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Performance analysis of cooperative spectrum monitoring in cognitive radio network

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Abstract

The imperfect spectrum monitoring (SM) is a major obstacle to detect the emergence of primary user (PU) quickly during the cognitive users' (CUs') data transmission which results data-loss and introduces the interference at PU. The cooperation in CUs for SM is an effective solution to improve its performance. Therefore, in this paper, a scenario, where CUs can cooperate with each other for SM is presented and have analyzed the effect of cooperation on various performance metrics namely, the data-loss, interference efficiency, and energy efficiency. An algorithm is illustrated for the computation of data-loss under various conditions of the traffic intensity of PU and probability of SM error. Moreover, the closed-form expressions of these metrics are derived for the cooperative and non-cooperative SM. Further, the simulation results are presented for various scenarios of traffic intensity, probability of SM error and channel gain between the CUs' transmitter to PU receiver. Furthermore, the Monte-Carlo simulation results are exploited to consider the random nature of the PUs' traffic intensity as well as to support the numerically simulated results.

Keywords Cognitive radio · Data loss · Energy efficiency · Interference efficiency · Throughput · Spectrum monitoring

1 Introduction

The cognitive radio (CR) is a prominent technology relying on the dynamic spectrum access (DSA) mechanism in order to overcome the spectrum scarcity issue which is originated due to static spectrum allocation policy [1–5]. For DSA, the unlicensed/cognitive user (CU) is allowed to access the spectrum of licensed/primary user (PU) in such a way that the PU communication remains impervious. The DSA mechanism comprises the spectrum sensing, spectrum analysis and decision, spectrum sharing/accessing and spectrum mobility [1]. The CU senses its environment in order to perceive the idle channels and then analyze these channels. Further, the most suitable channel is selected according to the CUs' application and share this channels' information with all other CUs in the network so that they avoid accessing the same channel. Furthermore, the communication is established on the same channel using appropriate spectrum accessing technique [6]. In addition to this, it is possible that the PU resume its communication during CUs' data transmission period and at that time the CU needs to stop the communication on that channel. However, in order to continue the CUs' unfinished transmission, the CU switches its communication on other suitable idle channel and this process is known as spectrum handoff/mobility [7, 8]. For the spectrum mobility, there is a need to detect the emergence of PU simultaneous to the data transmission by CU which is a challenging task however the spectrum monitoring (SM) allows this functionality for CU. In the SM, the CU exploits the statistics of

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the received signal such as receiver error count (REC), energy level etc. to detect the emergence of PU [9].

The SM is proposed by Boyd et al. [9]. in 2012 and further explored by various researchers [10–13]. The key idea for SM is the change in the receiver statistics i.e. error count. The CU receiver receives the data (in the form of packets) with tolerable number of error in the packet which is known as REC. The emergence of PU creates interference at the CU receiver which increases the number of errors and that change in REC is used to detect the emergence of PU. Similarly, the energy level also increases on the emergence of PU which is also used to detect the same. In [10], the authors have investigated the problem of SM over the Rayleigh fading channels and have explored the concept of multiple antennas on the CU in order to reduce the effect of multipath fading using the diversity combining techniques. It is reported that the proposed technique outperforms the only REC technique. In [11], the authors have proposed an energy ratio SM algorithm for the orthogonal frequency division multiplexing (OFDM) based cognitive radio network (CRN) and reported that the proposed approach outperforms the receiver statistics method in terms of detection delay however, the complexity is twice than that of the energy detector. Orooji et al. [12] have proposed a decision statistic for SM using REC and have analyzed the detection and false-alarm probabilities. Furthermore, the authors have exploited an optimization problem to maximize the channel utilization using constraint on the detection delay. Recently, the authors in [13] have analyzed the effect of SM on the "energy and data loss of CU" and "interference at the PU due to CU transmission". It is observed that the introduction of SM in the high-traffic CRN (HTCRN) improves "energy- and data-loss of the CU" as well as the "interference at the PU due to CU transmission" as compared to that of the conventional (without SM system) HTCRNs. In [8], the authors have exploited the SM and prediction techniques simultaneously, to improve the performance of spectrum mobility/handoff. The AND and OR fusion rules are used to combine the results of both techniques. Various SM techniques discussed in [9–13] are considered to be perfect which means these are able to detect the emergence of PU quickly and correctly (spectrum monitoring error is zero). However, the consideration of SM as a perfect phenomenon is an impractical scenario since the SM relies on the received signal which is affected by the channel having random nature. Therefore, in [14], the authors have introduced the concept of imperfect SM and studied its effects on data-loss, power wastage, interference efficiency and energy efficiency in CRNs [14]. This study reveals that the imperfection in SM degrades the performance of CRN. To the best-of-authors' knowledge, the prominent ways to overcome the effects of imperfection in SM are unexplored. A potential way to manage the imperfections is cooperation among CUs. Therefore, to improve the performance of CRN with imperfect SM, we have exploited the cooperation among CUs in this paper. The contribution in this paper is summarized as follows.

