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Cluster Based Cooperative Sub-carrier Sensing Using Antenna Diversity Based Weighted Data Fusion

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Abstract Cooperative spectrum sensing (CSS) is used in cognitive radio (CR) networks to improve the spectrum sensing performance in shadow fading environments. Moreover, clustering in CR networks is used to reduce reporting time and bandwidth over-head during CSS. Thus, cluster based cooperative spectrum sensing (CBCSS) has manifested satisfactory spectrum sensing results in harsh environments under processing constraints. On the other hand, the antenna diversity of multiple input multiple output (MIMO) CR systems can be exploited to further improve the spectrum sensing performance. This paper presents the CBCSS performance in a CR network which is comprised of single as well as multiple antenna CR systems. We give theoretical analysis of CBCSS for orthogonal frequency division multiplexing (OFDM) signal sensing and propose a novel fusion scheme at the fusion center which takes into account the receiver antenna diversity of the CRs present in the network. We introduce the concept of weighted data fusion in which the sensing results of different CRs are weighted proportional to the number of receiving antennas they are equipped with. Thus, the receiver diversity is used to the advantage of improving spectrum sensing performance in a CR cluster. Simulation results show that the proposed scheme outperforms the conventional CBCSS scheme.

Keywords Cognitive Radio · cooperative spectrum sensing · cluster based sensing · weighted data fusion.

1 Introduction

In last few years there has been revolutionary and an unprecedented rise in wireless standards. The development of these wireless standards has resulted in overcrowded spectrum due to which concepts of software defined radio [1] and cognitive

Address(es) of author(s) should be given radio (CR) [2] have become the focus of research. The cognition capability of a CR is defined as the ability of the CR transceiver to sense the surrounding radio environment, analyze the captured information and accordingly decide the best course of action(s) to efficiently use the spectrum for communication. For practical implementation of this concept, IEEE 802.22 wireless regional area network (WRAN) group established 802.22 WRAN CR standard [3] for communication over the unutilized spectrum.

A significant and most vital feature of CR is spectrum sensing (SS). CRs should make sure that SS results are highly reliable to avoid intolerable interference to licensed or primary users (PUs). The metrics of SS techniques are probability of detection (P_d), probability of false alarm (P_f), and probability of missed detection (P_m). The SS techniques present in literature include energy detection [4–6], cyclostationary detection [7], matched filter detection [8], covariance based detection [9], autocorrelation based sensing [10], and joint time frequency based detection [11].

Individual sensing has the drawback of low P_d due to multi-path fading, shadowing and receiver uncertainty. To cope with this problem, CRs cooperate with each other for sensing white spaces called cooperative SS (CSS). The cooperation among CRs provides increase in agility, reduces false alarms and ensures more accurate signal detection than individual SS. CSS is classified into three categories [12] based on the method of sharing sensed data: centralized [13, 14], distributed [15], and relay-assisted [16, 17]. Distributed and relay-assisted CSS schemes have the disadvantage of increased complexity but enjoy better performance as compared to centralized CSS schemes.

As an important element of CSS, we have also focused on data fusion schemes [12]. Data fusion is the method of uniting the reported SS results (received from individual CRs) for achieving the cooperative decision. In literature there are two main types of data fusion schemes, soft and hard combining. To obtain the cooperative decisions it is simpler to apply hard combining, also known as linear fusion rule, as compare to soft combining. The widely used types of hard combining fusion rules are AND, OR and Majority rules. In proposed work all these types are explored for the proposed algorithm.

Wireless communication systems can be divided in to four forms with respect to antenna diversity: Single input single output (SISO), single input multiple output (SIMO), multiple input single output (MISO) and multiple input multiple output (MIMO). Use of multiple antennas at the receiver side to have receive diversity is used to receive signals from several independent channels to combat the effects of fading and hence improve the signal to noise ratio (SNR). There are several methods to combine the multipath signals called diversity combining techniques [18] such as selection combining (SC), equal gain combining (EGC) and maximal ratio combining (MRC). SC and MRC both require knowledge of SNR at the receiver where as EGC does not need the knowledge of SNR at the receiver and is one of the simplest linear combining technique. The output SNR of EGC is the sum of SNRs on all branches [4], which helps increasing P_d of the received signal. In proposed scheme it is assumed that PUs are working with single antennas where as the CRs present in environment are of both types single antenna and multiple antennas. CRs with multiple antennas use EGC as diversity combining technique in proposed scheme. CRs with large number of antennas give better sensing results and vice versa. Hence weights are assigned to the decision of CRs according to the number of antennas they are equipped with.

For large number of cooperating CR users, CSS may result into excessive overhead. To overcome this problem, CRs are grouped into clusters for more efficient cooperative sensing i.e. cluster based CSS (CBCSS). Grouping CRs into clusters improves performance and reduces computational cost, workload on individual nodes, cooperation delay, and induced overhead. CBCSS techniques [19] need specific clustering algorithms like random, reference based, statistical based and distance based [20], on the basis of which CRs are grouped together. Random clustering can easily be implemented while being unreliable. The remaining are location based clustering. In this paper, it is assumed that clustering has been done by upper layers and that any of energy efficient geographical based algorithms may be adopted to avoid performance degradation and propagation delays.

CSS techniques for orthogonal frequency division multiplex (OFDM) signals already exist in literature [21, 22]. The underlying idea of this work is to develop an efficient CBCSS technique for the OFDM signal environment like 3GPP LTE and LTE-Advanced [23]. In this paper subcarrier detection of OFDM signals is explored to exploit the advantages of using non-contiguous OFDM (NC-OFDM) [24] modulation technique in CR systems. In case of OFDM systems, generally, the subcarrier allocation is time-frequency block (TFB) based and thus subcarrier sensing can result in the knowledge of neighboring subcarrier availability as well which when incorporated with the sensing results can further improve the sensing performance. After sensing free holes in the spectrum, CRs make sure to start communication over free holes while keeping the minimum interference to the occupied spectrum used by the PUs. This process can be easily done by the CRs by utilizing NC-OFDM as their modulation technique. In our scenario, CRs sense the free subcarriers of the PU's OFDM signal and using NC-OFDM the CRs assign zero to the occupied subcarriers and send data on free subcarriers. In this paper it is assumed that PUs are using OFDM for transmission and CRs are using NC-OFDM as their modulation technique.

The main contributions of this paper are:

- The effects of antenna diversity reception are analyzed in the context of cooperative as well as cluster based spectrum sensing.
- Cooperation in spectrum sensing among MIMO systems is discussed and it is shown that MIMO systems based sensing outperforms SISO systems based sensing.
- A novel data fusion scheme for fusion centers is proposed which is based on the receiver antenna diversity. We propose to assign more weights to the sensing decisions sent from CRs with higher number of receiving antennas than the ones with lesser number of receiving antennas.
- Sensing performance is evaluated by presenting the P_d and P_f of proposed scheme. The results of proposed scheme are also compared with conventional CBCSS scheme [19].

