; however under the hypothesis H_1, for a complex-valued phase-shift keying signal, $T(r)$ has mean $N\sigma_n^2(1+\gamma)$ and variance $N\sigma_n^4(1+\gamma)^2$, where σ_n^2 and γ are the noise variance and received SNR at each CU due to PU, respectively. Further, the false-alarm probability (P_f) and detection probability (P_d) at each CU is computed as

Table 1 Performance affecting parameters and approaches employed by various researchers for improvement of the throughput, SS error and EE

Reference	Rule at FC	No of antennas	Reporting channels	Throughput enhancement approach	Sensing error minimisation approach	EE approach
[13]	majority	multi-antenna	imperfect	✘	• Censoring threshold	✘
[14]	—	single	perfect	• Analysed throughput but no approach for enhancement	• Opted the suitable threshold according to SNR	✘
[22]	OR	single	imperfect	• Optimised sensing and reporting time, Decision thresholds	✘	✘
[23]	OR	two separate antennas for transmission and reception	perfect	• Performed sensing and data transmission at the same time. • Employed particle swarm optimisation and brute-force search method	✘	✘
[25]	OR	multi-antenna	perfect	✘	• Opted the suitable threshold	✘
[26]	majority	single	perfect	• Opted the suitable threshold	• Opted the suitable threshold	✘
[33]	*k*-out-of-*M*	single	perfect	✘	• Optimised the cooperative rule at FC	✘
[27]	*k*-out-of-*M*	multi-antenna	imperfect	• Maximised the throughput by reducing the no. of CUs	✘	✘
[29]	AND, OR	single	imperfect	✘	✘	• Selected the optimal sleeping rate and threshold value • Censoring schemes • Sleeping schemes.
[30, 32]	OR	• single • multi-antenna	perfect	✘	✘	• Selected best sensing CU nodes • Minimised the sensing time • Active and sleeping schemes. • Censoring
[31]	OR	single	perfect	✘	✘	• Minimised the energy consumed in sensing
[40]	*k*-out-of-*M*	single	imperfect	• Analysed throughput but no approach for enhancement	• Optimised the *K* value in *k*-out-of-*M* fusion rule	• Optimised the *K* in *k*-out-of-*M* rule to maximised EE
[41]	OR	single	perfect	✘	• Maximised the sensing reliability index with respect to threshold	✘
[42]	*k*-out-of-*M*	single	perfect	• Jointly optimised the sensing time and *k*	✘	✘
proposed	*k*-out-of-*M*	multi-antenna	imperfect	• Analysed the throughput but no approach for enhancement	• Optimised the *K* value in *k*-out of *M* fusion rule at different SNR	• Censoring with two different threshold selection approaches

$P_f = P_r(T(r) \geq \lambda | H_0)$ and $P_d = P_r(T(r) \geq \lambda | H_1)$ and its values under Gaussian channel can be expressed as [21]:

$$P_f = \frac{1}{2}\mathrm{Erfc}\left(\frac{\lambda - N\sigma_n^2}{\sqrt{2N\sigma_n^4}}\right) \tag{2}$$

$$P_d = \frac{1}{2}\mathrm{Erfc}\left(\frac{\lambda - N\sigma_n^2(1+\gamma)}{\sqrt{2N\sigma_n^4(1+\gamma)^2}}\right) \tag{3}$$

$$P_m = 1 - P_d \tag{4}$$

$$P_e = P(H_0)P_f + P(H_1)P_m \tag{5}$$

where P_m and P_e are the miss-detection and SS error probabilities of each CU, respectively. Further, $P(H_0)$ and $P(H_1)$ are the probabilities of PU or licensed channel being idle and busy, respectively, in a chosen frequency band. Therefore, the SS error of CU is defined as the sum of the wrong prediction of CU about the idle and active state of the licensed channel [14].

4 Performance analysis of the proposed system model

In this section, we have derived the expressions for sensing error and EE in the CSS technique under the non-censoring and censoring approaches for the AWGN channel. The analysis has been performed while taking into consideration the following parameters: (i) number of antennas of CUs, (ii) SS threshold selection approach of CU, (iii) reporting error probability, and (iv) idle/active state probability of the licensed channel. The SS threshold selection approaches, which are employed in this section for computation of λ (λ_f or λ_e) is considered to be CFAR and MEP, where λ_f is the threshold value for the CFAR approach while λ_e is the threshold for the MEP approach. The mathematical expressions for λ_f and λ_e are given as follows [43]:

$$\lambda_f = \left\{ \sqrt{\frac{2}{N}} \mathrm{Erfc}^{-1}\left(2\overline{P_f}\right) + 1 \right\} N\sigma_n^2 \quad (6)$$

$$\lambda_e(\mathrm{AWGN}) = \frac{N\sigma_n^2}{2} \left\{ 1 + \sqrt{1 + \frac{2(2+\gamma)\ln(1+\gamma)}{N\gamma}} \right\} \left(\frac{1+\gamma}{1+(\gamma/2)} \right) \quad (7)$$

where $\overline{P_f}$ is the targeted value of false-alarm probability.

4.1 Multiple antennas

It is reported in the available literature [25, 27, 44] that the multiple antennas are employed at CU for receiver diversity in order to get a detection performance improvement. Atapattu *et al.* in [25] have employed square-law combining (SLC) and square law selection (SLS) receiver diversity techniques for SS in CRN. In the proposed analysis, we have assumed SLS-based combining schemes due to its least complexity. In SLS, the maximum SNR branch (γ_j) of multiple antennas is selected by each CU, i.e.

$$\gamma^{\mathrm{SLS}} = \max_{j=1,2,\ldots,L_a} \gamma_j \quad (8)$$

where L_a denotes the number of antennae at each CU. Therefore, the false-alarm probability and detection probability at each CU under SLS can be computed with the help of (8) and are given as [27]

$$P_f^{\mathrm{SLS}} = 1 - \mathrm{Prob.}\left(\gamma^{\mathrm{SLS}} < \lambda \middle| H_0\right) \quad (9)$$

$$P_d^{\mathrm{SLS}} = \mathrm{Prob.}\left(\gamma^{\mathrm{SLS}} \geq \lambda \middle| H_1\right) \quad (10)$$

Further, (9) and (10) can also be written as

$$P_f^{\mathrm{SLS}} = 1 - (1 - P_f)^{L_a} \quad (11)$$

$$P_d^{\mathrm{SLS}} = 1 - (1 - P_d)^{L_a} \quad (12)$$

where P_f and P_d are the false-alarm and detection probabilities, respectively, of CU when CU employed single antenna.