- We have proposed a potential and feasible framework of cooperative SM (CM) for CRN which is analyzed for different scenarios of the traffic intensity and spectrum monitoring error.
- The closed-form expressions of the achieved throughput, data-loss, interference efficiency and energy efficiency are derived.
- The Monte-Carlo simulations are exploited in order to consider the effect of random events i.e. traffic intensity of PU.

This paper is structured as follows. In the Sect. 2, the system model of the proposed framework is described. The Sect. 3 comprises performance analysis of the proposed system model and simulation results with their analysis are presented in Sect. 4. Finally, Sect. 5 concludes the work with future perspectives.

2 System model

In the proposed system model, a PU network is considered in which the transceiver pair communicates using a channel having bandwidth B as shown in Fig. 1. The CRN comprises N number of CU pair which are allowed to exploit the spectrum of PU in such a way that all the CUs get equal bandwidth and thus the bandwidth allocated to each CU is B/N. The proposed model comprises high-traffic environment having traffic intensity of PU greater than 0.5. Therefore the CUs perform spectrum prediction in the previous time frame during the data transmission in order to select the channel with highest idle probability for spectrum sensing in the current frame. This result the improvement in the sensing process since it saves the sensing time and energy spent on the sensing of active channels [15–18]. Here, the time allocated for spectrum prediction in the time frame (T) is null however, the fix power (P_P) is required. The spectrum prediction is well explored in literature [15–18]. Therefore, in this paper, the key intent is on cooperative SM.

In the current frame, the CU performs spectrum sensing for time τ and starts data transmission for time $(T - \tau)$ with power P_1 on the idle sensed channel. In the data transmission period, the process of SM is performed, simultaneous to the data transmission in order to know the emergence of PU. The SM emerges as a significant phenomenon only when the PU resumes its communication during the data transmission, therefore, in order to consider this event, we have assumed that the probability of PUs'