2 System Model

Consider an environment in which CRs with different number of antennas are randomly deployed. A cluster is formed of these CRs following any efficient geographical based clustering algorithm. In Figure 1(a) a scenario with down link transmission of PU OFDM signals is shown in which there are several MCs which are transmitting their SS information to main head (MH) through their respective main cluster heads (MCHs). In Figure 1(b) a typical MC is shown with single and multiple antennas CRs which are transmitting their SS decisions to MCH. Here CR[1x1] is 1 TX and 1 RX antenna CR, CR[2x2] is 2 TX and 2 RX antennas CR and CR[4x4] is 4 TX and 4 RX antennas CR. Thus inside a MC, we have, for instance, VSC1, VSC2 and VSC3 of 1, 2 and 4 TX/RX antenna CRs respectively. MCH takes SS decisions based on decisions sent from CRs present inside MC.

Fig. 1 to be placed here

PU time domain discrete OFDM symbol [23], which is to be sensed by the CRs, is represented by following equation:

$$x[n] = \frac{1}{N}\sum_{k=1}^{N} d_k e^{\frac{j2\pi kn}{N}}, \tag{1}$$

where N is the the inverse discrete fourier transform (IDFT) size, d_k are the data symbols to be sent over N subcarriers, and $n = 1, 2, ..., N$.

The time domain discrete OFDM signal along with AWGN is received at CR RX. The CR RX converts the received serial stream of data to parallel stream and passes it through the Q point discrete fourier transform (DFT) block hence transforming time domain signal to frequency domain as follows:

$$c[q] = \sum_{p=1}^{Q} x_p e^{\frac{-j2\pi pq}{Q}}, \tag{2}$$

where x_p is the received OFDM sampled signal, and $q = 1, 2, .., Q$. After Q point DFT block we get L signal samples against each subcarrier. L signal samples over the n-th subcarrier are extracted from total Q samples of $c[q]$ as follows:

$$s_n[l] = c[L(n-1)+l], \tag{3}$$

where l = 1,2,...,L, and L is the number of samples per subcarrier and L can be called as over sampling factor also, which equals to Q/N hence Q should be greater than or equal to N.

After passing from an AWGN channel, the received L samples of n-th subcarrier are given as:

$$r_n[l] = \begin{cases} G_n[l] & H_0 \\ s_n[l] + G_n[l] & H_1 \end{cases} \tag{4}$$

where hypothesis H_0 means that only AWGN is present at the n-th subcarrier i.e. subcarrier is vacant. Hypothesis H_1 means that signal is present i.e. frequency band at the n-th subcarrier is occupied. $G_n[l]$ represents L samples of AWGN against n-th subcarrier. The CR energy computation block forms the decision statistics E_n by computing energy using L signal samples corresponding to the n-th subcarrier as follows:

$$E_n = \sum_{l=1}^{L} \Big[\mid r_n[l] \mid \Big]^2. \tag{5}$$

E_n is compared with threshold value (λ) to detect the presence/absence of PU signal. Threshold is a common parameter for the P_f, P_d and P_m. The common practice of setting threshold is based on P_f [25]. The decision making block at CR marks subcarrier as vacant when E_n is less than threshold and occupied when E_n is greater than threshold. This procedure is repeated for all subcarriers and subsequently CR determines number of free and used subcarriers.

3 Effect of Antenna Diversity on Individual SS

As discussed earlier there are two types of CRs present in the environment and hence in the MC: single antenna CRs and CRs with multiple antennas. In this section the effect of number of antennas on the expressions of P_d and P_f is discussed. Because of multiple antennas and use of EGC as diversity reception technique, the SNR of the received signal increases and hence the P_d also improves along with reduction in P_f as discussed below.

3.1 Single Antenna CRs

Now we discuss P_d and P_f for the single antenna CRs. Since AWGN obeys Gaussian distribution of zero mean and variance σ_n^2, therefore, on computing energy E_n, the distribution is changed. So under hypothesis H_0, E_n obeys central chi-square distribution (χ^2) with $2L$ degrees of freedom (L real components plus L imaginary components) and under hypothesis H_1, E_n obeys non-central chi-square distribution with $2L$ degrees of freedom and non centrality parameter Υ [26] which is equal to SNR [6]. DFT and IDFT blocks do not affect the gaussian distribution [27].

P_f is defined as the probability that the received energy at n-th subcarrier (E_n) is greater than threshold when signal is not present. By using definition of upper incomplete gamma function $\Gamma(u,v)$ [26], P_f is given as:

$$P_f = \frac{\Gamma(L, \lambda/2)}{\Gamma(L)} \tag{6}$$

P_d is defined as the probability that E_n is greater than threshold when signal is present. By using definition of generalized marcum Q function $Q_a(u,v)$ [28], P_d is given as:

$$P_d = Q_L(\sqrt{\Upsilon}, \sqrt{\lambda}) \tag{7}$$

3.2 Multiple Antennas CRs

Now we discuss the SS performance for multiple antenna CRs. From (3), the received L samples of n-th subcarrier, from the m-th antenna, are given as:

$$r_n^m[l] = \begin{cases} G_n^m[l] & H_0 \\ s_n^m[l] + G_n^m[l] & H_1 \end{cases} \tag{8}$$

where hypothesis H_0 means n-th sub-carrier is vacant. Hypothesis H_1 means n-th sub-carrier is occupied. Using EGC spatial diversity technique energy computation block computes energy for M antennas of the CR for the n-th sub-carrier as follows

$$E_n = \sum_{m=1}^{M} \sum_{l=1}^{L} \Big[\mid r_n^m[l] \mid \Big]^2 \tag{9}$$

where M are the number of antennas the CR is equipped with. Adding M independent non central χ^2 variates with $2L$ degrees of freedom and non-centrality parameter $\varUpsilon_m$, results in another non-central χ^2 variate with $2ML$ degrees of freedom and non-centrality parameter $\varUpsilon_t$. As EGC increases SNR of the signal by adding SNRs at all M branches [4] hence

$$\varUpsilon_t = \sum_{m=1}^{M} \varUpsilon_m \tag{10}$$

As the degree of freedom of both distributions is changed from L to ML, P_f and P_d for multiple antenna CRs are given as follows:

$$P_f = \frac{\varGamma(ML, \lambda/2)}{\varGamma(ML)} \tag{11}$$

$$P_d = Q_{ML}(\sqrt{\varUpsilon_t}, \sqrt{\lambda}) \tag{12}$$

The equations for sensing performance parameters (P_d and P_f) for single and multiple antenna CRs reveal that sensing performance with multiple antennas is better than that with single antenna CRs. Consequently, the sensing results from multiple antenna CRs should be treated as more reliable.

4 Cluster based cooperative spectrum sensing

In this section we shall discuss the conventional CBCSS. As discussed earlier, cooperation among CRs is required to achieve reliable SS results. In individual SS, the results from a certain CR may be erroneous due to the reason that the primary user was behind some obstacle (hidden node problem). Thus a false sensing decision may lead to interference with the primary user. To avoid such scenario, cooperative spectrum sensing was proposed in which several CRs sense a certain environment and then share their sensing results to a fusion center. The fusion center combines those sensing results in an intelligent manner to achieve a more reliable SS result. The fusion rule could be AND, OR, majority rule etc. Please note that there are control channels over which the sensing information is shared between the fusion center and CRs [12].