4.2 Non-censoring approach with imperfect reporting

The sensing results of each CU which is transmitted through imperfect reporting channels can be received at FC with some error. Moreover, there are four probable scenarios considered in Table 3 where FC receives the sensing results from CUs in favour of busy state of PU channel. These scenarios are either due to the perfect or imperfect sensing and reporting. The false-alarm ($P_f^{r,\mathrm{SLS}}$) and detection probabilities ($P_d^{r,\mathrm{SLS}}$) received at FC due to each CU under imperfect reporting channel can be computed with the help of Table 3 and are expressed as

$$P_f^{r,\mathrm{SLS}} = \left(1 - P_f^{\mathrm{SLS}}\right)P_e^r + P_f^{\mathrm{SLS}}\left(1 - P_e^r\right) \quad (13)$$

$$P_d^{r,\mathrm{SLS}} = \left(1 - P_d^{\mathrm{SLS}}\right)P_e^r + P_d^{\mathrm{SLS}}\left(1 - P_e^r\right) \quad (14)$$

$$P_m^{r,\mathrm{SLS}} = 1 - P_d^{r,\mathrm{SLS}} \quad (15)$$

where P_e^r is the reporting error probability, $P_f^{r,\mathrm{SLS}}$, $P_d^{r,\mathrm{SLS}}$ and $P_m^{r,\mathrm{SLS}}$ are the false-alarm, detection and miss-detection probabilities received at FC due to imperfect reporting channels when each CU employed multiple antennas. Afterwards, FC applies k-out-of-M cooperative rules to take the global decision about the status of PU

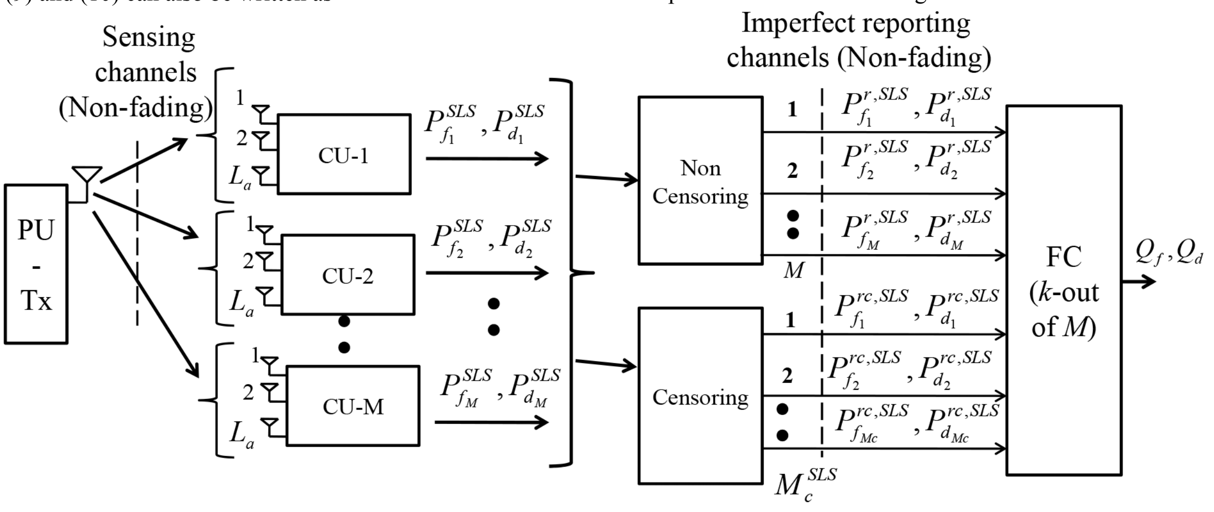

Fig. 1 *Schematic diagram of the proposed CRN system model*

Table 2 List of acronyms used in the system model

Symbols	Acronyms
$P_{f_i}^{\mathrm{SLS}}$	false-alarm probability of the i^{th} CU when CU employed L_a number of antennas
$P_{d_i}^{\mathrm{SLS}}$	detection probability of the i^{th} CU when CU employed L_a number of antennas
$P_{f_i}^{r,\mathrm{SLS}}$	false-alarm probability of the i^{th} CU received at FC under imperfect reporting channel with non-censoring approach
$P_{d_i}^{r,\mathrm{SLS}}$	detection probability of the i^{th} CU, received at FC under imperfect reporting channel with non-censoring approach
$P_{f_i}^{rc,\mathrm{SLS}}$	false-alarm probability of the i^{th} CU received at FC under imperfect reporting channel with censoring approach
$P_{d_i}^{rc,\mathrm{SLS}}$	detection probability of the i^{th} CU, received at FC under imperfect reporting channel with censoring approach
L_a	number of antennas
PU-Tx	PU transmitter
Q_f	false-alarm probability at FC
Q_d	detection probability at FC

*SLS is the square law selection.

Table 3 False-alarm and detection probabilities of CU received at FC under the non-censoring and censoring approaches

True state of PU channel	State of PU channel detected by CU	PU channel state received at FC	Detection/false-alarm probability of CU at FC under imperfect reporting with non-censoring	Detection/false-alarm probability of CU at FC under imperfect reporting with censoring
busy	busy	busy	$P_{\rm d}^{\rm SLS}(1-P_{\rm e}^{\rm r})$	$P_{\rm d}^{\rm SLS}(1-P_{\rm e}^{\rm r})$
busy	free	busy	$(1-P_{\rm d}^{\rm SLS})P_{\rm e}^{\rm r}$	0
free	busy	busy	$P_{\rm f}^{\rm SLS}(1-P_{\rm e}^{\rm r})$	$P_{\rm f}^{\rm SLS}(1-P_{\rm e}^{\rm r})$
free	free	busy	$(1-P_{\rm f}^{\rm SLS})P_{\rm e}^{\rm r}$	0

