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Spectrum monitoring in heterogeneous cognitive radio network: How to cooperate?

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Abstract: The spectrum-monitoring is a prominent technique to detect the reappearance of the primary user (PU) during the cognitive users' (CUs) data transmission. However, the imperfect spectrum monitoring (SM) causes a delay in the identification of PU that introduces interference at PU as well as data-loss. The cooperation among CUs for SM is a proficient solution to diminish these impairments of imperfection. Thus, in this study, a scenario of the heterogeneous cognitive radio network (CRN) is presented in which the CUs perform cooperation among them for SM and have analysed the impact of cooperation on several performance metrics such as the data-loss, interference efficiency and energy efficiency. An algorithm is presented for the evaluation of data-loss for different circumstances of the traffic intensity of PU and probability of SM error in the proposed heterogeneous CRN. In addition to this, the closed-form expressions for the cooperative and non-cooperative SM of these metrics are derived. Furthermore, the simulation results are illustrated for different state-of-affairs of the probability of SM error and traffic intensity.

1 Introduction

Recently, the cognitive radio is emerged as a key technology to overcome the dilemma of spectrum scarcity where the cognitive user (CU) senses the channel and performs data transmission when the sensed channel is perceived as idle otherwise move for another frequency [1, 2]. During the CUs' data transmission, the emergence of the primary user (PU) is a prospective event which needs to detect immediately to stop the CU transmission that results in the data-loss improvement and avoid the interference with PU [3–7]. The identification of emergence/reappearance of PU during the CUs' data/information transmission is achieved via the spectrum monitoring (SM). In this technique, the CU exploits the received signal characteristics, for instance, receiver error count (REC) and the ratio of the energy for the current window to the previous window (energy ratio) to detect the reappearance of PU [8]. Initially, the SM using REC is projected by Boyd *et al.* [8] and further, it is investigated by several scientists [9, 10]. It is worth to mention that the CU receiver receives the data (in the form of packets) with tolerable number of error in a packet which is known as REC. The reappearance of PU generates the interference at CU receiver that results the significant increase in a number of errors and this variation in REC is employed to perceive the recurrence of PU. In the similar way, the energy rising on the reappearance of PU is employed for its detection. Orooji *et al.* [11] have examined the SM for Rayleigh fading channels and have exploited multiple antennas on the CU to improve the multipath fading effect via the diversity combining techniques. Ali and Hamouda [9] have introduced the 'energy ratio SM' technique and stated that the projected technique performs well when compared with the receiver statistics method with respect to detection delay. On the other hand, the complexity is twofold as compared to the energy detection technique. Orooji *et al.* [10] have projected a decision-statistic for the SM using REC and have appraised the detection and false-alarm probabilities. Moreover, in order to improve the channel utilisation, the authors have examined an optimisation problem where the constraint in applied on the 'detection delay'. In recent past, Thakur *et al.* [12] have investigated the consequence of SM on the energy and data-loss of CU as well as on the interference at the PU due to CU transmission. It is reported that the use of SM in the 'high-traffic CRN' (HTCRN) improves energy and data-loss of CU and the 'interference at PU due to CU transmission' when compared with the conventional (without SM system) HTCRNs.

The SM is a function of the received signal that is influenced due to random nature of the channel. Therefore, the consideration of perfect SM is an impractical state-of-affairs. Thus, we have introduced the notion of 'imperfect SM' and examined its consequences on data-loss, power wastage, interference efficiency (IE) and energy efficiency (EE) in the cognitive radio networks (CRNs) [13]. Further, we have analysed that the imperfection in SM deteriorates the performance of CRN. Therefore, the cooperation among the CUs is a potential way to manage the imperfect SM in the practical scenario. Recently, we have analysed the effect of cooperation in CRN for the homogeneous environment which means all the CUs have an equal probability of SM error [14] ['A CRN is defined as a homogeneous/heterogeneous CRN if all the CUs have same/different operating characteristics such as the probability of error, channel conditions, hardware impairments, delay profiles and so on [14]. In the proposed CRN, the homogeneous/heterogeneous nature is considered in terms of probability of SM error which is due to different channel conditions and hardware impairments to every CU.']. Awoyemi *et al.* [15] have analysed and developed a resource allocation model for heterogeneous CRN with delay considerations.

The heterogeneity for CUs is assumed with reference to different service demands and capacities of each CU pair. Further, the authors have exploited the concept of queuing theory to manage the service and capacity demands of each CU pair. The optimality is achieved via queuing theory by moving one CUs demands from one queue to another queue where they have a better chance of enhanced services which results in the improved performance of CRN. However, this heterogeneous nature is not exactly suited for the SM scenarios. Therefore, we have considered a practical scenario in which every CU has a different value of SM error due to different channel conditions and hardware impairments. Moreover, there is no mechanism to diminish the effect of imperfections in spectrum sensing [15], however, the improvement is achieved by using queuing theory only.

Therefore, it is worth to analyse the performance of cooperative CRN for heterogeneous CUs with different values of the 'probability of SM error' to diminish the effect of imperfections. The potential contribution of the authors is summarised as follows:

- We have projected a prospective and practicable framework of cooperative SM for heterogeneous CRN and is analysed for various state-of-affairs of the 'traffic intensity' as well as the 'probability of SM error'.
- A closed-form mathematical expression of the 'Poisson-binomial distribution' (PBD) is derived which is exploited to formulate probability of x number of CUs confirmation among N number of CUs for the emergence of PU.
- The closed-form mathematical expressions for the achieved throughput, data-loss, IE and EE are derived and numerically simulated results are presented.

The remaining of the paper is structured as follows. The fundamental difference between the spectrum sensing and SM techniques is illustrated in Section 2. Moreover, Section 2 also comprises background regarding the cooperative communication and the PBD. The system model of the proposed framework is described in Section 3, however, Section 4 discusses the analysis of the proposed system model. The simulation results with potential discussion are presented in Section 5. Finally, Section 6 concludes the paper as well as presents future perspectives.

2 Background

2.1 Spectrum sensing and spectrum monitoring (SM)

In general, the spectrum sensing and SM are assumed to be the same to detect the channel state either active or idle. The key concern of this section is to comprehend the fundamental difference between the spectrum sensing and SM. The spectrum sensing is a popular approach that allows the CU to sense the surrounding environment in order to identify the state of channels (active or idle) [3, 16]. When the channel state is indentified as idle only then the CU started communication otherwise senses another channel. The key technique utilised for spectrum sensing is the energy detection, where the CU receiver compares the received energy level with the predefined threshold and if it is greater than the threshold, the channel state is decided as active otherwise idle [4]. For the spectrum sensing, the binary hypotheses assumed for the received signal $r(t)$ are H_0 and H_1, which signifies the absence and the presence of the PU, respectively,

$$r(t) = \begin{cases} h \cdot s(t) + w(t) & H_1, \\ w(t) & H_0, \end{cases} \tag{1}$$

where h, $w(t)$, and $s(t)$ denote the magnitude of channel gain, additive white Gaussian noise (AWGN), and transmitted signal of the PU, respectively. The prominent errors in the spectrum sensing process are the false-alarm and misdetection [4]. The false-alarm is defined as the error of false detection of PU on the channel if originally/actually the PU is absent and represented by the probability of false-alarm ($P_{\rm f}$). The misdetection error occurs when the CU misses the detection of PU when originally PU is present on the channel which is represented by the probability of misdetection ($P_{\rm m}$). The false-alarm of PUs' presence on the channel restricts the CUs to access that channel which results in the resource wastage, i.e. spectrum wastage. On the other hand, the misdetection allows CUs to establish the communication simultaneous to the PU which results in the data-collision/loss, power wastage and causes the interference at PU.