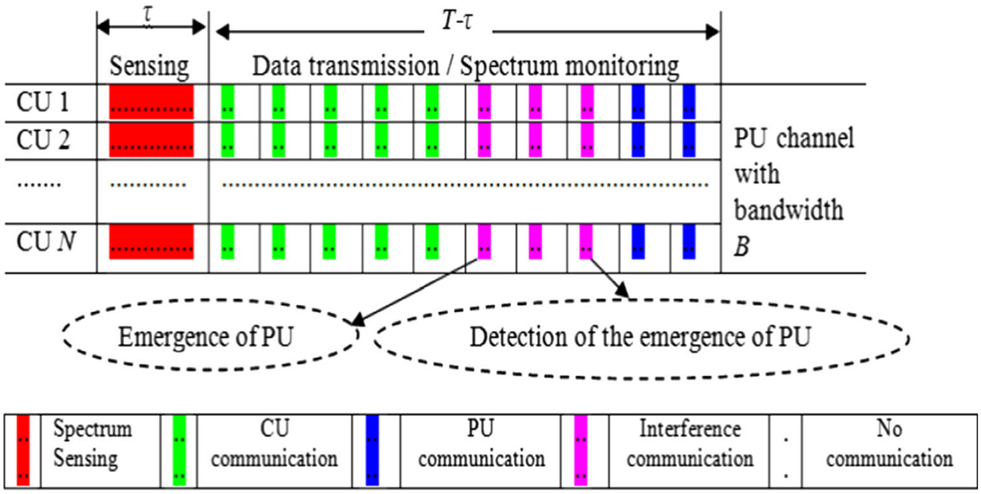

Fig. 1 The scenario of the proposed cooperative SM in cognitive radio networks

emergence in the data transmission period is provided by the traffic intensity of PU (ρ). The traffic intensity of PU is assumed to be a binary stochastic hypothesis, in which 0 and 1 represents the idle and active channels, respectively [19]. Moreover, the average arrival and channel holding time of PU is modeled as Poisson distribution (parameter λ) and Binomial distribution (parameter μ), respectively [20]. Thus the probability of channel to be active/busy ($P(H_1)$) is defined as: $P(H_1) = \mu/\lambda$ however, the probability of the channel being idle ($P(H_0)$) is defined as: $P(H_0) = (\lambda - \mu)/\lambda$. In the considered model, the probability of the channel to be idle $P(H_1)$ is assumed as the traffic intensity of the PU channel (ρ) which means $\rho = P(H_1) = \mu/\lambda$. The large value of traffic intensity means the PU emerges in the initial part of data transmission period however the low value signifies the emergence of PU in the later part. The number of packet transmitted during the data transmission period is N_0. In addition to this, every CU performs spectrum sensing during sensing period individually and cooperate with each other to formulate the final decision on the state of channel i.e. either idle or active. If the final decision is active, all the CUs start data transmission in the form of packets. For cooperation, the CUs need to share the data with the fusion center and one effective way of data sharing for moving users is presented in [21]. There is prospect that the PU resumes its communication during the data transmission then at this time, it is the responsibility of the CU to detect the emergence of PU and stops the communication. The detection of emergence of PU is potential phenomenon which is achieved by applying SM. In the proposed model, the SM is assumed as the imperfect phenomenon which is a feasible scenario and imperfections in this process are presented by the probability of SM error (P_{me}) The imperfection in SM means the emergence of PU is not detected immediately, however detected after certain detection delay. This imperfection causes due to channel uncertainties and/or the hardware system errors. The higher value of P_{me} indicates that there is more delay in the detection of PU. The delay in detection of the emergence of PU results the continuation of CU communication and causes the data collision/loss as well as introduces the significant interference at PU. The interference power at PU depends on the channel gain between CU transmitter and PU receiver $\left(h_{sp}\right)$ which is also known as interference link. Therefore, in order to diminish the effect of imperfections, the cooperation between CUs play an important role. The CUs decide the state of emergence of PU either 0 or 1and reports to the controlling unit (CU) where the final decision is achieved by combining all the reported state using l out of N rule, which is a hard decision combining rule used to fuse the data. If the final decision confirms the emergence of PU, all the CUs stop their communication otherwise continues. Further, the cooperation in the SM improves the probability of SM error. When the data are fused using l out of N rule (hard fusion rule), the probability of SM error (Q_{me}) is defined as [22]:

$$Q_{me} = \sum_{j=l}^{N} ({}^{N}_{j}C)(P_{me})^{j}(1-P_{me})^{N-j} \qquad (1)$$

where C signifies the mathematical combination. Moreover, N_{PPU},N_{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, channel gain from CU transmitter to PU receiver, respectively.

3 Performance analysis of proposed CRN

In this section, the effect of imperfect SM on the data-loss of proposed CRN is illustrated. The data-loss occurs in the CRN when the PU reappears during the data transmission of CU and the probability of reappearance is yielded by the traffic intensity of PU. The perfect SM is an impractical scenario in which the reappearance of PU is detected very quickly which means within a data packet time[1] (loss of that single packet). On the other hand, the imperfect SM is a feasible scenario in which the data-loss is the function of the probability of SM error (P_{me}). In the considered CRN, the fix number of packets gets lost among the total number of packets, which depends on the SM error. In the considered CRN, the computation of number of packets lost among total number of packets follows the Binomial distribution [20]. The Binomial distribution yields the discrete probability distribution, $P_p(x/X)$, to achieve exactly x successes out of X Bernoulli trials (where the results of each Bernoulli trial is true with probability p and false with probability $(1-p)$). Similarly, in the proposed CRN, the discrete probability distribution $P(k/No)$ of obtaining exactly k number of packets lost out of No (where the data-loss result is true with probability P_{me} and false with probability $(1-P_{me})$.Thus, the probability of data-loss due to probability of SM error in the non-cooperative SM[2,3] (NCM) is defined as:

$$P_{NCM}\left(\frac{k}{No}\right) = {}^{No}_{\ k}C \cdot (P_{me})^k (1-P_{me})^{No-k} \tag{2}$$

Similarly, the probability of data-loss due to probability of SM error in the cooperative monitoring (CM) is presented as:

$$P_{CM}\left(\frac{k}{No}\right) = {}^{No}_{\ k}C \cdot (Q_{me})^k (1-Q_{me})^{No-k} \tag{3}$$

Further, the average number of data packets lost (k_{avg}) (see footnotes 2, 3) for the cooperative and non-cooperative monitoring are evaluated, respectively by computing the expectation of variables as follows:

$$k_{NCM\_avg} = \sum_{k=1}^{No} k \cdot P_{NCM}\left(\frac{k}{No}\right) \tag{4}$$

$$k_{CM\_avg} = \sum_{k=1}^{No} k \cdot P_{CM}\left(\frac{k}{No}\right) \tag{5}$$

There is loss of one single packet even for $P_{me} = 0$. Therefore, to compute the total number of packet lost in the CRN (k_{an}) for both the cases, one packet need to add to k_{avg} which is presented as: $k_{an\_NCM} = \left(1 + k_{avg\_NCM}\right)$ and $k_{an\_CM} = \left(1 + k_{avg\_CM}\right)$.