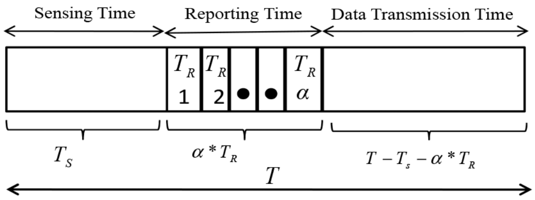

Fig. 2 *Frame structure of CSS CRN*

channel. Since in the non-censoring approach, all M CUs report to the FC therefore, the total false-alarm ($Q_{\rm f}^{\rm r,SLS}$) and detection probability ($Q_{\rm d}^{\rm r,SLS}$) at FC is represented as follows:

$$Q_{\rm f}^{\rm r,SLS} = \sum_{l=k}^{M}\binom{M}{l}\left(P_{\rm f}^{\rm r,SLS}\right)^{l}\left(1-P_{\rm f}^{\rm r,SLS}\right)^{M-l} \tag{16}$$

$$Q_{\rm d}^{\rm r,SLS} = \sum_{l=k}^{M}\binom{M}{l}\left(P_{\rm d}^{\rm r,SLS}\right)^{l}\left(1-P_{\rm d}^{\rm r,SLS}\right)^{M-l} \tag{17}$$

$$Q_{\rm e}^{\rm r,SLS} = P(H_0)Q_{\rm f}^{\rm r,SLS} + P(H_1)\left(1-Q_{\rm d}^{\rm r,SLS}\right) \tag{18}$$

where the value of k represents the number of CUs, report to the FC, having decision in favour of PU presence, to provide active channel decision, M is the total number of CUs reporting their local SS decision to the FC [38] and $Q_{\rm e}^{\rm r,SLS}$ is the SS error after the cooperation in CSS.

4.3 Censoring approach with imperfect reporting

In the censoring scenario, the SS results of some particular CUs are reported to the FC, in which the approach employed for selection of CUs for participating in the censoring has been considered differently by different researchers. For example, in [13], the CU forward its local SS decision to FC only when the corresponding reporting channel of CU is considered reliable in the fading scenario. Here, the reliable reporting channel of CU is the one whose estimated channel's fading coefficient is greater than the censoring threshold value, therefore the SS results of only these CUs will be sent to the FC. However, Rago *et al.* in [45] and Jiang and Chen [46] have applied the censoring process by sending the SS results of those CUs whose local likelihood ratio value have a sufficient level of confidence under the perfect and imperfect reporting channels. However, Sun *et al.* [47] have transmitted the reliable SS results to the FC, where the double threshold selection approach is used to measure the reliability of CUs, is considered. Therefore, the SS results of those CUs are transmitted only, whose collected energy does not lie between the two threshold values. However, the researchers in [27] have considered the censoring scheme where the CU's claims the sensing decision in favour of hypothesis H_1, forwards their SS result to the FC. In the proposed analysis, we have also employed censoring scheme of [27] by assuming that the CUs detecting the busy state of PU channel, only send their sensing results to FC. The reason for selecting this approach of censoring is due to its simple implementation in our proposed model. Therefore, firstly we compute the number of cooperative CUs ($M_{\rm c}^{\rm SLS}$) sending the sensing results to FC with the help of Table 3 as given below [27]:

$$M_{\rm c}^{\rm SLS} = \left\lceil M\left\{P(H_0)P_{\rm f}^{\rm SLS} + P(H_1)P_{\rm d}^{\rm SLS}\right\}\right\rceil \tag{19}$$

where $\lceil . \rceil$ indicates the ceiling function and $M_{\rm c}^{\rm SLS} \le M$. With the help of $M_{\rm c}^{\rm SLS}$ value, FC will know about number of CUs reporting in a sensing period. In addition, the received false-alarm and detection probabilities at FC while considering the imperfect reporting channels can be determined from Table 3 and is given as

$$P_{\rm f}^{\rm rc,SLS} = P_{\rm f}^{\rm SLS}(1-P_{\rm e}^{\rm r}) \tag{20}$$

$$P_{\rm d}^{\rm rc,SLS} = P_{\rm d}^{\rm SLS}(1-P_{\rm e}^{\rm r}) \tag{21}$$

$$P_{\rm m}^{\rm rc,SLS} = 1 - P_{\rm d}^{\rm rc,SLS} \tag{22}$$

Moreover, the false-alarm ($Q_{\rm f}^{\rm rc,SLS}$), detection ($Q_{\rm d}^{\rm rc,SLS}$) and error probability ($Q_{\rm e}^{\rm rc,SLS}$) at FC with censoring under imperfect reporting channels are computed as

$$Q_{\rm f}^{\rm rc,SLS} = \sum_{l=k}^{M_{\rm c}^{\rm SLS}}\binom{M_{\rm c}^{\rm SLS}}{l}\left(P_{\rm f}^{\rm rc,SLS}\right)^{l}\left(1-P_{\rm f}^{\rm rc,SLS}\right)^{M_{\rm c}-l} \tag{23}$$

$$Q_{\rm d}^{\rm rc,SLS} = \sum_{l=k}^{M_{\rm c}^{\rm SLS}}\binom{M_{\rm c}^{\rm SLS}}{l}\left(P_{\rm d}^{\rm rc,SLS}\right)^{l}\left(1-P_{\rm d}^{\rm rc,SLS}\right)^{M_{\rm c}-l} \tag{24}$$

$$Q_{\rm e}^{\rm rc,SLS} = P(H_0)Q_{\rm f}^{\rm rc,SLS} + P(H_1)\left(1-Q_{\rm d}^{\rm rc,SLS}\right) \tag{25}$$

Further, for the perfect reporting channels, the sensing error under non-censoring/censoring approaches at FC can be computed from (18) and (25), respectively, by placing $P_{\rm e}^{\rm r} = 0$ in (13)–(14) and (20)–(21).

4.4 Energy efficiency

For the computation of EE, we have presented the frame structure of CRN for CSS in Fig. 2. In a chosen band of spectrum all CUs (M) sense the channel simultaneously for $T_{\rm s}$ sensing duration. Subsequently, the sensing decision of each CU is reported to the FC during $T_{\rm R}$ with time division multiple access scheme.

Therefore, the total reporting time equals to $\alpha T_{\rm R}$, where α is the number of CUs reporting the sensing decision to FC. In the non-censoring scenario, α will equate to M however, it is $M_{\rm c}$ for the censoring scenario. Consequently, the data transmission time will be $T - T_{\rm s} - \alpha T_{\rm R}$. Further, EE is computed as the ratio of average number of bits transmitted successfully to the average energy consumed [48] as given below:

$$\text{EE} = \frac{C}{E_{\rm Total}} \tag{26}$$

where C is the average number of successfully transmitted bits and $E_{\rm Total}$ is the average energy consumed by CRN in single frame.