The SM is an important phenomenon in which the CU monitors the spectrum during data transmission to indentify the reappearance of PU [8]. The prime difference between the spectrum sensing and SM is that the CU needs to detect the PU during the data transmission, which means the CU needs to perceive the presence of PU signal $s(t)$ with the already existing CU signal $C(t)$ and noise $w(t)$. Therefore, the binary hypotheses of the SM for the received signal $r(t)$ are H_0 and H_1, that signifies the absence and the presence of the PU, respectively,

$$r(t) = \begin{cases} h \cdot s(t) + w(t) + C(t) & H_1, \\ w(t) + C(t) & H_0. \end{cases} \tag{2}$$

The key intent of SM implementation is to identify the reappearance of PU during the data transmission. The error occurs in the SM process if the CU misses the detection of the emergence of PU, therefore the role of misdetection error is prominent. However, the false-alarm error does not have a significant role. Therefore, the probability of the SM error is inspired by the probability of misdetection. The probability of SM error is defined as the delay in detection of PU. There will be more delay in the identification of the emergence of PU with higher values of the probability of SM error.

2.2 Cooperative communication

In the cooperative CRN, all the CUs make a decision (yes/no) on the bases of received information from the radio resource environment and send this decision to the central node/fusion centre (FC) in order to yield the final decision by combining all individual decisions [17, 18]. The type of cooperation where the individual CU sends the decision rather than the received information is known as hard-combining rules [19–21]. The hard-combining rule comprises OR, AND, and M-out-of-N-rules (MOON rule). In the MOON rule, the final decision (yes/no) is confirmed if M-out-of-N CUs supports the same [22, 23]. The mathematical modelling of the distribution function of the M number of CUs' confirmation (yes/no) is achieved by the binomial distribution if all the CUs decide the decision with same probability [24].

The binomial distribution is a potential approach in order to yield the 'discrete probability distribution', $P_p(x/X)$, to yield 'exactly x successes out of X Bernoulli trials'. However, the outcome of every Bernoulli trial is correct with probability p and false with probability $(1-p)$ which is well explored in the mathematics as well as implemented in various engineering applications such as communication engineering, computer engineering, signal and image processing and so on. One popular application of the binomial distribution is in cooperative communication to yield the probability of error after cooperation when MOON rule is used to combine the results from various observation points (nodes/CUs). The key limitation of binomial distribution is that it supports the homogeneous environment, i.e. every Bernoulli trial is true with equal probability p and false with $(1-p)$. However, in most of the feasible scenarios, every node has a different probability of error either due to hardware or channel conditions. Therefore, it is worth to analyse the considered network for such a feasible scenario and for this purpose, we need to explore the PBD [25]. The PBD is defined to yield the 'discrete probability distribution' $P_p(x/X)$, to achieve exactly x successes out of X Bernoulli trials (where the outcome of the $i^{\rm th}$ Bernoulli trial is correct with probability p_i and false with probability $(1-p_i)$. Various researchers have presented their investigation to compute the closed-form expression of the PBD [26, 27]. Wang [25] has derived the probability of having x successful trials out of total X trials which is defined as follows [10]:

$$P_p\left(\frac{x}{X}\right) = \sum_{A \in F_x} \prod_{i \in A} P_i \prod_{j \in A^c} \left(1 - P_j\right) \tag{3}$$

where F_x is the set of all subsets of x integers that can be selected from the set $\{1,2,3,4,\ldots,X\}$. For instance, if $X=4$ and $x=2$, then $F_x = \{\{1,2\},\{1,3\},\{1,4\},\{2,3\},\{2,4\},\{3,4\}\}$ and A^c denotes the complement of A. The number of elements in the set F_x is $(X!/((X-x)!\,x!))$. The large value of X results in the large values of elements which is very difficult and complex to yield and results in the increase in computational complexity. Thus, the computational complexity is very large for this approach and by keeping this in mind the Fernandez and Williams [27] have exploited the discrete Fourier transform to achieve the closed-form expression for the PBD as follows:

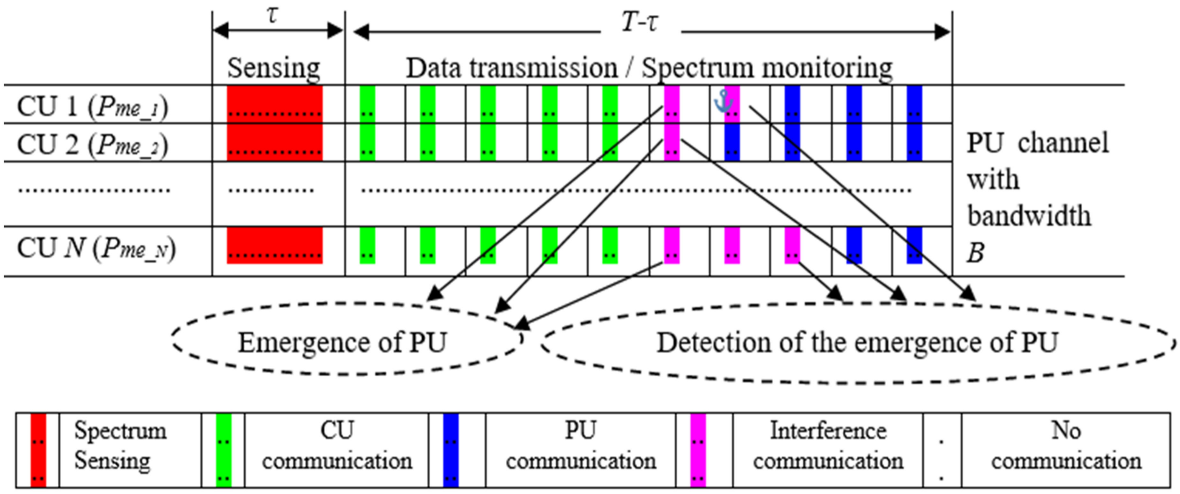

Fig. 1 *Schematic diagram of the proposed cooperative SM scenario in CRNs*

$$P_p\left(\frac{x}{X}\right) = \frac{1}{X+1}\sum_{l=0}^{N} C^{-lx}\prod_{m=1}^{N} 1 - P_m + C^l P_m \tag{4}$$

where $C = e^{((2\pi i)/(X+1))}$ and $i = \sqrt{-1}$. In this paper, $P_p(x/X)$ yields the complex number of probability which is against the norms/axioms of probability theory. Therefore, in order to overcome this issue, we have followed the fundamental steps of formation of the x successes out of X number of events [27] and have exploited the MATLAB 2010a [28]. We conclude that the expression in (4) has a deficiency which is avoided by taking the absolute value of the computed probability. Therefore, the improved form of (2) is as follows:

$$P_p\left(\frac{x}{X}\right) = \left|\frac{1}{X+1}\sum_{l=0}^{X} C^{-lx}\prod_{m=1}^{X} 1 - P_m + C^l P_m\right| \tag{5}$$