In the proposed CRN, the communication is established using frame structures which means after fix time interval i.e. the frame time (T), the CU periodically repeats the process of spectrum sensing and data transmission. Therefore, it is possible that the CU switches from data transmission mode to spectrum sensing mode of the next frame, immediately after the emergence of PU because of ending of the data transmission interval. In this case, the number of packets lost relies on the time of emergence of PU which is the function of traffic intensity (ρ) in the proposed CRN. Thus, the complete data loss in the proposed CRN (k_{comp}) is not only the function of the SM error but also of the traffic intensity of PU.

Therefore, to find the complete data-loss in the proposed CRN, there is need to compute the total number of packets to be transmitted after the emergence of PU (k_{TAEPU}) which relies on the traffic intensity and computed as:$k_{TAEPU} = (1-\rho) \times No$. The complete data loss in the non-cooperative (k_{comp_NCM}) and cooperative (k_{comp_CM}) CRN is:

$$k_{comp\_NCM} = \left\{ \begin{array}{ll} k_{an\_NCM} & if\ k_{TAEPU} \geq k_{an\_NCM} \\ k_{TAEPU} & if\ k_{TAEPU} < k_{an\_NCM} \end{array} \right\} \tag{6}$$

$$k_{comp\_CM} = \left\{ \begin{array}{ll} k_{an\_CM} & if\ k_{TAEPU} \geq k_{an\_CM} \\ k_{TAEPU} & if\ k_{TAEPU} < k_{an\_CM} \end{array} \right\} \tag{7}$$

If the number of packets to be transmitted after the emergence of PU is greater than the total number of packets lost due to monitoring error for the non-cooperative and cooperative case, then the complete data loss in the proposed CRN is k_{an_NCM} and k_{an_CM}, respectively, otherwise k_{TAEPU}. The complete data-loss of the proposed CRN for the non-cooperative is illustrated in Algorithm 1, where three *scenarios are discussed as follows*. (1) $\rho = 0$, which means the PU will not appear in the data transmission phase which results no data loss even if the proposed system has SM error which means, in this special case there is no significant role of the SM. (2) $(0 < \rho < 1)$ && $(P_{me} = 0)$, which means the emergence of PU is confirmed and the monitoring system is perfect. In this case, the emergence of PU is detected within a packet transmission time and particular that packet data get lost. 3) $(0 < \rho < 1)$ && $(P_{me} = 0)$, which is a practical state of affairs. If we avoid the effect of ρ, the data loss in this case due to monitoring error is the function of P_{me} as derived in (2). However, the total data-loss is the number of packets lost due to P_{me} plus one data packet, because the particular packet lost even when P_{me} is zero. On the other hand, on the consideration of the effect of ρ, the complete data loss in the proposed CRN becomes the function of both the P_{me} and ρ, which is calculated as given in (6). Similarly, in the cooperative case, the data-loss becomes the function of Q_{me} and ρ which is derived in (7).

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[1] Assumption: The perfect SM system is very quick and ideal, even though a particular packet is required to compute decision statistics.

[2] The subscript NCM represents the non-cooperative spectrum monitoring

[3] The subscript CM represents the cooperative spectrum monitoring.

Algorithm-1: Calculation of Data Loss in the HTCRN

```
Input ($No, P_{me}, \rho$)
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;
    $P_{me}$ :Probability of SM error;
    $k_{avg}$ : Average number of packets lost due to SM error;
    $\rho$ : 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
    $P\left(\frac{k}{No}\right) \leftarrow ({}^{No}_{k}C)(P_{me})^{k}(1-P_{me})^{No-k}$;
Step-3 Computation of average number of packets lost due to monitoring
error and of $k_{an}$
            Let $k_{avg} \leftarrow 0$ ;
            for $k \leftarrow 1{:}No$
              $k_{avg} \leftarrow \left(k_{avg} + k.P\left(\frac{k}{No}\right)\right)$;
            end
              $k_{an} = 1 + k_{avg}$;
Step-4 Computation of the total number of packets to be transmitted after
        the emergence of PU
              $k_{TAEPU} = (1-\rho) \times No$;
Step-5 Complete Data-loss in the HTCRN
If {($\rho \leftarrow 0$)&& ($P_{me} \leftarrow$ any value) }  then
    $k_{comp} \leftarrow 0$ packet ;
  elseif {($0 < \rho \leq 1$)&& ($P_{me} \leftarrow 0$) }  then
    $k_{comp} \leftarrow 1$ packet ;
  elseif {($0 < \rho \leq 1$)&& ($0 < P_{me} \leq 1$) }  then
    if ($k_{TAEPU} \geq k_{an}$)then
                $k_{comp} \leftarrow k_{an}$;
    else                              then
                $k_{comp} \leftarrow k_{TAEPU}$;
    end
  end
  end
end
END
```