Table 4 EE matrix

Cases	Actual state of licensed channel	Predicted state of licensed channel by CU	Probability of respective case being true (p)	Data transmission	Successful transmitted data (bits)	Energy consumed in Joule (with/without censoring)
I	idle	idle	$p_1 = P(H_0)(1 - P_f)$	yes	$C = p_1(T - T_s - \alpha^* T_R)R$	$E_1 = M^* E_s + \alpha^* E_R + E_T$
II	idle	busy	$p_2 = P(H_0)(P_f)$	no	0	$E_2 = M^* E_s + \alpha^* E_R$
III	busy	idle	$p_3 = P(H_1)(1 - P_d)$	yes	0	$E_3 = M^* E_s + \alpha^* E_R + E_T$
IV	busy	busy	$p_4 = P(H_1)(P_d)$	no	0	$E_4 = M^* E_s + \alpha^* E_R$

Input: Threshold selection approach (TSA) = {CFAR, MEP}, Reporting channel (RC) ={Imperfect, Perfect}, Event sequence (ES) = {Censoring, Non-censoring}, γ
Output: K_{opt}
Initialization: N, σ_n^2, M, $P(H_0)$, $p \in (0,1]$, γ_{set} = [-20,-8], L_a
if $\gamma \in \gamma_{set}$
if TSA = = CFAR
  $\lambda \leftarrow \lambda_f$
else
  $\lambda \leftarrow \lambda_e$
end if
compute P_f and P_d using (2) and (3) respectively
compute P_f^{SLS} and P_d^{SLS} using (11) and (12) respectively
if RC = = Imperfect
  $P_e^r \leftarrow p$
else
  $P_e^r \leftarrow 0$
end if
if ES = = Censoring
compute M_c^{SLS} using (19)
find $P_f^{rc,SLS}$ from (20) and $P_d^{rc,SLS}$ using (21)
find $Q_e^{rc,SLS}$ from (25)
compute K_{opt} from (33)
else
find $P_f^{r,SLS}$ from (13) and $P_d^{r,SLS}$ using (14)
find $Q_e^{r,SLS}$ from (18)
compute K_{opt} from (31)
end if
end if

Fig. 3 *Algorithm 1: Computation of optimal k at FC*

With the help of Fig. 2, we observed that CRN frame structure has following four phases: (i) sensing phase (ii) reporting phase (iii) transmitting phase, and (iv) idle phase (when licensed channel is busy) where energy will be consumed. Another component of energy consumption is the power consumed by the circuit components, however we have neglected the energy consumed by circuit component and CU in idle phase. Therefore, the energy is consumed only in sensing, reporting and transmission which are expressed as E_S, E_R, and E_T, respectively. Moreover, these value can be computed as: $E_s = P_S T_S$, $E_R = P_R T_R$, $E_T = P_T(T - T_S - T_R)$, where P_S, P_R and P_T are the power consumed in sensing, reporting and data transmission phases of the single frame structure of CRN.

Further, in Table 4 we have considered four cases on the basis of actual and predicted states by CU of licensed channels. From Table 4, it is clear that the successful data transmission occurs only in Case 1, however CU consumed energy in all four cases. Therefore, from the frame structure of Fig. 2, it is clear that all M CUs sense the channels for T_S duration therefore the total energy consumed in sensing is $M^* E_s$; and total energy consumed in reporting phase is $\alpha^* E_R$, where α CUs report to the FC. Further, in Case 2 and Case 4, the predicted state by CU of the licensed channel is busy therefore, CU will not transmit the data and hence no energy is consumed in transmission for Case 2 and Case 4. Therefore, E_{Total} can be computed as

$$E_{Total} = p_1 E_1 + p_2 E_2 + p_3 E_3 + p_4 E_4 \quad (27)$$

and average number of successfully transmitted bits is

$$C = P(H_0)(1 - P_f)(T - T_s - \alpha^* T_R)R \quad (28)$$

where R is the throughput of secondary link and can be computed as [18]: $R = \log_2(1 + \gamma_{sec})$, where γ_{sec} is the SNR of the link between CU transmitter and CU receiver. Further, EE can be computed as

$$EE = \frac{P(H_0)(1 - P_f)(T - T_s - \alpha^* T_R)R}{p_1 E_1 + p_2 E_2 + p_3 E_3 + p_4 E_4} \quad (29)$$

5 Optimisation of voting rule in CSS

In this section, we have presented the optimal value of K to minimise the sensing error when k-out-of-M rule is employed at FC under the non-censoring and censoring approaches. Zhang *et al.* [33] have also presented the optimal value of K for the predefined value of threshold, however without considering the effect of licensed channel's idle/busy probability, multi-antenna effect, and reporting error probability. However, we have computed threshold values at different SNR with CFAR and MEP threshold selection approaches and achieved the optimal K at different SNR by considering all above parameters with censoring, which is a significant contribution with respect to Zhang *et al.* [33].

5.1 Non-censoring scenario with multiple antennas under imperfect reporting

In this scenario, the sensing error under CSS technique is given as $Q_e^{r,SLS}$ from (18). The main objective is to minimise the sensing error with respect to k, i.e. $\left(\partial Q_e^{r,SLS}(k)/\partial k\right) = 0$. Further, the appropriate value of k at which sensing error is minimised is given as

$$K = \frac{M^* \mathrm{Log}\left(\left(P_m^{r,SLS}/1 - P_f^{r,SLS}\right)\right) + \mathrm{Log}((P(H_1)/P(H_0)))}{\mathrm{Log}\left(\left(P_f^{r,SLS}\right)\left(P_m^{r,SLS}\right)/\left(1 - P_f^{r,SLS}\right)\left(1 - P_m^{r,SLS}\right)\right)} \quad (30)$$

$$K_{opt} = K \quad (31)$$

where K_{opt} is the optimal K value. The derivation of (30) is given in Appendix 1 of this paper.

5.2 Censoring approach with multiple antennas under imperfect reporting

In this scenario, the sensing error under CSS is given as $Q_e^{rc,SLS}$ from (25) and appropriate value of K is computed by $\left(\partial Q_e^{rc,SLS}(k)/\partial k\right) = 0$, which is presented as

$$K = \frac{M_c^{SLS} * \mathrm{Log}\left(\left(P_m^{rc,SLS}/1 - P_f^{rc,SLS}\right)\right) + \mathrm{Log}((P(H_1)/P(H_0)))}{\mathrm{Log}\left(\left(P_f^{rc,SLS}\right)\left(P_m^{rc,SLS}\right)/\left(1 - P_f^{rc,SLS}\right)\left(1 - P_m^{rc,SLS}\right)\right)} \quad (32)$$

$$K_{opt} = K \quad (33)$$

The detail derivation of (32) is given in Appendix 2. Further, the computation of K_{opt} under censoring and non-censoring approaches for CFAR or MEP threshold selection is presented in Algorithm 1 (see Fig. 3).