Further, in the MOON rule, the decision yes/no is confirmed when M number of nodes says yes/no. Therefore, the probability of decision yes/no is confirmed when M or greater than M number of users will say yes/no. Thus, the probability of this event is defined as follows:

$$P_p(\text{yes/no}) = \sum_{x=M}^{X} P_p\left(\frac{x}{X}\right) \tag{6}$$

3 System model

The projected system model of heterogeneous CRN comprises a transceiver pair of PU network that communicates via a channel of bandwidth B as depicts in Fig. 1. The heterogeneous CRNs consist of N number of CU pairs that are permitted to use the PUs' spectrum in a way so that each CU yields equal bandwidth and therefore the bandwidth assigned to every CU is B/N.

The CU communication is established via time frame (T) where time τ is devoted for spectrum sensing and (T–τ) for the data transmission. The number of packets transmitted in the sensing period without the emergence of PU is N_0. In the projected system model, a high-traffic environment is assumed (the traffic intensity of PU is >0.5). The CUs execute 'spectrum-prediction' process in the preceding time frame during the data transmission to pick the channel having an utmost idle probability for the spectrum sensing process in the present frame. Consequently, this sensing performance improves significantly because it improves the need for sensing time and energy spent to sense the active channels [27]. Since the spectrum prediction is performed in the background, therefore, the time devoted is zero, however, the certain power (P_P) is necessary to execute this process. The spectrum prediction is well matured technique presented in several reported kinds of literature [29–31], therefore, this paper mainly emphasises on the cooperative SM.

The CUs accomplish spectrum sensing with time τ and then establishes data/information transmission for time (T–τ) by using power P_1 on the idle sensed channel in the current time frame. Further, the SM process is implemented simultaneously to the data transmission in the data-transmission interval to know the 'reappearance of PU'. The role of SM seems prominent merely if the PU recommences its communication during the CUs' data-transmission interval. Therefore, with the consideration of this event, the probability of PUs' reappearance during the data-transmission interval is obtained using traffic intensity (ρ) of the PU. The traffic intensity of PU is supposed as a binary-stochastic hypothesis, where 0 and 1 signify the idle and busy/active states of channels, respectively [23]. Further, the typical arrival and channel occupancy time of PU is modelled using the Poisson distribution (metric λ) and binomial distribution (metric μ), respectively [32]. Therefore, the 'probability of channel to be active' ($P(H_1)$) or idle ($P(H_0)$) is presented as $P(H_1) = \mu/\lambda$, and $P(H_0) = (\lambda - \mu)/\lambda$, respectively. In the anticipated system model, the probability of channel to be idle $P(H_1)$ is considered as a traffic intensity of the PU channel $\rho = P(H_1) = \mu/\lambda$. The higher value of ρ signifies the PU reappearance in the starting phase of data-transmission period, however, the lower value corresponds to its reappearance in the later part. Moreover, every CU senses the state of channel (active or idle) during the sensing interval exclusively and cooperates among themselves to yield the final decision that is either idle or active. If this decision confirms the channels' idle state, then every CU transmits the data in the form of packets. Due to the prospect of the PUs' emergence during the CUs' data transmission, it is the accountability of CU to identify the reappearance of PU and stop its communication.

The identification of the reappearance of PU is a prospective phenomenon in the CRNs which is comprehended by using the SM technique. In the considered system model, the SM is supposed as the feasible imperfect phenomenon and the imperfections are presented by the probability of SM error (P_{me}). For the projected network, P_{me_i} denotes the probability of SM error for the i^{th} CU″, where $i = 1,2,3,\ldots,N$. The imperfection in SM indicates that the reappearance of PU is not indentified instantly, however, it is indentified after assured time delay known as detection delay. This imperfection occurs due to channel unpredictability and/or the hardware system impairments. The large value of P_{me} signifies the more delay in identification of PU and the continuation of CU communication in this detection delay of PU results in the data-loss and instigates significant interference at PU. In addition to this, the 'interference power at PU' receiver is the function of the 'channel gain of CU transmitter to PU receiver (h_{sp})' that is interpreted as the interference link. Thus, the cooperation among CUs plays a significant role to accomplish the effect of imperfections. The state-of-reappearance of PU either 0 or 1 is decided by CUs and sends to the FC where the final decision is taken by uniting the reported results of all the state. Henceforth, all the CUs stop the communication if the final decision validates the reappearance of PU otherwise continue. Further, the cooperation of CUs in SM decreases the 'probability of SM error'. If the data are fused via MOON rule which is discussed in the preceding section, the probability of SM error ($Q_{\rm me}$) is defined and presented by (7) as follows:

$$Q_{\rm me} = \sum_{j=M}^{N} \left| \frac{1}{N+1} \sum_{l=0}^{N} C^{-lM} \prod_{m=1}^{N} 1 - P_{{\rm me}_m} + C^{l} P_{{\rm me}_m} \right| \quad (7)$$

where $N_{\rm PPU}$, $N_{\rm PCU}$, h_{ss}, and h_{sp} denote the noise power at PU receiver, noise power at CU receiver, channel gain from CU transmitter to CU receiver, and channel gain from CU transmitter to PU receiver, respectively.

4 Performance analysis of proposed CRN

This section discusses the consequence of imperfect SM on the 'data-loss of the projected heterogeneous CRN' and closed-form mathematical expressions of the achieved throughput, data-loss, IE and EE are derived. The data-loss occurs in the heterogeneous CRN with the reappearance of PU in the data-transmission period and the probability of this reappearance is achieved by the 'traffic-intensity of PU'. However, the perfect SM is an unfeasible scenario where the reappearance of PU is indentified very quickly that signifies within a data packet time (loss of that single packet). In contrast, the imperfect SM is a practical scenario where the data-loss is a function of the probability of SM error ($P_{\rm me}$) [Assumption: 'The perfect SM system is very quick and ideal, even though a particular packet is required to compute decision statistics.']. In the projected heterogeneous CRN model, the particular number of packets lost among the total number of packets (No) that relies on the SM error. Moreover, the computation of a number of packets lost among a total number of packets in the considered CRN follows the binomial distribution [24]. Therefore, in the considered heterogeneous CRN, the discrete probability distribution $P(k/No)$ to yield exactly k number of packets lost out of No (where the data-loss result is true for the $i^{\rm th}$ CU with probability P_{me_i} and false with probability $(1 - P_{me\_i})$.