Due to the imperfection in SM, the CU unable to detects the emergence of PU quickly, and continue the data transmission, even after the emergence of PU which results the interference at the PU receiver. The CU transmission starts interfering with the PU transmission when the PU emerges and continue this till the detection of emergence. As the detection of emergence of the PU during data transmission period is the function of P_{me} and Q_{me} for non-cooperative and cooperative case, respectively, therefore the interference at the PU is also the function of P_{me} and Q_{me}.

For the non-cooperative SM case, the number of packets lost after the emergence of PU, relies on the P_{me} and Q_{me}. The starting time (I_s) and ending time (I_E) of the interference at PU depends on the traffic intensity (ρ) of PU and on the P_{me} and Q_{me} for the cooperative and non-cooperative SM cases, respectively, which are computed as:

$$I_s = \{(1-\rho) \times (T - (T_s))\} + \{(T_s)\} \tag{8}$$

$$I_{E\_NCM} = I_s + \left(k_{comp\_NCM} \cdot PT\right) \tag{9}$$

$$I_{E\_CM} = I_s + \left(k_{comp\_CM} \cdot PT\right) \tag{10}$$

where PT is the packet duration and defined as:$PT = (T - T_s)/No$. Now, the various performance metrics have to compute by using the above analysis of the data-loss in Algorithm 1. The performance metrics exploited further are the achieved throughput and data-loss, interference efficiency and energy efficiency which are computed as follows.

3.1 Computation of achieved throughput and data loss

The throughput obtained due to collision free data-transmission is defined as the achieved throughput (RA), whereas the throughput obtained during collision is considered as data-loss of the network. The achieved throughput of the proposed CRN is computed as:

$$RA = ((I_s - T_s)/T) \times log_2\left(1 + \frac{P_1 h_{ss}}{N_{PCU}}\right) \tag{11}$$

In the non-cooperative SM, k_{comp_NCM} number of packets lost which relies on the probability of the SM error due to which the total data loss time is: $k_{comp} \times PT$. Therefore, the data-loss in this case is calculated as:

$$DL_{NCM} = \left(\frac{(k_{comp\_NCM} \times PT)}{T}\right) \times log_2\left(1 + \frac{P_1 h_{ss}}{N_{PCU}}\right) \tag{12}$$

Similarly, in case of cooperative SM the data loss (DL_{CM}):

$$DL_{CM} = \left(\frac{(k_{comp\_CM} \times PT)}{T}\right) \times log_2\left(1 + \frac{P_1 h_{ss}}{N_{PCU}}\right) \tag{13}$$

3.2 Computation of the interference efficiency

The interference efficiency (IE) [23, 24] is a prominent performance metric if the CU introduces interference at the PU which is defined as the number of bits transmitted per unit of energy imposed on the PU. In the proposed CRN, it is ratio of the achieved throughput to the power received at PU receiver when the original state of PU is active and due to which the units are bits/joule/Hz. Now, the power received at PU receiver due to CU transmission is considered as the interference to the PU communication (IF) and for the non-cooperative and cooperative SM denoted as IF_{NCM} and IF_{CM}, respectively, which are computed as:

$$IF_{NCM} = \left(\frac{k_{comp\_NCM} \times PT}{T}\right) \times P_1 \times h_{sp} \tag{14}$$

$$IF_{CM} = \left(\frac{k_{comp\_CM} \times PT}{T}\right) \times P_1 \times h_{sp} \tag{15}$$

Further, the interference efficiency for the non-cooperative and cooperative SM case is computed as follows:

$$IE_{NCM} = \frac{RA}{IF_{NCM}} \tag{16}$$

$$IE_{CM} = \frac{RA}{IF_{CM}} \tag{17}$$

3.3 Computation of the energy efficiency

The energy efficient nature of CRN supports the green communication concept and liberates the customers from futile power consumption. Therefore, the effect of non-cooperative and cooperative SM on the energy efficiency of the proposed CRN is analyzed. The energy efficiency (*EE*) [25, 26] is defined as the ratio of achieved throughput to the power consumed by the system and its units are bits/joule/Hz. The power consumed for the non-cooperative and cooperative SM case is defined as:

$$PC_{NCM} = \left(\frac{(I_{E\_NCM} - T_s)}{T} \times P_1\right) + P_s + P_P \tag{18}$$