However, γ_{set} presented in Algorithm 1 (Fig. 3), represents the SNR received at the CU terminal due to PU transmission over sensing channels.

Table 5 Parameters for simulation

Parameter	Value	Parameter	Value
N	25 000	T_R	0.001 s
$\overline{P_f}$	0.1	P_S	0.02 W
M	10	P_R	0.1 W
T	0.1 s	P_T	0.1 W
T_S	0025 s	γ_s	20 dB

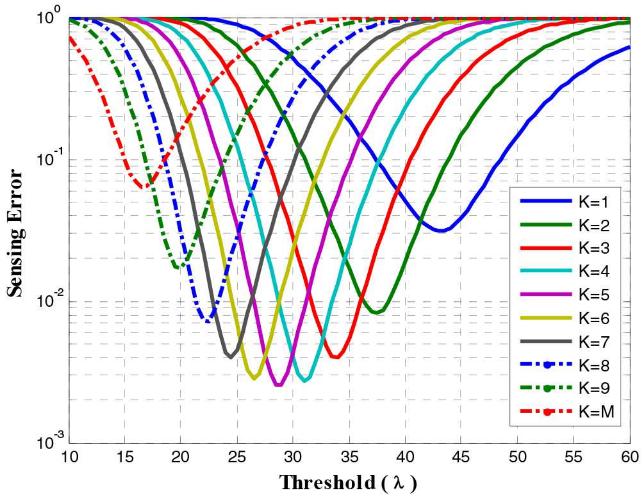

Fig. 4 *Variation in sensing error with the threshold for different values of K, $L_a = 1$, $P_e^r = 0$ [27, 33]*

6 Simulation results

In this section, we have demonstrated the MATLAB simulated results of the proposed CRN system. The parameters employed for simulation of the results are presented in Table 5, where γ_s is the SNR between two CUs link, i.e. between CU transmitter and CU receiver.

The variation in sensing error with threshold (λ) for different values of K *in* k-out-of-M rule which was presented by Li *et al.* in [27] and Zhang *et al.* in [33] is shown in Fig. 4. It is clear from Fig. 4 that for any value of K, the sensing error is a convex function of λ, which provides a minimum value of sensing error. Therefore, at different selected threshold, the value of K is different to minimise the sensing error.

Further, we have illustrated the optimal value of K at different SNR to minimise the sensing error while considering the combined effect of multiple antennas (L_a) employed by CU, reporting error probability (P_e^r) and licensed channel's idle/busy probability ($P(H_0)$/ $P(H_1)$). Therefore, in Figs. 5*a* and *b*, we have employed CFAR and MEP threshold selection approaches and achieved the optimal K at different SNR to minimise the sensing error in the non-censoring approach. Further, Figs. 5*a* and *b* demonstrated that at fixed SNR under perfect reporting channel ($P_e^r = 0$), as L_a increases, the optimal K also increases due to increment in P_f and decrement in P_m. However, for same value of $P(H_0)$ and L_a, the optimal K decreases when P_e^r increases due to increment in both P_f and P_m.

Moreover, in Fig. 6, we have presented the variation in sensing error with γ while employing the majority rule and optimal K at FC under CFAR and MEP threshold selection approaches. From Fig. 6, it is clear that the proposed approach with optimal K provides less sensing error as compared to that of the majority rule employed in [26] and also improvement with respect to OR and AND rule when CFAR approach is employed. However, MEP approach provides nearly same sensing error with both the majority and our proposed optimal rule selection schemes. In addition, the effect of variation in reporting error probability and number of antennas employed at each CU on the sensing error at different

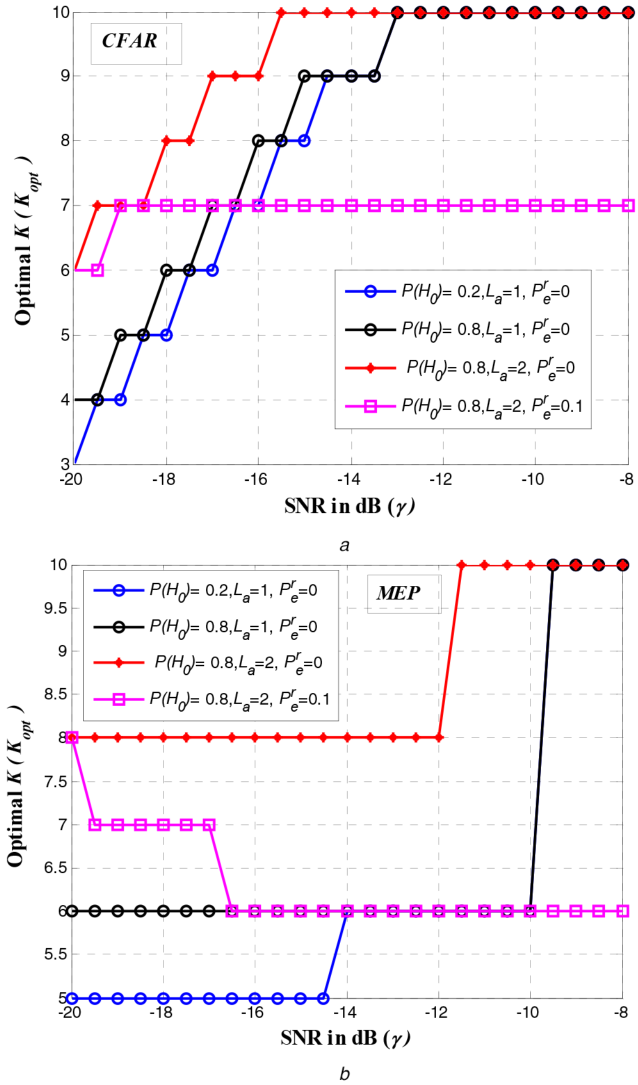

Fig. 5 *Variation in the optimal number of CUs at FC (K_{opt}) with SNR at different values of $P(H_0)$, L_a and P_e^r under the non-censoring scenario with* ***(a)*** CFAR, ***(b)*** MEP

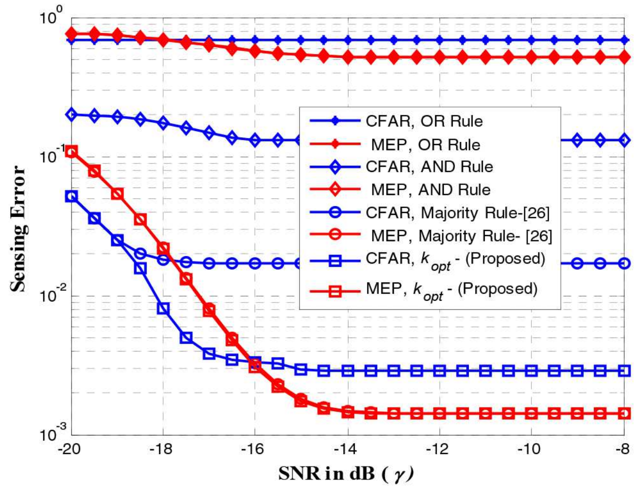

Fig. 6 *Variation in sensing error with SNR at $P(H_0) = 0.8$, $L_a = 1$, and $P_e^r = 0.1$*

SNR is presented in Fig. 7, while employing optimal value of K under CFAR and MEP threshold selection approaches.