Thus, the probability of data-loss due to $P_{\rm me}$ for the $i^{\rm th}$ CU″ in the non-cooperative SM (NCM) ['The subscript NCM represents the non-cooperative SM.'], ['The subscript CM represents the cooperative SM.'], ['The subscript i represents the $i^{\rm th}$ CU.'] is defined as follows:

$$P_{{\rm NCM}_i}\left(\frac{k}{No}\right) = \binom{No}{k} \left(P_{{\rm me}_i}\right)^k \left(1 - P_{{\rm me}_i}\right)^{No-k} \quad (8)$$

Similarly, the probability of data-loss due to $P_{\rm me}$ in the cooperative SM for all the CUs is presented as follows:

$$P_{\rm CM}\left(\frac{k}{No}\right) = \binom{No}{k} \left(Q_{\rm me}\right)^k \left(1 - Q_{\rm me}\right)^{No-k} \quad (9)$$

Further, the average number of data packets lost ($k_{\rm avg}$) for the $i^{\rm th}$ CU in the case of cooperative and non-cooperative SM are evaluated by computing the expectation of variables as follows:

$$k_{NCM\_avg\_i} = \sum_{k=1}^{No} k \cdot P_{NCM\_i}\left(\frac{k}{No}\right) \quad (10)$$

$$k_{CM\_avg} = \sum_{k=1}^{No} k \cdot P_{\rm CM}\left(\frac{k}{No}\right) \quad (11)$$

However, a single packet will be lost even if $P_{\rm me} = 0$. Thus, there is need to add one packet in $k_{\rm avg}$ for the computation of total number of packets lost in the heterogeneous CRN (k_{an}) in both the cases, that is presented as $k_{an\_NCM\_i} = \left(1 + k_{avg\_NCM\_i}\right)$ and $k_{an\_CM} = \left(1 + k_{{\rm avg}_{\rm CM}}\right)$. Since the communication is set-up via the frame structures that signifies after the particular time interval, i.e. the frame time (T), the CU periodically replicates the spectrum sensing and data transmission processes. Thus, it is a prospective event that the CU switches from data transmission mode to spectrum sensing mode of the next frame, instantly on the reappearance of PU due to finish of the data-transmission period.

In this situation, the number of packets lost depends on the time of reappearance of PU that relies on traffic intensity (ρ) of the proposed heterogeneous CRN. Thus, the complete data-loss in the proposed heterogeneous CRN ($k_{\rm comp}$) does not merely depends on SM error but also on the traffic intensity of PU. Therefore, to accomplish the complete data-loss in the projected heterogeneous CRN, we must compute the total number of packets to be transmitted after the emergence of PU ($k_{\rm TAEPU}$) that depend on the 'traffic intensity' and computed as $k_{\rm TAEPU} = (1 - \rho) \times No$. The complete data-loss in the non-cooperative ($k_{comp\_NCM\_i}$) CRN for the $i^{\rm th}$ CU and in cooperative (k_{comp_CM}) for all CUs is as follows:

$$k_{comp\_NCM\_i} = \begin{Bmatrix} k_{an\_NCM\_i} & \text{if } k_{\rm TAEPU} \ge k_{an\_NCM\_i} \\ k_{\rm TAEPU} & \text{if } k_{\rm TAEPU} < k_{an\_NCM\_i} \end{Bmatrix} \quad (12)$$

$$k_{comp\_CM} = \begin{Bmatrix} k_{an\_CM} & \text{if } k_{\rm TAEPU} \ge k_{an\_CM} \\ k_{\rm TAEPU} & \text{if } k_{\rm TAEPU} < k_{an\_CM} \end{Bmatrix} \quad (13)$$

If the number of packets to be transmitted after the emergence of PU is significantly more as compared to that of the total number of packets lost due to monitoring error for the non-cooperative (for $i^{\rm th}$ CUs) and cooperative case (for all CUs), then the total data-loss in the proposed heterogeneous CRN is presented as $k_{an\_NCM\_i}$ and k_{an_CM}, respectively, otherwise $k_{\rm TAEPU}$. The average data-loss of complete heterogeneous CRN in the non-cooperative case is $k_{comp\_NCM} = (1/N)\sum_{i=1}^{N} k_{comp\_NCM\_i}$, however, remains the same in the cooperative case as is presented in (13). The complete data-loss of the $i^{\rm th}$ CU in the proposed CRN for the non-cooperative ($k_{comp\_NCM\_i}$) is demonstrated by Algorithm 1 (see Fig. 2), where three scenarios are discussed as follows. (1) $\rho = 0$, signifies that the PU will not emerge during the data transmission period and results in zero data-loss even when the proposed heterogeneous CRN has SM error. (2) $(0 < \rho < 1)$ && $(P_{\rm me} = 0)$, that indicates the reappearance of PU is confirmed and the SM is a perfect phenomenon. Here, the reappearance of PU is indentified within a particular packet transmission time and that packet data get lost. (3) $(0 < \rho < 1)$ && $(P_{\rm me} = 0)$ is a practical condition. The data-loss in this case due to SM imperfections and without considering the effects of ρ relies on $P_{\rm me}$ is presented by (10) and (11). Furthermore, the complete data-loss is the number of packets lost due to $P_{\rm me}$ in addition to the single data packet, as that single data packet has lost even though the $P_{\rm me}$ is null. However, with the consideration of the effect of ρ, the total data-loss relies on both the $P_{\rm me}$ and ρ, which is computed using (12). In the similar way, the data-loss relies on the $Q_{\rm me}$ and ρ for the cooperative SM that is presented by (13).

The CU is unable to perceive the reappearance of PU swiftly due to the imperfect SM and continue the data transmission, even after the 'reappearance of PU' that causes the 'interference-at-PU' receiver. This interference will occur with the PU transmission when the PU reappears and continues until the detection of its reappearance. Since the 'detection of reappearance of PU during data-transmission period' relies on the $P_{\rm me}$ and $Q_{\rm me}$ for non-cooperative and cooperative SM, respectively, therefore the interference at the PU is also relies on the $P_{\rm me}$ and $Q_{\rm me}$.

In the case of non-cooperative SM, the number of packets lost after the reappearance of PU depends on the P_{me_i} for the $i^{\rm th}$ CU. The starting time ($I_{\rm s}$) and ending time ($I_{\rm E}$) of the interference-at-PU relies on the traffic intensity (ρ) of PU and on the P_{me_i} and $Q_{\rm me}$ in the case of cooperative and non-cooperative SM, respectively, that are evaluated as follows:

$$I_{\rm s} = \{(1 - \rho) \times (T - (\tau))\} + \{(\tau)\} \quad (14)$$

Input (No, P_{me}, ρ)
Output ($k_{avg}, k_{an}, k_{TAEPU}, k_{comp}$)

BEGIN

Step-1 ***Variable declaration***

No : "Total number of packets in the data transmission phase";
k : "Number of packets lost due to spectrum monitoring error";
P_{me_i} : "Probability of SM error of the i^{th} CU";
k_{avg} : "Average number of packets lost due to SM error";
ρ : "Traffic intensity of PU";
k_{an} : "Average number of packets lost in the network without considering the effect of traffic intensity";
k_{TAEPU} : "Total number of packets to be transmitted after the emergence of PU"
k_{comp} : "Complete data-loss in the proposed CRN."