Moreover, cluster based SS was proposed to avoid reporting delays and bandwidth over-head. In conventional CBCSS [19] scheme all the CRs spread in environment are equipped with single antenna. Clustering is performed based on some location based algorithm. All CRs within clusters first perform individual SS and report their individual spectrum observations to randomly chosen main cluster head (MCH). All MCHs then apply any of hard combining data fusion scheme on received results and send their decisions to randomly chosen MH. Finally the MH gives the verdict on the free and occupied spectrum by applying the same or some other data fusion rule and inform the lower levels. All CRs are equipped with single antenna so they have the P_f and P_d given in equation (6) and (7) respectively. The cooperative probability of false alarm using OR data fusion rule for z-th MC is as below [12]:

$$P_{f_{MC_z}}^{OR} = 1 - \prod_{b=1}^{B}(1 - P_{fz,b}) \tag{13}$$

where B is the number of CRs in the z-th MC, and $P_{fz,b}$ is the probability of false alarm of the b-th CR in the z-th MC, which is given in (6) for the case of CR with single antenna. The cooperative probability of correct detection using OR data fusion rule for z-th MC is

$$P_{d_{MC_z}}^{OR} = 1 - \prod_{b=1}^{B}(1 - P_{dz,b}) \tag{14}$$

where $P_{dz,b}$ is the probability of detection of the b-th CR in the z-th MC, which is given in (7) for the case of CR with single antenna. In AND data fusion rule if even one of the members of z-th MC sends decision as logical zero, the final decision taken by MCH is also zero against that n-th sub-carrier. The cooperative probability of false alarm using AND data fusion rule for z-th MC is

$$P_{f_{MC_z}}^{AND} = \prod_{b=1}^{B}(P_{fz,b}) \tag{15}$$

The cooperative probability of correct detection using AND data fusion rule for z-th MC is

$$P_{d_{MC_z}}^{AND} = \prod_{b=1}^{B}(P_{dz,b}) \tag{16}$$

The MCHs send their results to the MH which performs the data fusion on these results to obtain the final decision. The equations about P_f and P_d at the MH level in both AND and OR data fusion rules are giving in Section 5.3.

5 Proposed Antenna Diversity Based Weighted Cooperative Sub-carrier Detection

In proposed scheme we assume that there are both single and multiple antenna CRs inside a MC. We exploit the antenna diversity of CRs to improve the SS performance in the cluster based cooperative spectrum sensing context.

As shown in Figure 1(a), the system model consists of several MCs with each MC having its own MCH. All MCHs send their decisions to MH. We assume that within each MC there are CRs of different types with regards to their antenna configurations. As shown in Figure 1(b), within an MC there are CRs with single antenna as well as CRs with multiple antenna. The novelty of this paper is that we propose to weight the sensing decisions from CRs according to their antenna diversity and derive the mathematical equations accordingly.

Each MCH which receives sensing decisions from the CRs in its cluster, weights them according to the number of antenna a CR is equipped with. It means that MCH would assign more weight to the decisions from CRs with more number of receiving antennas since their sensing ability is improved due to the receiving antenna diversity and vice versa.

Then each MCH would send its weighted decision to MH who would fuse the decisions following some fusion rule (AND, OR etc.) and make the final decision about the occupancy of the spectrum slot.

Now, the effect of cooperation of CRs on the expressions of P_d and P_f for AND and OR data fusion rules [29] are discussed along with P_f and P_d of MCH and MH. The decisions taken by the CRs against each sub-carrier are combined using the hard combining data fusion rules hence achieving the increased P_d of the MC ($P_{d_{MC}}$) and reduced P_f of the respective MC ($P_{f_{MC}}$). The CRs present in z-th MC (MC_z) start the process of cooperation, after individual sensing, for achieving maximum cooperative probability of correct detection $P_{d_{MC_z}}$ and minimum cooperative probability of false alarm $P_{f_{MC_z}}$ of the MC. In the process of cooperation the CRs share their results with their respective MCH in the form of zeros and ones. The MCH then makes decision by applying specific data fusion rule on the received results.

5.1 Without Weights Data Fusion at MCH

In this section we discuss the effect of fusing the decisions of CRs in CBCSS. In OR data fusion rule if any one of the members of z-th MC sends decision as logical one against n-th sub-carrier, then the MCH also makes the final decision as logical one against that sub-carrier. In this way the cooperative probability of false alarm using OR data fusion rule for z-th MC is as below [12]:

$$P^{OR}_{f_{MC_z}} = 1 - \prod_{t=1}^{T} \Big(\prod_{b_t=1}^{B_t} (1 - P^t_{fz,b_t}) \Big) \tag{17}$$

$$P^{OR}_{f_{MC_z}} = 1 - \Big(\Big(\prod_{b_1=1}^{B_1} (1 - P^1_{fz,b_1}) \Big) \Big(\prod_{b_2=1}^{B_2} (1 - P^2_{fz,b_2}) \Big) .. \Big(\prod_{b_T=1}^{B_T} (1 - P^T_{fz,b_T}) \Big) \Big) \tag{18}$$

where T is the number of types of CRs present in the environment. Please note that CRs with same number of antennas are placed in the same type. B_t is the number of CRs of type t in the z-th MC, and P^t_{fz,b_t} is the probability of false alarm of the b_t-th CR of type t in the z-th MC, which is given in (6) for the case of CR with single antenna and (11) for the case of CR with multiple antennas respectively. The cooperative probability of correct detection using OR data fusion rule for z-th MC is

$$P^{OR}_{d_{MC_z}} = 1 - \prod_{t=1}^{T} \Big(\prod_{b_t=1}^{B_t} (1 - P^t_{dz,b_t}) \Big) \tag{19}$$

where P^t_{dz,b_t} is the probability of detection of the b_t-th CR of type t in the z-th MC, which is given in (7) for the case of CR with single antenna and (12) for the case of CR with multiple antennas respectively. In AND data fusion rule if even one of the members of z-th MC sends decision as logical zero, the final decision taken by MCH is also zero against that n-th sub-carrier. The cooperative probability of false alarm using AND data fusion rule for z-th MC is

$$P^{AND}_{f_{MC_z}} = \prod_{t=1}^{T} \Big(\prod_{b_t=1}^{B_t} (P^t_{fz,b_t}) \Big) \tag{20}$$

The cooperative probability of correct detection using AND data fusion rule for z-th MC is

$$P^{AND}_{d_{MC_z}} = \prod_{t=1}^{T} \Big(\prod_{b_t=1}^{B_t} (P^t_{dz,b_t}) \Big) \tag{21}$$