Depending on the values of SNR, the selected threshold provides different values of P_f and P_d from (2) and (3). Further, (13) and (14) values got affected from these aforementioned values

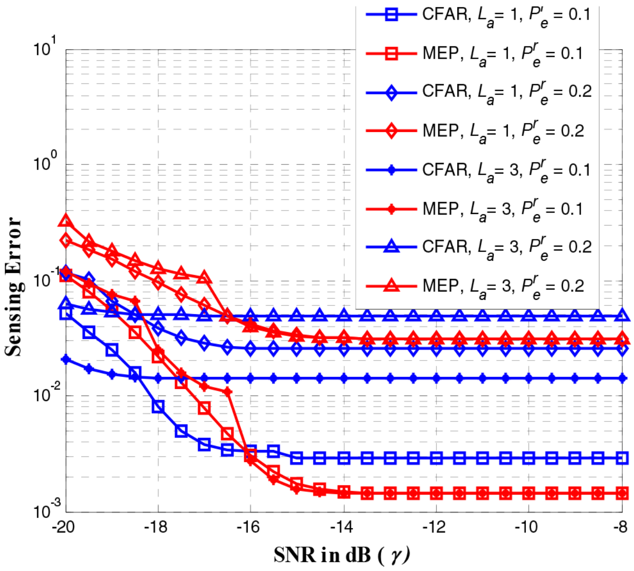

Fig. 7 *Variation in sensing error with SNR for different values of L_a and P_e^r at $P(H_0) = 0.8$*

of P_f, P_d, P_e^r along with number of antennas and hence the combined effect of all these values result in the overall error at the FC in (18), which is shown in Fig. 7. However, at high SNR, increase in false-alarm probability with MEP approach is less as compared to that of the CFAR approach. Therefore, at high SNR, MEP approach provides less sensing error when CU has employed multiple antennas. Further, Figs. 8*a* and *b* show the variation in the optimal value of *K* for the censoring scenario with SNR in CFAR and MEP threshold selection approaches.

It is obvious from comparison of Figs. 5 and 8 that the optimal *K* value required in the censoring approach is less in comparison to that of the non-censoring scenario for both CFAR and MEP threshold selection. Moreover, Fig. 9 presents the variation in sensing error with SNR while employing optimal *K* in CFAR and MEP threshold selection approaches for different values of L_a and P_e^r under the censoring approach.

From Fig. 9, it is clear that under the censoring approach, for fixed value of L_a and P_e^r, the sensing error is nearly constant with variation in SNR due to constant value of optimal *K* in CFAR. Moreover, for the fixed value of L_a and P_e^r, the sensing error is less in MEP approach as compare to that of the CFAR approach due to less value of false-alarm and miss-detection probabilities achieved. Further, the variation in EE with SNR under the censoring and non-censoring approaches by using CFAR and MEP threshold selection are presented in Fig. 10.

We have employed optimal *K* for all SNR to yield the energy efficiency under both the censoring and non-censoring approaches. In Fig. 10, it is illustrated that in the non-censoring approach, the performance of CFAR and MEP are nearly same however with the censoring approach, an MEP threshold selection approach slightly outperforms the CFAR. Further, the EE achieved in censoring approach is significantly higher as compared to that of the non-censoring approach for both threshold selection approaches (CFAR or MEP). This is due to a smaller number of CUs reporting to FC in censoring, resulting in an energy consumption reduction during the reporting phase.

From the results illustrated in Fig. 10, it is computed that the percentage enhancement in EE in censoring approach is 19.53 and 19.9% with CFAR and MEP approaches, respectively, in comparison to non-censoring approach. Since the MEP threshold selection technique in censoring approach has provided higher EE as compared to that of CFAR, therefore, Fig. 11 depicts the variation in EE with SNR and the number of antennas for the MEP threshold selection under the censoring. It is illustrated from Fig. 11 that at high SNR, the effect of variation in antenna on EE is nearly constant. However, the EE decreases with increase in the

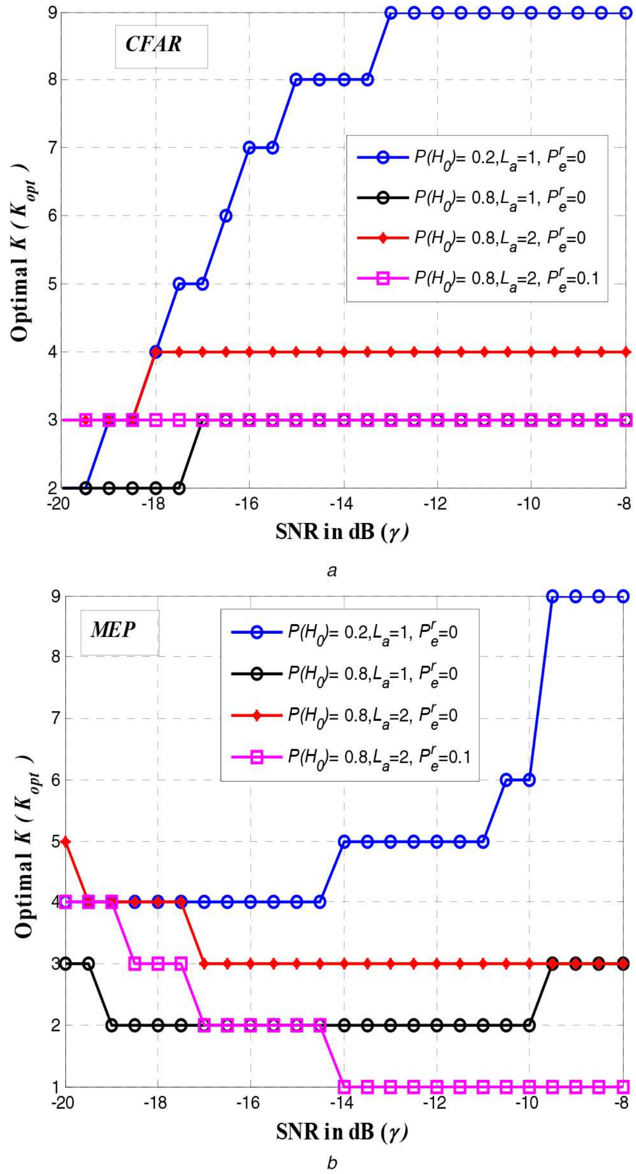

Fig. 8 *Variation in the optimal number of CUs at FC (K) with SNR at different values of $P(H_0)$, L_a, and P_e^r under the censoring scenario with* ***(a)*** CFAR, ***(b)*** MEP