Step-2 ***Computation of probability of k number of packet lost among No***

$$P_{NCM\_i}\left(\frac{k}{No}\right) \leftarrow {}^{No}_{k}Comb.\,(P_{me\_i})^{k}(1-P_{me\_i})^{No-k};$$

Step-3 ***Computation of average number of packets lost due to monitoring error and of k_{an}***

Let $k_{NCM\_avg\_i} \leftarrow 0$;
for $k \leftarrow 1{:}No$
$k_{NCM\_avg\_i} \leftarrow \left(k_{NCM\_avg\_i} + k.\,P_{NCM\_i}\left(\frac{k}{No}\right)\right);$
end
$k_{an\_NCM\_i} = 1 + k_{NCM\_avg\_i};$

Step-4 ***Computation of the total number of packets to be transmitted after the emergence of PU***

$$k_{TAEPU} = (1-\rho) \times No;$$

Step-4 ***Complete Data-loss in the HTCRN***

If {$(\rho \leftarrow 0)$&& ($P_{me\_i} \leftarrow$ any value) } **then**
$k_{comp\_i} \leftarrow 0$ packet ;
elseif{$(0 < \rho \le 1)$&& ($P_{me\_i} \leftarrow 0$) } **then**
$k_{comp\_i} \leftarrow 1$ packet ;
elseif{$(0 < \rho \le 1)$&& ($0 < P_{me\_i} \le 1$)} **then**
if ($k_{TAEPU} \ge k_{an\_NCM\_i}$) **then**
$k_{comp\_i} \leftarrow k_{an\_NCM\_i};$
else **then**
$k_{comp\_i} \leftarrow k_{TAEPU};$
end
end
end
end
END

Fig. 2 *Algorithm 1: Computation of data-loss in the heterogeneous CRN for i^{th} CU in the non-cooperative SM*

$$I_{E\_NCM\_i} = I_{\rm s} + \left(k_{comp\_NCM\_i} \times PT\right) \tag{15}$$

$$I_{E\_CM} = I_{\rm s} + \left(k_{comp\_CM} \times PT\right) \tag{16}$$

where PT denotes the packet-duration and defined as $PT = (T-\tau)/No$. Now, the several performance metrics need to evaluate via preceding study of the data-loss in Algorithm 1 (Fig. 2). Further, the performance metrics investigated are the achieved throughput, data-loss, IE, and EE that have been evaluated as follows.

4.1 Calculation of throughput and data-loss

The throughput of CU achieved without collision is defined as the achieved throughput (RA), while the throughput attained during the collision is assumed as data-loss of the CRN. In the proposed heterogeneous CRN, the achieved throughput will be same for all the CUs since the time of collision free data-transmission ($I_{\rm s} - \tau$) remains the same. Therefore, the achieved throughput of the proposed HCRN with N number of CUs is evaluated as follows:

$$RA = N \times ((I_{\rm s} - \tau)/T) \times \log_2\left(1 + \frac{P_1 h_{ss}}{N_{\rm CU}}\right) \tag{17}$$

In the case of the non-cooperative SM, $k_{comp\_NCM\_i}$ a number of packets lost that depends upon the $P_{\rm me}$ which results in the total data loss time equal to $k_{\rm comp} \times PT$ for the $i^{\rm th}$ CU. Therefore, the average data-loss in the complete CRN is the sum of data-loss of N number of CUs is evaluated as follows:

$$DL_{\rm NCM} = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{(k_{{\rm comp}_{{\rm NCM}_i}} \times PT)}{T}\right) \times \log_2\left(1 + \frac{P_1 h_{ss}}{N_{\rm CU}}\right) \tag{18}$$

In a similar way, the data-loss ($DL_{\rm CM}$) for the cooperative SM is as follows:

$$DL_{\rm CM} = \frac{N}{N} \times \left(\frac{(k_{{\rm comp}_{\rm CM}} \times PT)}{T}\right) \times \log_2\left(1 + \frac{P_1 h_{ss}}{N_{\rm CU}}\right) \tag{19}$$

4.2 Calculation of IE

The IE [33] came into the picture and plays a vital role when the CU interferes with PU that is defined as the 'number of bits transmitted per unit of energy imposed on the PU'. In the projected system model, it is the ratio of the achieved throughput to the power received at the PU receiver if the true state of PUs is active and units is bits/joule/Hz. Further, the average power reached the PU receiver due to the cognitive communication is assumed as the interference at the PU (IF) that is signified as $IF_{\rm NCM}$ and $IF_{\rm CM}$, for non-cooperative and cooperative SM, which are evaluated as follows:

$$IF_{\rm NCM} = \frac{1}{N}\sum_{i=1}^{N}\left(\left(\frac{k_{{\rm comp}_{{\rm NCM}_i}} \times PT}{T}\right) \times P_1 \times h_{sp}\right) \tag{20}$$

$$IF_{\rm CM} = \frac{N}{N}\left(\left(\frac{k_{{\rm comp}_{\rm CM}} \times PT}{T}\right) \times P_1 \times h_{sp}\right) \tag{21}$$

Moreover, the IE in case of the non-cooperative and cooperative SM is evaluated as follows:

$$IE_{\rm NCM} = \frac{RA}{IF_{\rm NCM}} \tag{22}$$

$$IE_{\rm CM} = \frac{RA}{IF_{\rm CM}} \tag{23}$$

4.3 Calculation of EE

The EE is very prominent and required nature for the next generation communication systems such as wireless sensor networks, Internet-of-Things and so on. Therefore, it is worth to examine the effect of non-cooperative and cooperative SM on the EE of the projected heterogeneous CRN. The EE [34, 35] is defined as the ratio of achieved throughput to the power consumed by the system and its unit is bits/joule/Hz. The time of data transmission with power P_1 is ($I_{E_{NCM\_i}} - \tau$) for the $i^{\rm th}$ CU and ($I_{E_{\rm CM}} - \tau$) for all the CUs in the non-cooperative and cooperative SM, respectively. Therefore, the average power consumption in the non-cooperative and cooperative SM is defined as follows:

$$PC_{\rm NCM} = \frac{1}{N}\sum_{i=1}^{N}\left(\left(\frac{(I_{E_{\rm NCM_i}} - \tau)}{T} \times P_1\right) + P_{si} + P_{Pi}\right) \tag{24}$$

$$PC_{\rm CM} = \frac{N}{N}\left(\left(\frac{(I_{E_{\rm CM}} - \tau)}{T} \times P_1\right) + P_s + P_P\right) \tag{25}$$

where P_{Pi} and P_{si} are the powers required for the spectrum prediction and sensing techniques in the $i^{\rm th}$ CU, however,