5.2 Weighted Data Fusion at MCH

In weighted combining of sensing decisions, the MCH assigns weight to the decision according to the number of antennas of the CRs i.e., the CRs having more number of antenna are assigned with the larger weight hence giving more value to the verdicts of the CRs with more number of antenna. When the sub-carrier sensing decisions of the CRs are assigned weights and combined using the OR data fusion rule then the P_f of the MC is given as

$$P^{OR}_{f_{MC_z}} = 1 - \prod_{t=1}^{T} \Big(\prod_{b_t=1}^{B_t} (1 - P^t_{fz,b_t}) \Big)^{w_t} \tag{22}$$

where w_t is the weight assigned to the CRs of type t. The P_d of the MC using OR data fusion rule is

$$P^{OR}_{d_{MC_z}} = 1 - \prod_{t=1}^{T} \Big(\prod_{b_t=1}^{B_t} (1 - P^t_{dz,b_t}) \Big)^{w_t} \tag{23}$$

The P_f of the MC using AND hard decision data fusion rule is

$$P^{AND}_{f_{MC_z}} = \prod_{t=1}^{T} \Big(\prod_{b_t=1}^{B_t} (P^t_{fz,b_t}) \Big)^{w_t} \tag{24}$$

The P_d of the MC using AND data fusion rule is

$$P^{AND}_{d_{MC_z}} = \prod_{t=1}^{T} \Big(\prod_{b_t=1}^{B_t} (P^t_{dz,b_t}) \Big)^{w_t} \tag{25}$$

The set of weights assigned to CR members in a MC is given as

$$\mathbf{w} = \{w_1, w_2, ..., w_T\} \tag{26}$$

where w_i is the weight assigned to the CRs belonging to the i-th type of CRs. The total number of CRs present in z-th MC is given below

$$\mathbf{B} = \sum_{i=1}^{T} B_i \tag{27}$$

where B_i is the number of type i CRs present in z-th MC. The assigned weights can be a function of $P_{d_{MC}}$, $P_{f_{MC}}$ and number of all types of CRs ($\mathbf{B}$) i.e.,

$$\mathbf{w} = f(P_{d_{MC}}, P_{f_{MC}}, \mathbf{B}) \tag{28}$$

Depending upon the sensing criteria, the weight vector $\mathbf{w}$ can be optimized to get the specific SS performance.

5.3 Data Fusion at MH

The MCHs send their results to the MH which then repeats the same process of data fusion, takes the final decision and passes it to the subordinate levels in reverse order so that CRs can have the knowledge of spectrum opportunities and thus avail the free sub-carriers for transmission using their efficient NC-OFDM physical layer. The results of combining MCs' decisions is described in this sub section. When the sub-carrier sensing decisions of the MCs are combined using the OR data fusion rule by the MH then the P_f of the MH is given as

$$P_{f_{MH}}^{OR} = 1 - \prod_{z=1}^{Z} (1 - P_{f_{MC_z}}^{OR}) \tag{29}$$

where Z is the total number of MCs present in the environment. The P_d of the MH using OR data fusion rule is

$$P_{d_{MH}}^{OR} = 1 - \prod_{z=1}^{Z} (1 - P_{d_{MC_z}}^{OR}) \tag{30}$$

The P_f of the MH using AND hard decision data fusion rule is

$$P_{f_{MH}}^{AND} = \prod_{z=1}^{Z} (P_{f_{MC_z}}^{AND}) \tag{31}$$

The P_d of the MH using AND data fusion rule is

$$P_{d_{MH}}^{AND} = \prod_{z=1}^{Z} (P_{d_{MC_z}}^{AND}) \tag{32}$$

The above equations are used at the MH level whether it is conventional CBCSS, or our proposed CBCSS scheme.

6 Simulation Results

This section shows simulation results of the proposed scheme. First the effect of antenna diversity is shown and then effects of cooperation and antenna diversity based cooperation (with and without weights at MCH) are provided. Next, SS performance at MH level is shown and after that, effect of different weights on the scheme is shown. Simulation parameters are provided in Table 1. For simulation results it is assumed that 3 types of CRs are present in environment: single antenna (1x1), dual antenna (2x2) and quadruple antenna (4x4) CRs. For simulations of proposed scheme, we are having 3 MCs and each MC contains 3 CRs with single antenna, 3 CRs with 2 antennas and 3 CRs with four antennas, unless mentioned otherwise. The proposed scheme is valid for any number of CRs inside any MC. The simulation parameters are summarized below in Table 1.

Table. 1 to be placed here

6.1 Diversity Effect

In this section effect of number of antennas on P_d and P_f is discussed. As the number of diversity paths increases the sensing results becomes more reliable because of increased SNR, resulting in increased P_d and reduced P_f. It can be seen in Figure 2 that 4x4 CR has better P_d as compared with 2x2 CR which has less P_d and 1x1 CR which has even lesser P_d. Figure 3 shows effect on P_f i.e., 4x4 CR has the least P_f as compared to 2x2 CR and 1x1 CR. These results illustrate possible SS gains that can be achieved by increasing number of antennas of a CR.

Fig. 2 to be placed here

Fig. 3 to be placed here

6.2 Cooperation Effect

6.2.1 Cooperation of Single Antenna CRs

In this section effect of cooperation with AND and OR data fusion techniques is discussed for single antenna (1x1) CRs.

OR Data Fusion: When 1x1 CRs cooperate with each other using OR data fusion rule, P_d increases with increasing number of cooperating 1x1 CRs as shown in Figure 4, because in OR rule, even if one of the cooperating 1x1 CRs decides that PU signal is present, MCH will also finalize this verdict causing a certain increase in P_d. On the other hand, with increasing number of cooperating 1x1 CRs using OR data fusion rule, P_f also increases [30], because even if one of cooperating 1x1 CRs gives the false decision, MCH will also finalize this false verdict which can cause a certain increase in P_f as shown in Figure 5.

AND Data Fusion: When 1x1 CRs cooperate with each other using AND data fusion rule, P_f decreases with increasing number of cooperating 1x1 CRs (Figure 5) because for MCH to give a false verdict "ALL" the cooperating 1x1 CRs should generate a false decision, which is very less likely to occur. On the other hand, when 1x1 CRs cooperate with each other using AND data fusion rule, P_d also decreases [30] with increasing number of cooperating 1x1CRs (Figure 4) because for MCH to decide that band is correctly occupied, "ALL" the cooperating 1x1 CRs should detect the PU signal correctly, which is very less likely to happen.

Hence for getting benefit from cooperation, the data fusion rules are used with a compromise between P_d and P_f performance of CRs i.e., OR data fusion rule should be used in the scenarios where P_d performance is of much more value than the P_f performance of CRs and AND data fusion rule should be used where P_f results matter more than P_d results.

Fig. 4 to be placed here

Fig. 5 to be placed here

6.2.2 Cooperation of Multiple Antenna CRs

In this section effect of cooperation of multiple antenna CRs is provided and discussed.