$$PC_{CM} = \left(\frac{(I_{E\_CM} - T_s)}{T} \times P_1\right) + P_s + P_P \tag{19}$$

where P_P and P_S are the powers required for the spectrum prediction and sensing techniques. Therefore the *EE* for the non-cooperative and cooperative SM case is computed as follows:

$$EE_{NCM} = \frac{RA}{PC_{NCM}} \tag{20}$$

$$EE_{CM} = \frac{RA}{PC_{CM}} \tag{21}$$

4 Results and discussion

This section presents the numerically simulated results of the data-loss, interference efficiency and energy efficiency for the proposed cooperative SM CRN model and have compared with the non-cooperative SM CRN. The IEEE 802.22 is the first wireless standard relies on cognitive radio [27] used to form the wireless regional area network (WRAN), therefore the simulation parameters selected in proposed CRN are inspired by WRAN standard and are presented in the Table 1. Moreover, in order to validate the proposed CRN, we have exploited the randomness in emergence of PU using traffic intensity of PU and the Monte-Carlo simulation for the 10,000 runs.

Table 1 The simulation parameters for the proposed HTCRN

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

The variations of data-loss (in the form of packets) for cooperative and non-cooperative SM are presented in Fig. 2. The cooperative SM outperforms the non-cooperative SM in terms of data-loss. Moreover, it is palpable that the data-loss for non-cooperative SM increases almost linearly however, in case of cooperative SM, it remains constant for certain value of P_{me} till the Q_{me} achieved the value which causes packet loss greater than one. The relation between the interference efficiency and probability of SM error for cooperative and non-cooperative SM with different traffic intensities is illustrated in Fig. 3. The interference efficiency is an improved metric in case of the cooperative monitoring as compared to that of the non-cooperative SM for all considered values of the traffic intensity. In addition to this, the non-cooperative SM depicts the exponential decay of interference efficiency with increase of probability of SM error, however, in case of cooperative monitoring, the interference efficiency follows the fix value till the Q_{me} causes data loss greater than one and then starts decaying. Moreover, the increase in ρ results the decrease in achieved throughput for certain value of P_{me} as well as Q_{me} and interference efficiency is the ratio of achieved throughput to the interference introduced at PU. Therefore, the interference efficiency is large for small values of ρ and reduces with its increment in both the cases of cooperative and non-cooperative SM.

The variations of interference efficiency with channel gain from CU transmitter to the PU receiver (h_{sp}) for various values of the traffic intensity is depicted in Fig. 4. The rate of change of interference efficiency is significantly large for small values of h_{sp} however it decays with increase in the h_{sp}. Moreover, the cooperative SM outperforms the non-cooperative SM in terms of interference efficiency. As the channel gain from CU transmitter to PU receiver increases for fix value of the channel gain form CU transmitter to CU receiver, the interference efficiency decays almost exponentially. The relation between the energy efficiency and probability of SM error for various values of the traffic intensity is presented in Fig. 5.

The energy efficiency is more in cooperative SM as compared to that of the non-cooperative SM however it

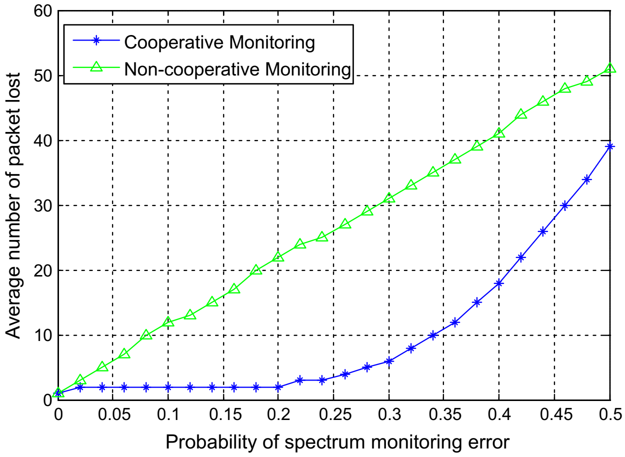

Fig. 2 The variations of data-loss with probability of SM error

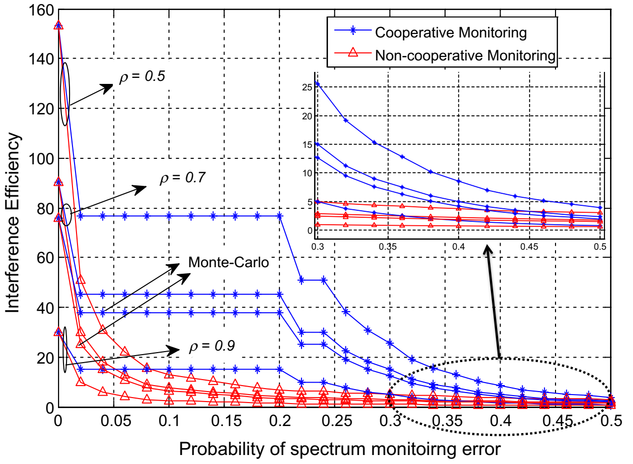

Fig. 3 The relation between interference efficiency (bits/joule/Hz) and probability of SM error