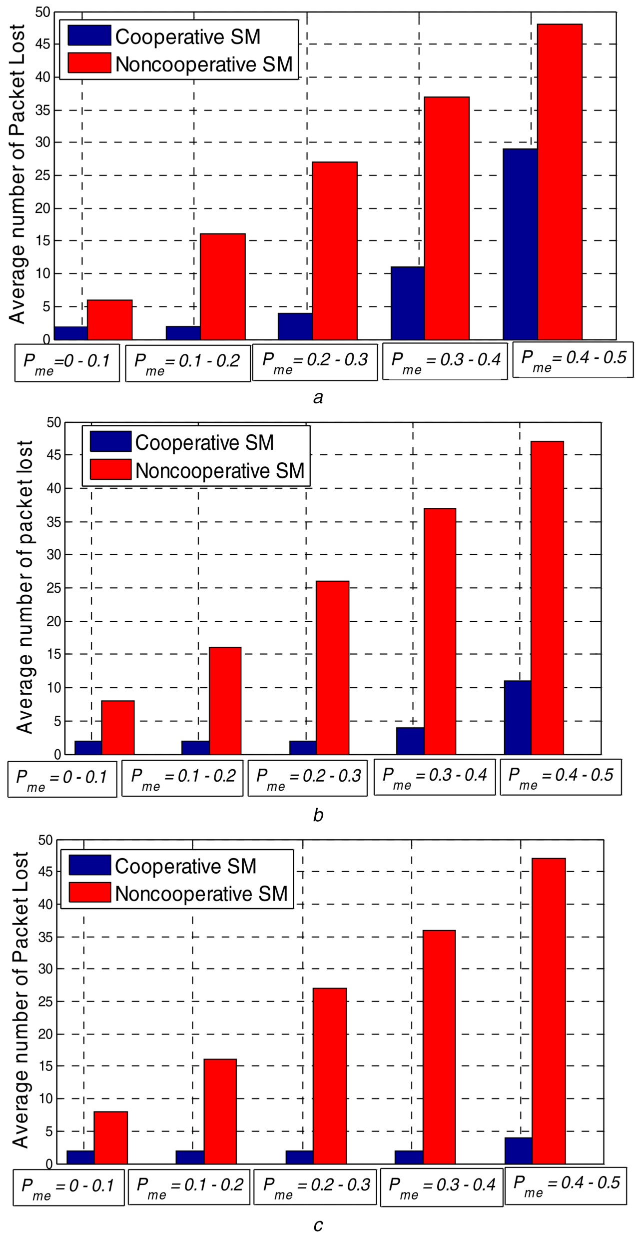

Fig. 3 *Average number of packets lost for*
(a) *$M = 6$*, ***(b)*** *$M = 7$* and ***(c)*** *$M = 8$*

$\forall i: P_{Pi} = P_P$ and $\forall i: P_{si} = P_s$. Therefore, the *EE* for the non-cooperative and cooperative SM case is evaluated as follows:

$$\mathrm{EE_{NCM}} = \frac{RA}{PC_{\mathrm{NCM}}} \tag{26}$$

$$\mathrm{EE_{CM}} = \frac{RA}{PC_{\mathrm{CM}}} \tag{27}$$

5 Results and discussion

In this section, we have illustrated the numerically simulated results for the data-loss, IE and EE of the projected cooperative SM over the heterogeneous CRNs environment [7]. Further, we have compared these results with that of the non-cooperative SM. As reported in [36], the IEEE 802.22 is the first wireless standard used for the 'wireless regional area network' (WRAN) with cognitive radio. Therefore, the simulation parameters for the projected heterogeneous CRN system model are chosen from WRAN standard which are tabulated in Table 1. The complete proposed heterogeneous CRN environment is framed by using MATLAB 2010a [28]. The alteration of data-loss (in the form of packets) for cooperative and non-cooperative SM in the proposed heterogeneous CRN for different values of M in the MOON rule is presented in Fig. 3 when the traffic intensity of CU is 0.5. The cooperative SM outperforms the non-cooperative SM with reference to the data-loss. In addition to this, it is perceived that the 'data-loss' for non-cooperative SM improves with the probability of errors P_{me}. However, it remains constant for the cooperative SM with reference to the certain value of P_{me} till the Q_{me} attained the value which causes packet loss greater than unity. Moreover, there is an improvement in the data-loss in the cooperative case with increase in the value of M as shown in Fig. 3. The variations of average IE in cooperative and non-cooperative heterogeneous CRN for various values of M are shown in Figs. 4–6. The IE is significantly more in the cooperative SM when compared to that of the non-cooperative in all the cases ($M = 6$, $M = 7$, and $M = 8$). The IE decreases with an increase in the value of the range of the P_{me} as well as ρ as depicted in Figs. 4–6. In addition to this, there is a significant improvement in the IE for the cooperative SM for large values of probability of SM error when we increase the value of M as shown in Figs. 4–6. In Fig. 4, for $M = 6$, $\rho = 0.5$, and $P_{\mathrm{me}} = 0.5$, the value of IE is 5.11 and that increases to ∼15.33 for $M = 7$ (Fig. 5) then attains the value ∼38.34 for $M = 8$ (Fig. 6). This reveals that for a large value of P_{me}, the cooperative SM with an optimal value of M has a significant role. The average EE in the cooperative and non-cooperative heterogeneous CRN for various values of M, P_{me} and ρ is depicted in Figs. 7–9, respectively. The cooperative SM outperforms when compared with the non-cooperative SM which is illustrated in Figs. 7–9. Moreover, there is a significant improvement in the EE for the cooperative SM for large values of P_{me} when M has sufficient value which can be analysed from Figs. 7–9. In Fig. 7, for $M = 6$, $P_{\mathrm{me}} = 0.5$, and $\rho = 0.5$, the value of EE is ∼0.33 which increases to 0.34 for $M = 7$ (Fig. 8) and 0.42 for $M = 8$ (Fig. 9). This signifies that for large value of P_{me}, the cooperative SM is an effective approach, however selection of M plays a key role.

Table 1 Considered simulation parameters in the proposed heterogeneous CRN

Parameter	Numerical value	Parameter	Numerical value
T	100 ms	No	100
N	10	P_1	6 W
τ	2.5 ms	N_{PPU}	0.4 W
P_P	0.2 W	P_S	0.2 W
h_{ss}	0.8	h_{sp}	0.2
N_{PCU}	0.4 W	—	—

6 Conclusion

This paper has exploited the PBD for cooperative SM in the heterogeneous CRN environments and has investigated its effect over the data-loss, achieved throughput, IE, and EE. The closed-form expression of the PBD is derived to yield the discrete probability distributions of M number of CUs are in errors out of N number of CUs when all the CUs have different values of probability of monitoring errors P_{me}. Moreover, the cooperative SM outperforms the non-cooperative SM in terms the conferred performance metrics. Thus, it is apparent that the selection of the MOON rule is a very prominent and interesting to improve the performance of cooperation. However, the optimisation with context to the selection of numerical values of M and N will be presented in the further communication.