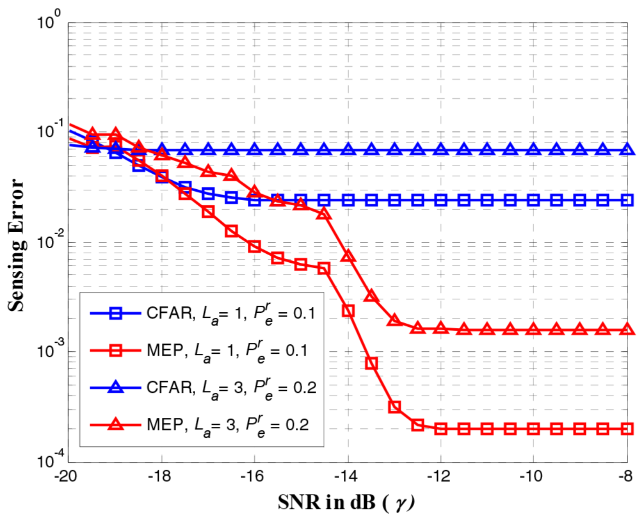

Fig. 9 *Variation in sensing error with SNR for different value of L_a and P_e^r at $P(H_0) = 0.8$, in the censoring scenario*

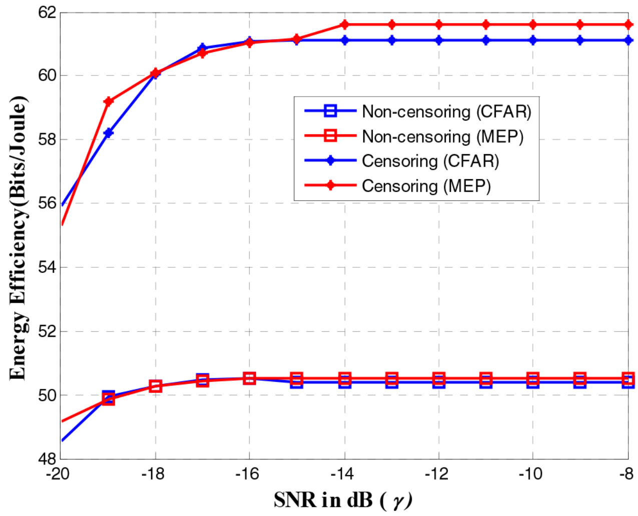

Fig. 10 *Variation in EE with SNR for CFAR and MEP threshold selection in censoring and non-censoring approaches at* $P(H_0) = 0.8$, $L_a = 1$ *and* $P_e^r = 0.1$

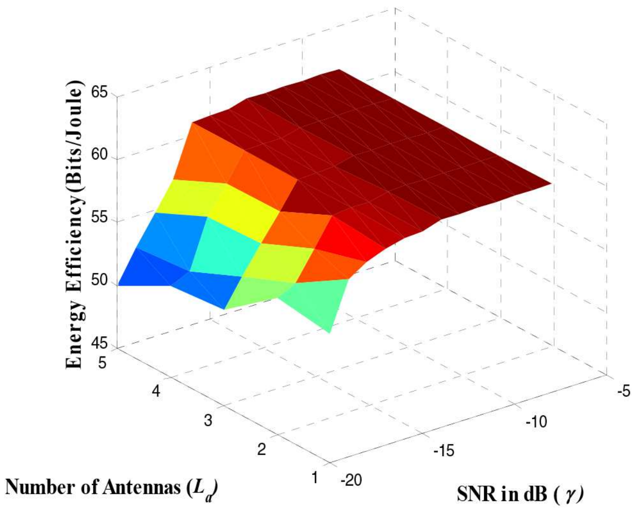

Fig. 11 *Variation in EE with SNR and* L_a *with MEP threshold selection under censoring approach* $P_e^r = 0.1$, $P(H_0) = 0.8$

number of antennas at low SNR due to increase in the value of K_{opt}.

7 Conclusion

In this paper, we have computed the optimal value of k at FC to reduce the sensing error under the censoring and non-censoring based CSS approaches. We have employed CFAR and MEP threshold selection methods to compute optimal k while considering the effect of variation of the number of antennas and reporting error probability. It has been illustrated that the optimal K selection at different SNR has provided minimum sensing error in comparison to the single rule selection (e.g. majority) at FC. Further, we have achieved the significant improvement in EE in censoring approach with both CFAR and MEP based threshold selection, as compared to non-censoring. Moreover, the analysis presented in this paper is for AWGN channel and can also be obtained for fading channels.

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10 Appendix

10.1 Optimal K computation in non-censoring approach

For the optimal K: $K_{\text{opt}} = \arg_k^{\min} Q_{\text{e}}^{\text{r, SLS}}(k)$ is achieved when $\left(\partial Q_{\text{e}}^{\text{r, SLS}}(k)/\partial k\right) = 0$.

$$\frac{\partial Q_{\text{e}}^{\text{r, SLS}}(k)}{\partial k} = Q_{\text{e}}^{\text{r, SLS}}(K+1) - Q_{\text{e}}^{\text{r, SLS}}(K) \tag{34}$$