When multiple antenna CRs cooperate with each other they give even better results than cooperation of 1x1 CRs i.e., effect of diversity (discussed in Section 6.1) combined with effect of cooperation (using any of data fusion rule, discussed in Section 6.2.1) can give better results (higher P_d and lesser P_f).

It can be seen in Figure 6 that when 3 4x4 CRs cooperate with each other using any of data fusion rules, they give higher P_d than 3 2x2 CRs cooperating with each other. Also notice (in Figure 6) that using OR rule give highest P_d than using AND rule, because of reasons discussed in Section 6.2.1.

In Figure 7 results for P_f are shown. When 3 4x4 CRs cooperate with each other using any of data fusion rules, they give lesser P_f than 3 2x2 CRs cooperating with each other. Also notice (in Figure 7) that using AND rule give least P_f than using OR rule, because of reasons discussed in Section 6.2.1.

Fig. 6 to be placed here

Fig. 7 to be placed here

6.3 Antenna Diversity based Cooperation Effect

As discussed earlier, in proposed scheme, each MCH fuses results of all its member cooperating CRs (using AND/OR data fusion rules) after assigning weights to their decisions depending on number of antennas they (member CRs) are equipped with. In this section results of MCs are discussed for both, with and without weights data fusion. Here the results of P_d and P_f of the MC of proposed scheme are compared with the P_d and P_f of MC of the conventional CBCSS scheme (in which all member CRs are single antenna CRs)[19].

6.3.1 Without Weights

For simulations of without weight results, it is assumed that conventional scheme's MC has 9 1x1 CRs, proposed scheme's MC has 3 1x1 CRs, 3 2x2 CRs, and 3 4x4 CRs and proposed MC's MCH is not assigning weights to any CR.

In Figure 8 it can be seen that P_d of proposed MC's MCH is higher than P_d of conventional MC's MCH because of presence of multiple antenna CRs in proposed MC, which when cooperate, provide gain to the SS performance of proposed scheme. Moreover, because of the reasons discussed earlier (in Section 6.2.1), Or rule P_d is higher than AND rule P_d.

In Figure 9 its shown that P_f of proposed MC's MCH is lesser as compared with conventional MC's MCH because of presence of multiple antenna CRs in proposed MC, which when cooperate, reduce the P_f of the proposed MC. Moreover also notice that P_f is lesser with AND data fusion rule for proposed MC than the P_f using OR rule (Section 6.2.1). It is consistent with the previous discussions.

6.3.2 With Weights

For simulations of with weights results, it is assumed that conventional scheme's MC has 9 1x1 CRs, proposed scheme's MC has 3 1x1 CRs, 3 2x2 CRs, and 3 4x4 CRs and proposed MC's MCH is assigning weights to CRs as follows

- weight assigned to 1x1 CRs each = 1 ($w_1 = 1$)
- weight assigned to 2x2 CRs each = 2 ($w_2 = 2$)
- weight assigned to 4x4 CRs each = 3 ($w_4 = 3$)

Please note that the weights selected for simulations are arbitrary. The weights can be optimized according to Eq. 28 to further improve the sensing performance though. In Figure 8 it can be seen that with weights P_d of proposed MC's MCH is even higher than without weights P_d of proposed MC's, hence performing better than conventional scheme, because of presence of multiple antenna CRs in proposed MC, which when cooperate with highest weight assigned to the highest no. of antenna CRs, further increase P_d of proposed scheme. Moreover, because of the reasons discussed earlier (in Section 6.2.1), Or rule with weights P_d is higher than AND rule P_d. In Figure 9 its shown that with weights P_f of proposed MC's MCH is even lesser than without weights P_f of proposed MC's MCH, hence performing better than conventional scheme, because of presence of multiple antenna CRs in proposed MC, which when cooperate with highest weight assigned to the highest no. of antenna CRs, further reduce the P_f of the proposed MC. Moreover also notice that P_f is lesser with AND data fusion rule than the P_f using OR rule (Section 6.2.1). It is consistent with the previous discussions.

Fig. 8 to be placed here

Fig. 9 to be placed here

6.4 SS Performance of MH

As discussed earlier, in proposed scheme, the MH fuses results of all MCHs of the CR network using same data fusion rule used for at lower layer (for data combining at MCH level). This section shows results of proposed scheme's MH (with and without weights) compared with conventional scheme's MH results.

In Figure 10 it can be seen that when weighted data fusion is done at MCH level, the proposed MH P_d is higher than without weights proposed MH P_d, which is higher than the conventional scheme results. Hence it can be said that for lesser SNR scenarios antenna diversity based weighted data fusion provides the highest P_d.

In Figure 11 it can be seen that when weighted data fusion is done at MCH level, the proposed MH P_f is lesser than without weights proposed MH P_f, which is lesser than the conventional MH P_f. Hence it can be said that for lesser SNR scenarios antenna diversity based weighted data fusion provides the least P_f.

Fig. 10 to be placed here

Fig. 11 to be placed here

6.5 Effect of Different Weights

This section provides additional results of proposed MCH to elaborate the importance of assigning highest weight to the highest no. of antenna CRs in . In Figure 12 and Figure 13 it can be seen that when more weights are assigned to the CR with more number of antennas, P_d improves further and reduction in P_f is observed. Here, we have compared the SS performance with two different weight combinations. The first combination of weights is w_1=1,w_2=2,w_4=3, where as the second combination is w_1=1,w_2=4,w_4=6. It can be seen that second combination has better performance than the first combination and than the conventional scheme. This result is in accordance with the theory i.e., more the weight to the CRs with more number of antennas, larger is the P_d and lesser is the P_f.

Fig. 12 to be placed here

Fig. 13 to be placed here

Figure 14 and Figure 15 shows effect of weights on the SS performance of proposed MH. It can be seen that Proposed MH with second combination of weights is performing better than the proposed MH with first combination of weights.

Fig. 14 to be placed here

Fig. 15 to be placed here

7 Conclusion

This paper shows the mathematical analysis and simulations results for a CBCSS schemes which takes into account the antenna diversity factor of the incumbent CR users. The mathematical expressions are provided for 2 hard fusion rules: AND and OR rule. The approach proposed in this paper uses the concept of weighted data fusion on the basis of number of antennas the CRs are equipped with. The more number of antenna a CR is equipped with, the better is its SS performance and hence more weight can be assigned to its sensing decision for achieving improved results. The simulation results show that this approach outperforms the conventional CBCSS.

8 Conflict of Interest

The authors declare that there is no conflict of interest.