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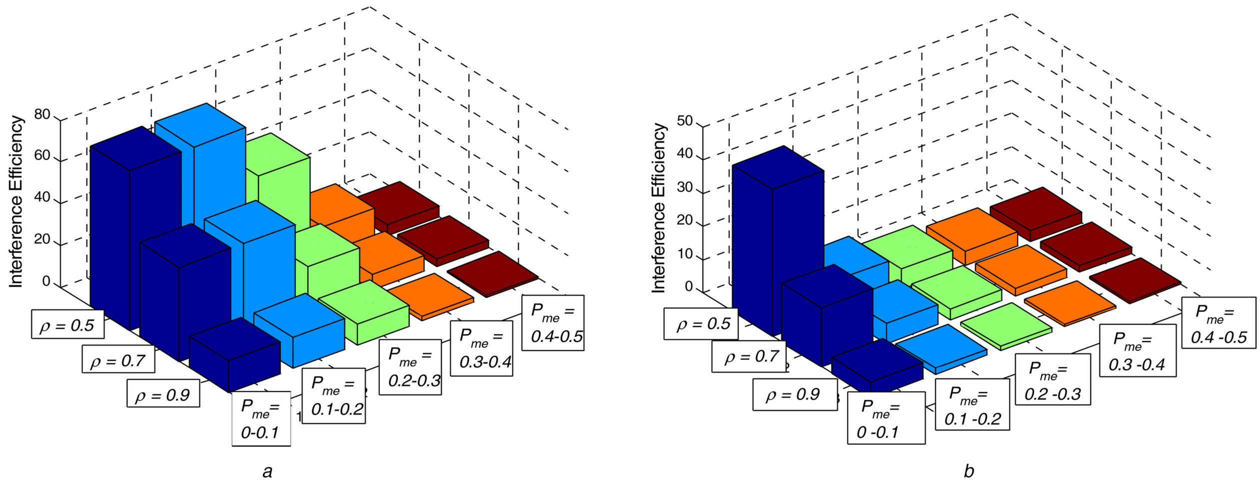