Find out the value of $Q_{\text{e}}^{\text{r, SLS}}(K+1)$ and $Q_{\text{e}}^{\text{r, SLS}}(K)$ from (18) is

$$Q_{\text{e}}^{\text{r, SLS}}(K+1) = P(H_0)\sum_{l=K+1}^{M}\binom{M}{l}\left(P_{\text{f}}^{\text{r, SLS}}\right)^{l}\left(1-P_{\text{f}}^{\text{r, SLS}}\right)^{M-l} + P(H_1)\left\{1-\sum_{l=K+1}^{M}\binom{M}{l}\left(P_{\text{d}}^{\text{r, SLS}}\right)^{l}\left(1-P_{\text{d}}^{\text{r, SLS}}\right)^{M-l}\right\} \tag{35}$$

$$Q_{\text{e}}^{\text{r, SLS}}(K) = P(H_0)\sum_{l=K}^{M}\binom{M}{l}\left(P_{\text{f}}^{\text{r, SLS}}\right)^{l}\left(1-P_{\text{f}}^{\text{r, SLS}}\right)^{M-l} + P(H_1)\left\{1-\sum_{l=K}^{M}\binom{M}{l}\left(P_{\text{d}}^{\text{r, SLS}}\right)^{l}\left(1-P_{\text{d}}^{\text{r, SLS}}\right)^{M-l}\right\} \tag{36}$$

Now, compute (34) from (35) and (36)

$$\frac{\partial Q_{\text{e}}^{\text{r, SLS}}(k)}{\partial k} = \binom{M}{Kl}\left\{P(H_1)\left(1-P_{\text{m}}^{\text{r, SLS}}\right)^{K}\left(P_{\text{m}}^{\text{r, SLS}}\right)^{M-K} - P(H_0)\left(P_{\text{f}}^{\text{r, SLS}}\right)^{K}\left(1-P_{\text{f}}^{\text{r, SLS}}\right)^{M-K}\right\} \tag{37}$$

For finding the value of K at which sensing error are minimise, put $\left(\partial Q_{\text{e}}^{\text{r, SLS}}(K)/\partial k\right) = 0$

$$\binom{M}{Kl}\left\{P(H_1)\left(1-P_{\text{m}}^{\text{r, SLS}}\right)^{K}\left(P_{\text{m}}^{\text{r, SLS}}\right)^{M-K} - P(H_0)\left(P_{\text{f}}^{\text{r, SLS}}\right)^{K}\left(1-P_{\text{f}}^{\text{r, SLS}}\right)^{M-K}\right\} = 0 \tag{38}$$

After solving (38), we get the solution for K given as

$$K = \frac{M^{*}\text{Log}\left(\left(P_{\text{m}}^{\text{r, SLS}}/1-P_{\text{f}}^{\text{r, SLS}}\right)\right) + \text{Log}((P(H_1)/P(H_0)))}{\text{Log}\left(\left(P_{\text{f}}^{\text{r, SLS}}\right)\left(P_{\text{m}}^{\text{r, SLS}}\right)/\left(1-P_{\text{f}}^{\text{r, SLS}}\right)\left(1-P_{\text{m}}^{\text{r, SLS}}\right)\right)}$$

10.2 Optimal K computation in the censoring approach

For optimal K, $K_{\text{opt}} = \arg{}_k^{\min} Q_{\text{e}}^{\text{rc, SLS}}(k)$ is achieved when, $\left(\partial Q_{\text{e}}^{\text{rc, SLS}}(K)/\partial k\right) = 0$.

$$\frac{\partial Q_{\text{e}}^{\text{rc, SLS}}(k)}{\partial k} = Q_{\text{e}}^{\text{rc, SLS}}(K+1) - Q_{\text{e}}^{\text{rc, SLS}}(K) \tag{39}$$

Find out the value of $Q_{\text{e}}^{\text{rc, SLS}}(K+1)$ and $Q_{\text{e}}^{\text{rc, SLS}}(K)$ from (25)

(see (40))

(see (41))

Compute (39) from (40) and (41)

$$\frac{\partial Q_{\text{e}}^{\text{rc, SLS}}(k)}{\partial k} = \binom{M_{\text{c}}^{\text{SLS}}}{Kl}\left\{P(H_1)\left(1-P_{\text{m}}^{\text{rc, SLS}}\right)^{K}\left(P_{\text{m}}^{\text{rc, SLS}}\right)^{M_{\text{c}}^{\text{SLS}}-K} - P(H_0)\left(P_{\text{f}}^{\text{rc, SLS}}\right)^{K}\left(1-P_{\text{f}}^{\text{rc, SLS}}\right)^{M_{\text{c}}^{\text{SLS}}-K}\right\} \tag{42}$$

For finding the value of K at which sensing error are minimise, put

$$\frac{\partial Q_{\text{e}}^{\text{rc, SLS}}(k)}{\partial k} = 0$$

$$\binom{M_c^{SLS}}{Kl}\left\{P(H_1)\left(1-P_m^{rc,SLS}\right)^K\left(P_m^{rc,SLS}\right)^{M_c^{SLS}-K}-P(H_0)\left(P_f^{rc,SLS}\right)^K\left(1-P_f^{rc,SLS}\right)^{M_c^{SLS}-K}\right\}=0 \quad (43)$$

After solving (43), we get the solution for K given as

$$K=\frac{M_c^{SLS}*\mathrm{Log}\left(\left(P_m^{rc,SLS}/1-P_f^{rc,SLS}\right)\right)+\mathrm{Log}((P(H_1)/P(H_0)))}{\mathrm{Log}\left(\left(P_f^{rc,SLS}\right)\left(P_m^{rc,SLS}\right)/\left(1-P_f^{rc,SLS}\right)\left(1-P_m^{rc,SLS}\right)\right)}$$

$$\begin{aligned}Q_e^{rc,SLS}(K+1)= \; & P(H_0)\sum_{l=K+1}^{M_c^{SLS}}\binom{M_c^{SLS}}{l}\left(P_f^{rc,SLS}\right)^l\left(1-P_f^{rc,SLS}\right)^{M_c^{SLS}-l} \\ & +P(H_1)\left\{1-\sum_{l=K+1}^{M_c^{SLS}}\binom{M_c^{SLS}}{l}\left(P_d^{rc,SLS}\right)^l\left(1-P_d^{rc,SLS}\right)^{M_c^{SLS}-l}\right\}\end{aligned} \quad (40)$$

$$\begin{aligned}Q_e^{rc,SLS}(K)= \; & P(H_0)\sum_{l=K}^{M_c^{SLS}}\binom{M_c^{SLS}}{l}\left(P_f^{rc,SLS}\right)^l\left(1-P_f^{rc,SLS}\right)^{M_c^{SLS}-l} \\ & +P(H_1)\left\{1-\sum_{l=K}^{M_c^{SLS}}\binom{M_c^{SLS}}{l}\left(P_d^{rc,SLS}\right)^l\left(1-P_d^{rc,SLS}\right)^{M_c^{SLS}-l}\right\}\end{aligned} \quad (41)$$