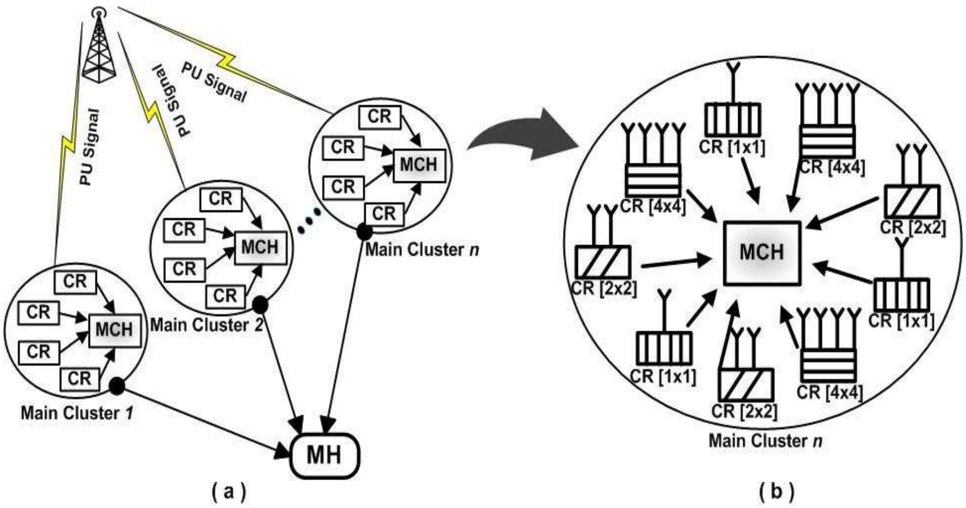

Fig. 1 (a) Overview of System Model. (b) Main Cluster (MC).

Parameter	Value
PU Modulation Scheme	QPSK
PU TX IDFT size (N)	64
CR RX DFT size (Q)	2048
Total no. of MCs	3

Table 1 Simulation parameters.

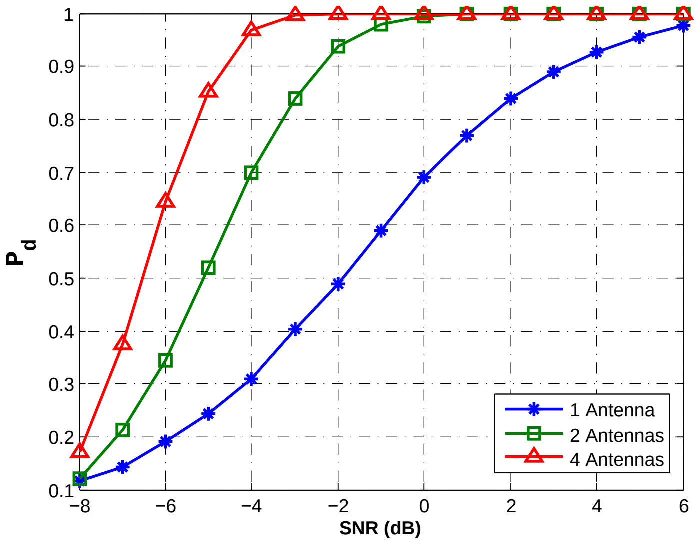

Fig. 2 Increasing P_d with increasing number of receive antennas of single CR.

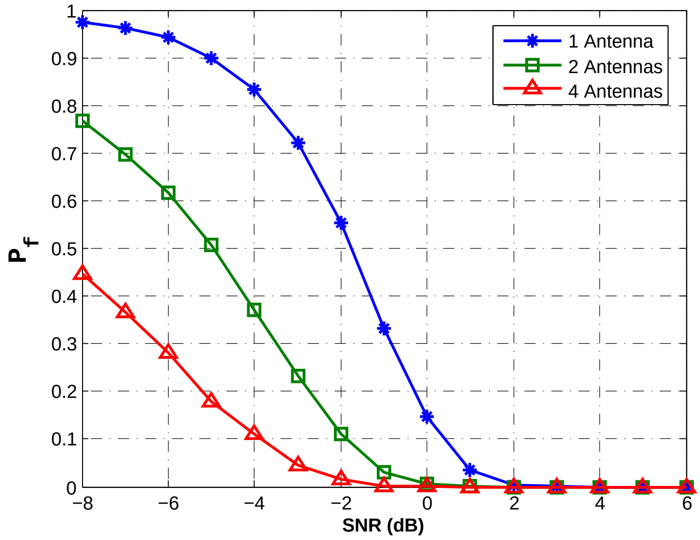

Fig. 3 Decreasing P_f with increasing number of receive antennas of single CR.

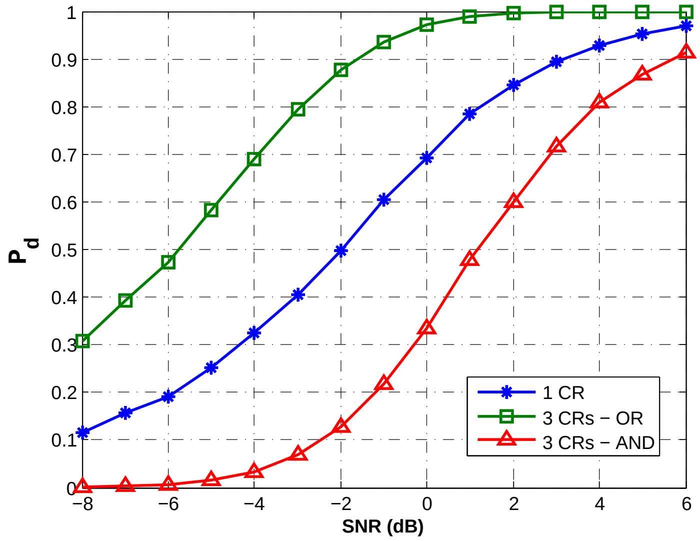

Fig. 4 Effect of cooperation of single antenna CRs on P_d with comparison of data fusion rules.

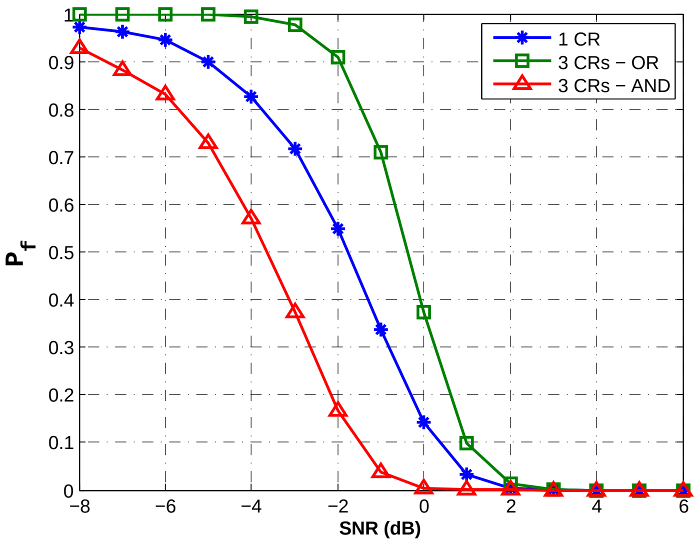

Fig. 5 Effect of cooperation of single antenna CRs on P_f with comparison of data fusion rules.