Fig. 4 *IE for M = 6 in*
(a) Cooperative SM and ***(b)*** Non-cooperative SM

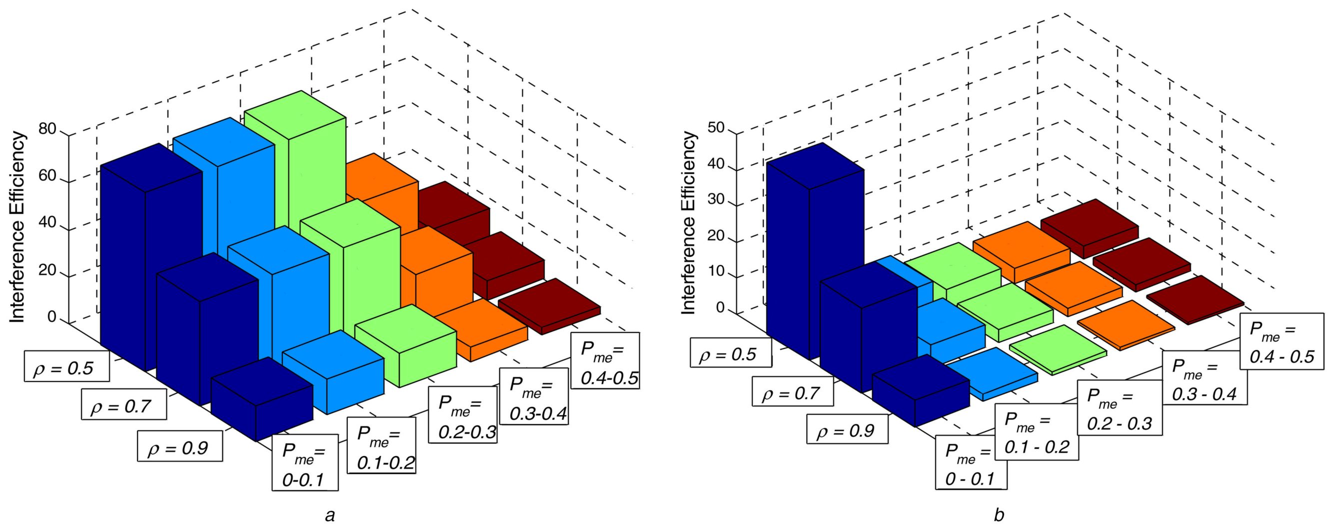

Fig. 5 *IE for M = 7 in*
(a) Cooperative SM and ***(b)*** Non-cooperative SM

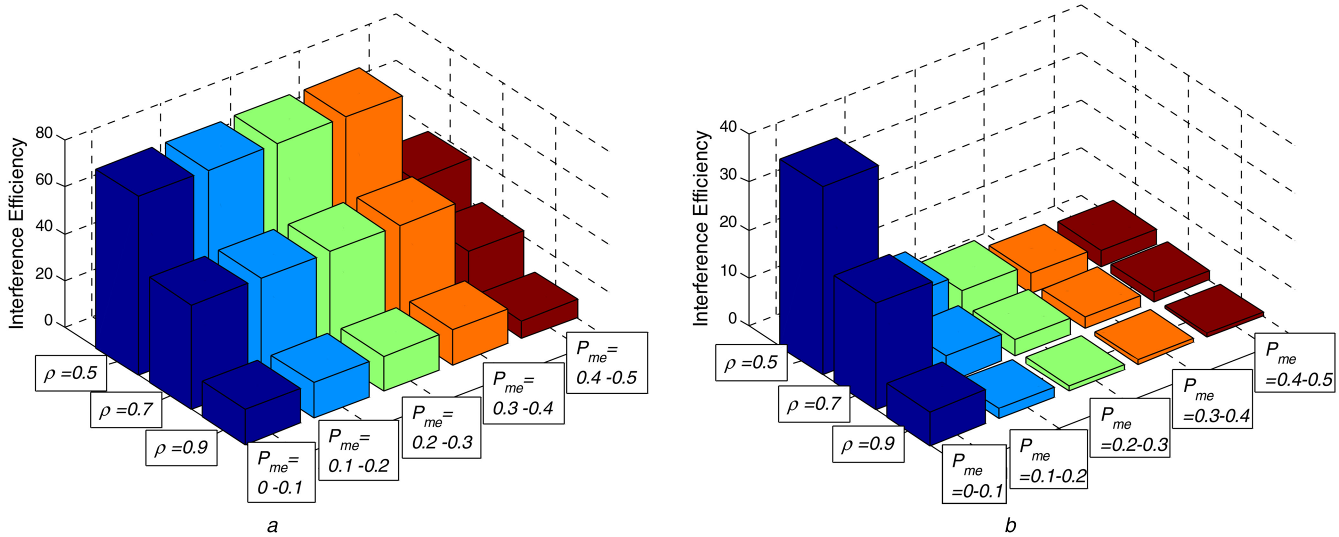

Fig. 6 *IE for M = 8 in*
(a) Cooperative SM and ***(b)*** Non-cooperative SM

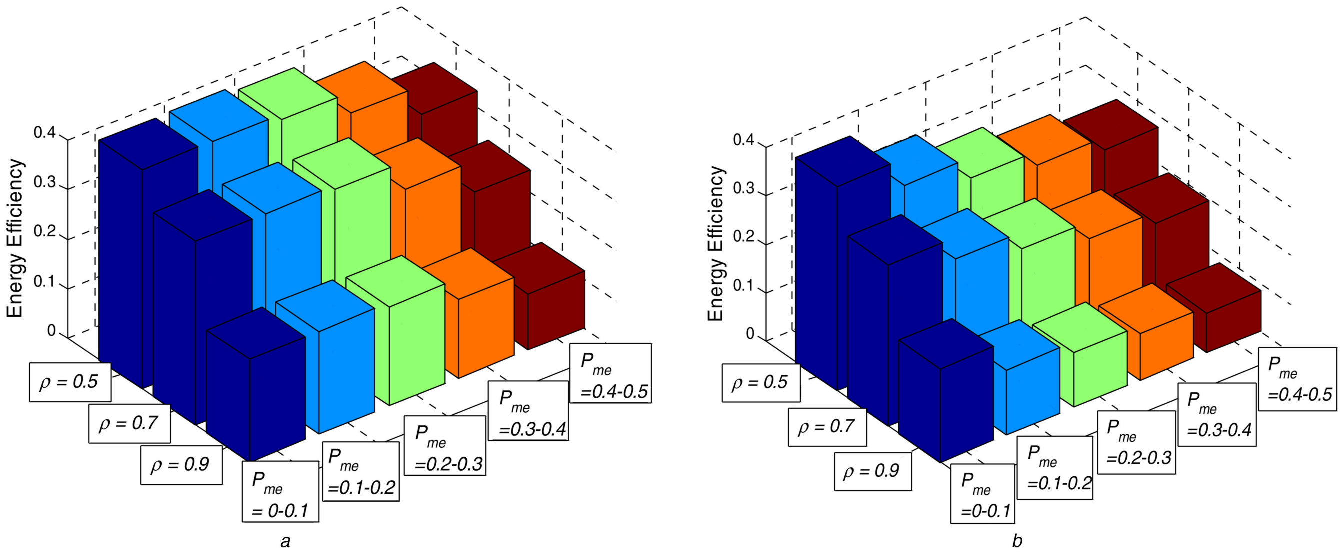

Fig. 7 *EE for M = 6 in*
(a) Cooperative SM and ***(b)*** Non-cooperative SM

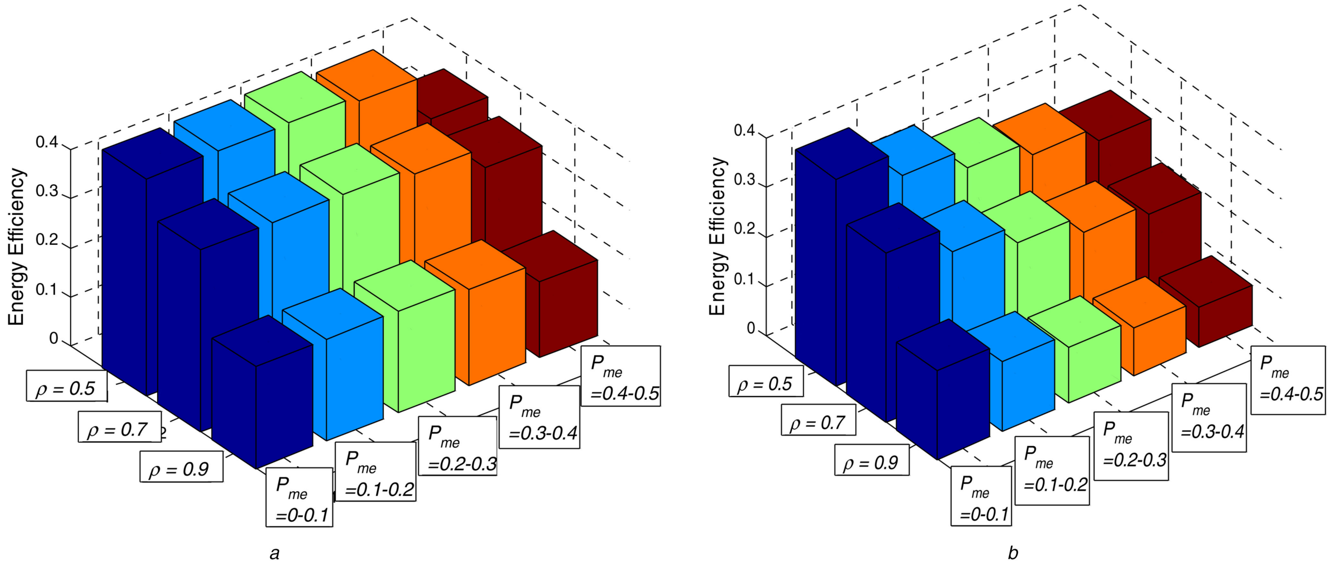

Fig. 8 *EE for M = 7 in*
(a) Cooperative SM and ***(b)*** Non-cooperative SM

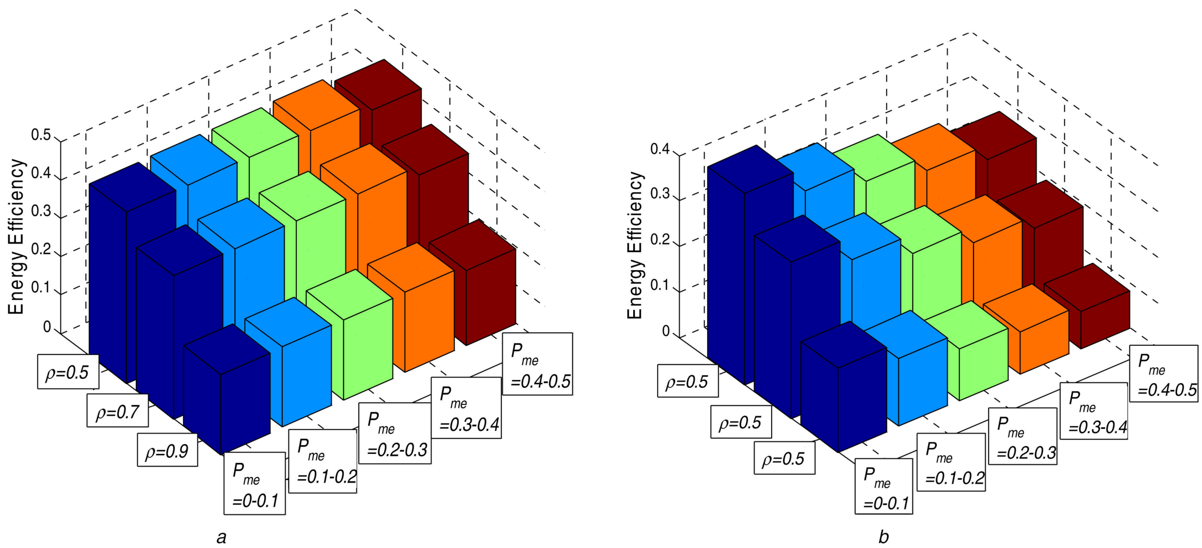

Fig. 9 *EE for M = 8 in*
(a) Cooperative SM and ***(b)*** Non-cooperative SM

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