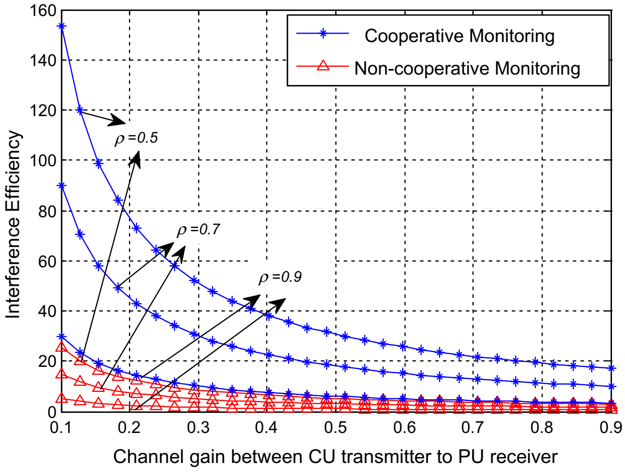

Fig. 4 The variations of interference efficiency (bits/joule/Hz) and channel gain from CU transmitter to PU receiver ($h_{ss} = 0.8$)

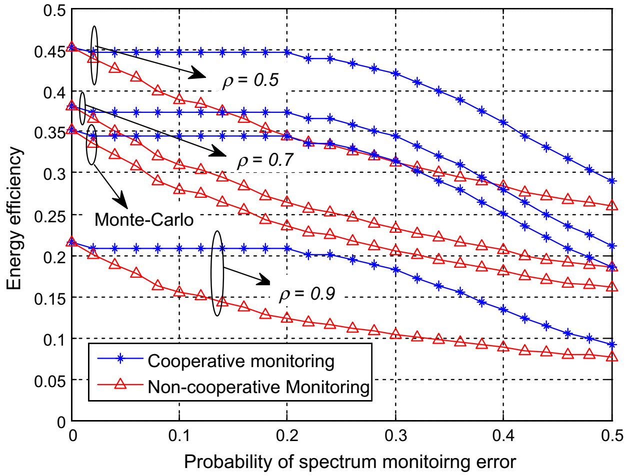

Fig. 5 The relation between energy efficiency (bits/joule/Hz) and probability of SM error

decreases with increase in the probability of SM error for both the cases i.e. non-cooperative and cooperative spectrum monitoring. In addition to this, the energy efficiency shows inversely proportional relation with the traffic intensity which means energy efficiency decreases with increase of the traffic intensity.

5 Conclusion

In this paper, we have exploited the cooperative SM in the CRN and have analyzed the data-loss, achieved throughput, interference efficiency as well as energy efficiency. It is concluded that the cooperative SM outperforms the non-cooperative SM in terms of the aforementioned performance metrics. Further, the Monte-Carlo simulations have been exploited to validate the numerically simulated results. This paper explores the homogeneous CRN in which all the CUs have same SM error, however the case of CUs with different SM error is more feasible which will be explored in the future communication.

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References

1. Haykin, S. (2005). Cognitive radio: Brain-empowered wireless communications. *IEEE Journal on Selected Areas in Communication, 23*(2), 201–220.
2. Mitola, J., & Maguire, G. Q. (1999). Cognitive radio: Making software radio more personal. *IEEE Personal Communication, 6*(4), 13–18.