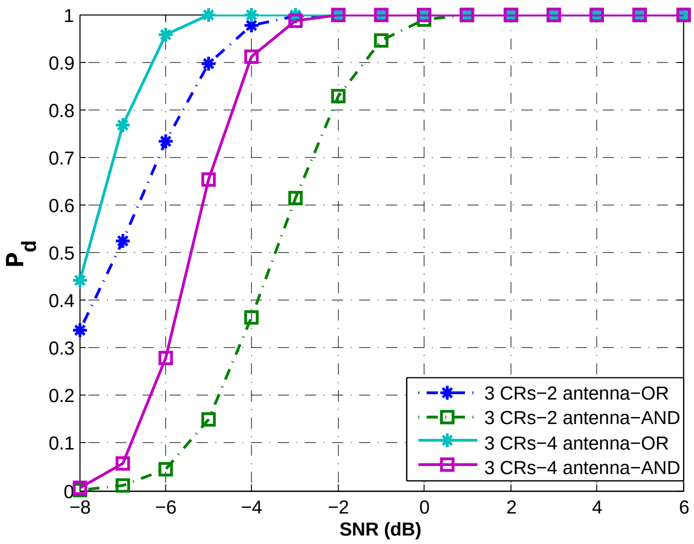

Fig. 6 Effect of cooperation of multiple antenna CRs on P_d with comparison of data fusion rules.

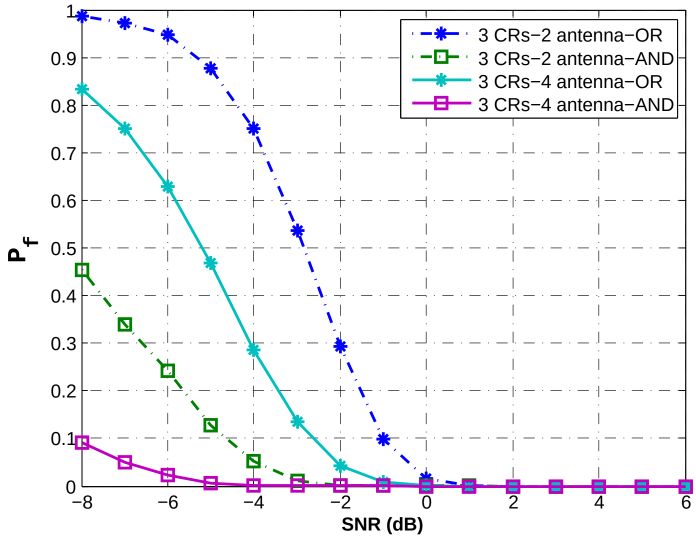

Fig. 7 Effect of cooperation of multiple antenna CRs on P_f with comparison of data fusion rules.

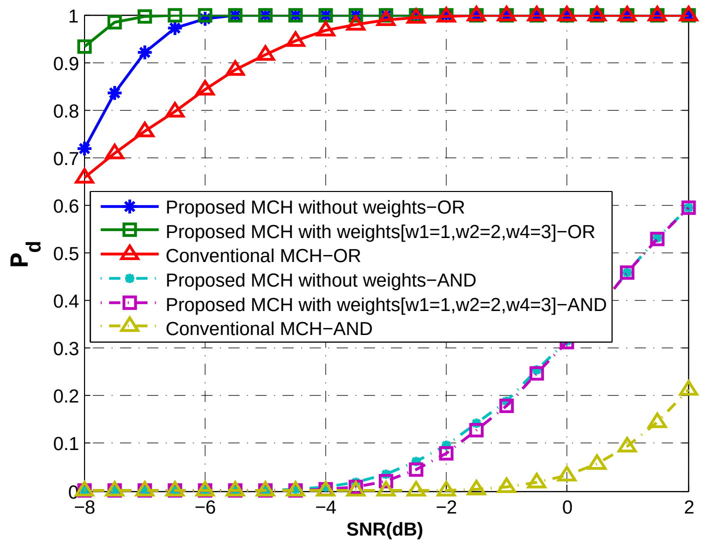

Fig. 8 Comparison of P_d of proposed scheme's MC with conventional scheme's MC with comparison of data fusion rules .

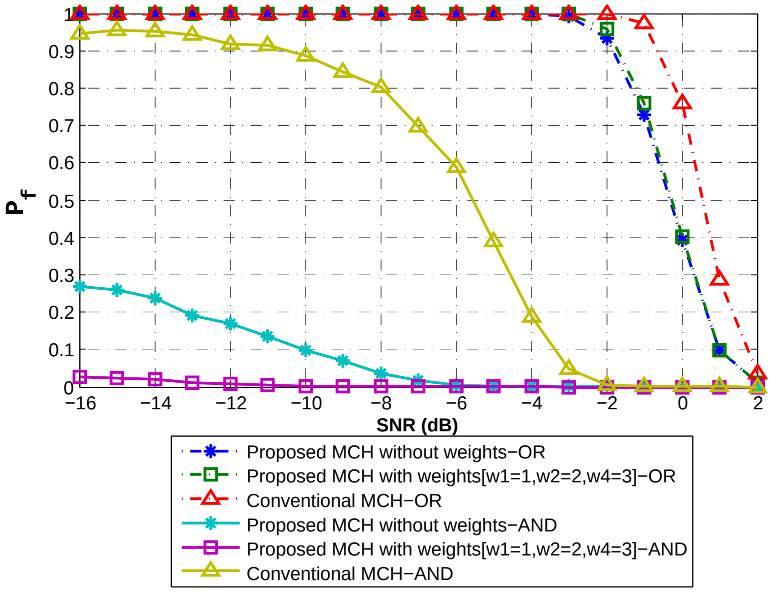

Fig. 9 Comparison of P_f of proposed scheme's MC with conventional scheme's MC with comparison of data fusion rules.

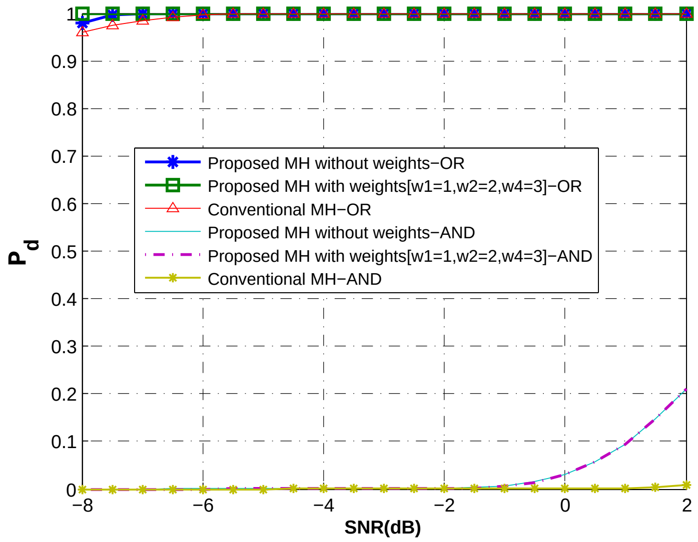

Fig. 10 Effect of weights on P_d of proposed scheme's MH using OR and AND rule

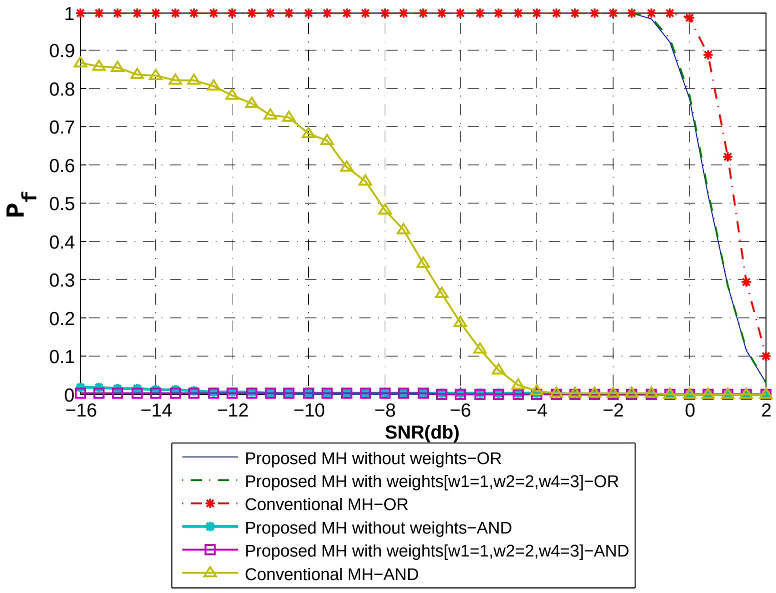

Fig. 11 Effect of weights on P_f of proposed scheme's MH using AND and OR rule.

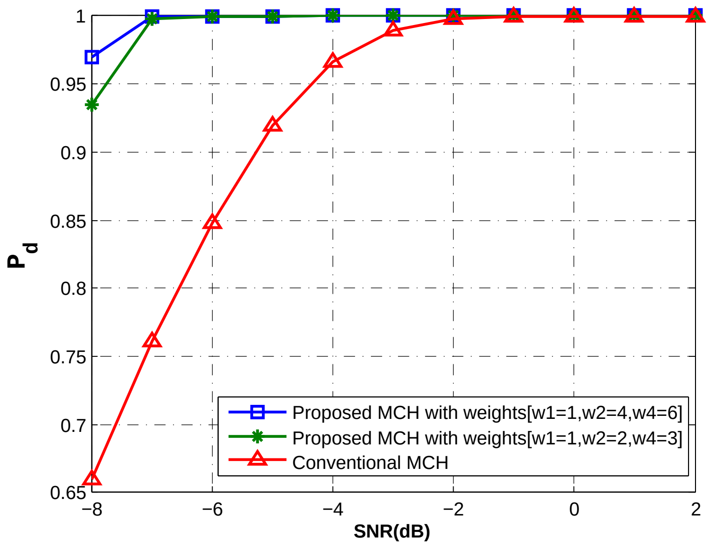

Fig. 12 Effect of different weights on P_d of proposed scheme's MCH

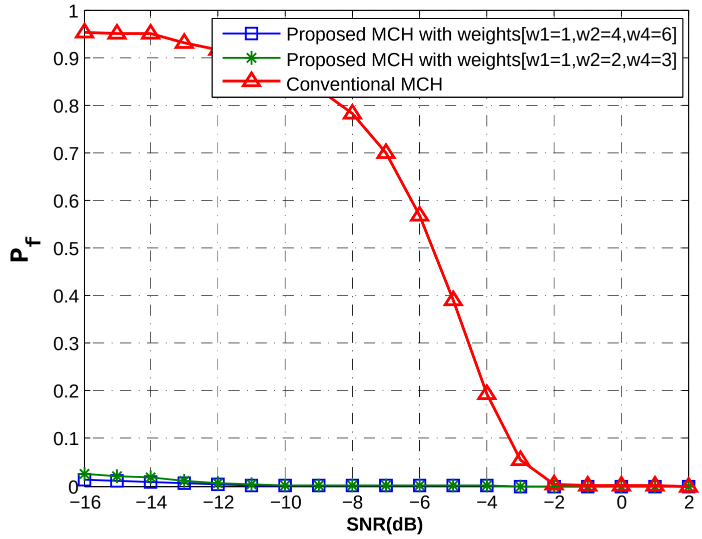

Fig. 13 Effect of different weights on P_f of proposed scheme's MCH

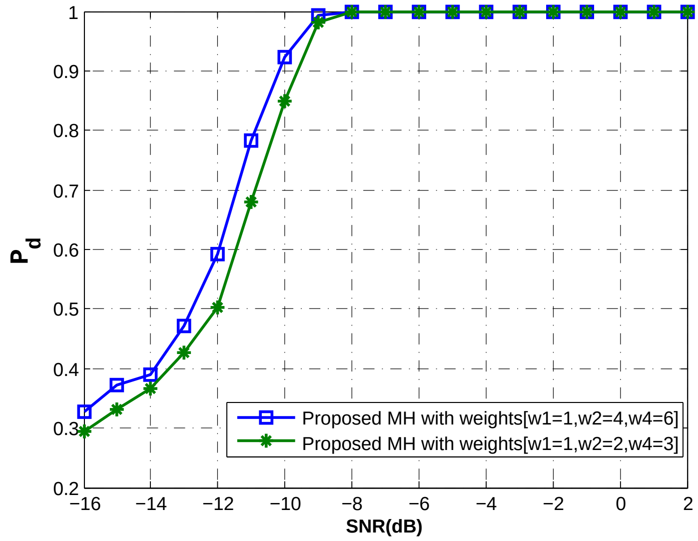

Fig. 14 P_d of proposed scheme's MH with different weights

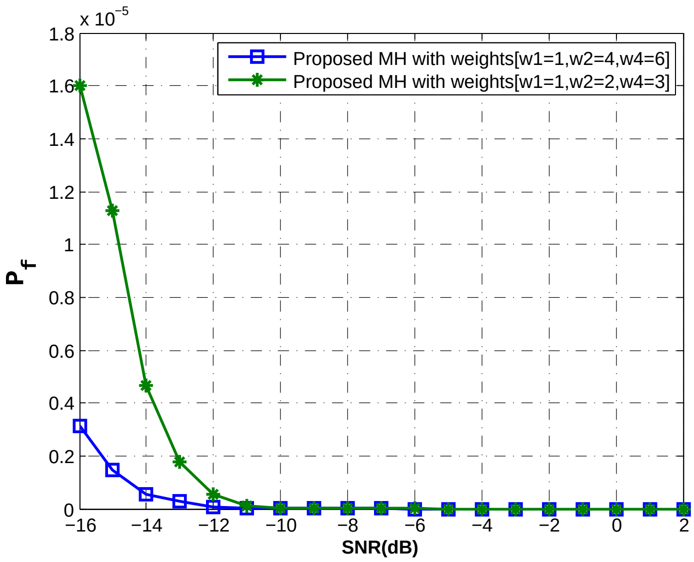

Fig. 15 P_f of proposed scheme's MH with different weights.

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