3. Zhao, Q., & Sadler, B. M. (2007). A survey of dynamic spectrum access: Signal processing, networking, and regulatory policy. *IEEE Signal Processing Magazine, 24*(3), 79–89.
4. Alkyldiz, I. F., Lee, W.-Y., Vuran, M. C., & Mohanty, S. (2006). NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey. *Computer Networks, 50*(13), 2127–2159.
5. Thakur, P., Singh, G., & Satashia, S. N. (2016). Spectrum sharing in cognitive radio communication system using power constraints: A technical review. *Perspectives in Science, 8,* 651–653.
6. Thakur, P., Kumar, A., Pandit, S., Singh, G., & Satashia, S. N. (2017). Advanced frame structures for hybrid spectrum accessing strategy in cognitive radio communication system. *IEEE Communication Letters, 21*(2), 410–413.
7. Christian, I., Moh, S., Chung, I., & Lee, J. (2012). Spectrum mobility in cognitive radio networks. *IEEE Communication Magazine, 6*(6), 114–121.
8. Thakur, P., Kumar, A., Pandit, S., Singh, G., & Satashia, S. N. (2017). Spectrum mobility in cognitive radio network using spectrum prediction and monitoring techniques. *Physical Communication, 24,* 1–8.
9. Boyd, S. W., Frye, J. M., Pursley, M. B., & Royster, T. C., IV. (2012). Spectrum monitoring during reception in dynamic spectrum access cognitive radio networks. *IEEE Transactions on Communication, 60*(2), 547–558.
10. Soltanmohammadi, E., Orooji, M., & Pour, M. N. (2013). Improving sensing-throughput trade-off for cognitive radios in Rayleigh fading channels. *IEEE Transactions on Vehicular Technology, 62*(5), 2118–2130.
11. Ali, A., & Hamouda, W. (2015). Spectrum monitoring using energy ratio algorithm for OFDM-based cognitive radio networks. *IEEE Transactions on Wireless Communication, 14*(4), 2257–2268.
12. Orooji, M., Soltanmohammadi, E., & Pour, M. N. (2015). Improving detection delay in cognitive radio using secondary-user receiver statistics. *IEEE Transactions on Vehicular Technology, 64*(9), 4041–4055.
13. Thakur, P., Kumar, A., Pandit, S., Singh, G., & Satashia, S. N. (2017). Performance analysis of high-traffic cognitive radio communication system using hybrid spectrum access, prediction and monitoring techniques. *Wireless Networks*. https://doi.org/10.1007/s11276-016-1440-7.
14. Thakur, P., Kumar, A., Pandit, S., Singh, G., & Satashia, S. N. (2017) Performance analysis of high-traffic cognitive radio network with imperfect spectrum monitoring technique. *IEEE Sensors Journal* **(under review)**.
15. Xing, X., Jing, T., Cheng, W., Huo, Y., & Cheng, X. (2013). Spectrum prediction in cognitive radio networks. *IEEE Wireless Communications, 20*(2), 90–96.
16. Barnes, S. D., Maharaj, B. T., & Alfa, A. S. (2016). Cooperative prediction for cognitive radio networks. *Wireless Personal Communications, 89*(4), 1177–1202.
17. Jian, Y., & Hang-Sheng, Z. (2015). Enhanced throughput of cognitive radio networks by imperfect spectrum prediction. *IEEE Communication Letters, 19*(10), 1338–1341.
18. Thakur, P., Kumar, A., Pandit, S., Singh, G., & Satashia, S. N. (2017). Performance analysis of cognitive radio networks using channel-prediction-probabilities and improved frame structure. *Digital Communication and Networks*. https://doi.org/10.1016/j.dcan.2017.09.012.
19. Pandit, S., & Singh, G. (2015). Backoff algorithm in cognitive radio MAC protocol for throughput enhancement. *IEEE Transactions on Vehicular Technology, 64*(5), 1991–2000.
20. Kay, S. M. (1998). *Fundamentals of Statistical Signal Processing: Detection Theory* (Vol. 2). Englewood Cliffs: Prentice Hall.
21. Jiang, C., Zhang, H., Han, Z., Ren, Y., Leung, V. C. M., & Hanzo, L. (2016). Information-sharing outage-probability analysis of vehicular networks. *IEEE Transactions on Vehicular Technology, 65*(12), 9479–9492.
22. Akyildiz, I. F., Lo, B. F., & Balakrishnan, R. (2011). Cooperative spectrum sensing in cognitive radio networks: A survey. *Physical Communication, 4*(1), 40–62.
23. Mili, M. R., & Musavian, L. (2017). Interference efficiency: A new metric to analyze the performance of cognitive radio networks. *IEEE Transactions on Wireless Communication, 16*(4), 2123–2138.
24. Thakur, P., Kumar, A., Pandit, S., Singh, G., & Satashia, S. N. (2017). Performance analysis of SMC-MAC protocol for distributed cognitive radio networks. *IEEE Transactions on Vehicular Technology* **(under review)**.
25. Chatterjee, S., Maity, S. P., & Acharya, T. (2016). Energy efficiency in cooperative cognitive radio network in the presence of malicious users. *IEEE System Journal*. https://doi.org/10.1109/jsyst.2016.2631219.
26. Karmokar, A., Naeem, M., & Anpalagan, A. (2015). Green metric optimization in cooperative cognitive radio networks with statistical interference parameters. *IEEE System Journal*. https://doi.org/10.1109/jsyst.2015.2451996.
27. IEEE 802.22 Standard, May 2005. [Online]. http://www.ieee802.org/22/.

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