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Performance Analysis of Cognitive Radios in a Cooperative Scheme over Nakagami Fading Channels

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***Abstract**: Radio spectrum is a primary requisite for wireless technologies and sensor networks. Due to the high demand and expense of the radio spectrum, it is guaranteed to extend its efficient utilization it. To expand the effective operation and serviceability of the radio spectrum in wireless communications, the notion of Cognitive Radio (CR) is presented in where the licensed spectrum of Primary User (PU) is used opportunistically by unlicensed CR users without interfering with the prioritized PU data transmission. Usually, a CR system is applied to detect empty radio bands by exploiting well-known spectrum sensing schemes and then unused spectrum is opportunistically used by the CR system. Various channels fading of the radio environment are to be considered while introducing different spectrum sensing approaches. In this regard, sensing time to find a vacant radio spectrum should be maintained minimum to reliably get the desired throughput. In this paper, an agreement issue is addressed between the time required for effective spectrum sensing and the achievable throughput of the CR network. Our proposed model illustrates the achievable throughput of CR node in cooperation provides better performance than stand-alone CR node. This is achieved by addressing the variation of the number of nodes under the Nakagami fading distribution. In conclusion, the maximum throughputs of the cooperative CR nodes are guaranteed as per simulation and data analysis.*

***Keywords**: Cognitive radio, Spectrum sensing, Nakagami Fading distribution, Fusion rule, Achievable throughput.*

I. INTRODUCTION

The requirement of electromagnetic radio frequency spectrum is increasing extremely with the newly developed and invented wireless technologies around the world day by day. As it is a fixed natural resource, it is sometime impossible to fulfill the demand of spectrum. The static spectrum allocation policy among the PU is operated by the government for a specific geographical region for a fixed time epoch. However, the interesting concept of CR has invented recently to figure out the spectrum scarcity by utilizing the limited resource. CR user utilizes the unlicensed radio band opportunistically when PU data transmission is not in operation.

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In any case, if a PU user starts data transmission then a CR user immediately off its transmission as interference to PU's activity is strictly forbidden in this case. Hence, CRs are needed to identify the activity of PU properly with low error rate and the sensing time should be minimized to get excellent performance. There are several sensing methodologies to find transmission opportunities to a CR node. The well-known spectrum sensing methods are energy based detection, feature based spectrum detection, and matched filter detection. Several aspects of spectrum sensing methods in CR can be employed suce as cooperative spectrum sensing (CSS) and non-cooperative or stand-alone (aka single transmitter sensing) CR spectrum sensing. In case of collaborative sensing approach a number of binary decision fusion rules can be pragmatic to increase the performance of detection probability [1]. Among the various spectrum sensing schemes energy based sensing is the simplest and popular technique as it involves lowest computational complication [1], [2]-[3]. This approach carries less complexity related to implementation issues [4], [5], [6], [7]. Fading channel plays an important role while discovering the existence of PU radio transmission. The received signal of the CR has influences from both diffuse and specular scattering, i.e., the electric field is composed of a strong component and various multipath contributions with less significant magnitude. The Nakagami-m distribution is an approximation of generic solution to the randomness of the radio channel [8]. The particular solution to this problem greatly depends on the complete information of the channel fading distribution and the correlations among the components of signals that comprises the total signal. Therefore, Nakagami distribution of the channel is a comprehensive model to the small scale fading which is used in practical fading channel considerations. The advantages of Nakagami channel distribution are of two folds as; (a) It is a simplified distribution which can model different fading environments (e.g. Rayleigh channel), and (b) It has higher flexibility and precision in matching some practical signal than the Rayleigh, lognormal or Rice distributions [8]. Cooperation among a group of CR nodes are employed in spectrum sensing so that the effect of multichannel fading can be minimized in the way of reliable radio band detection. In order to combine sensing result in CSS mode, multiple recognized fusion rules such as binary OR and AND rule, the majority rule, and Chair-Varshney optimal fusion rule are applied to enhance the detection performance in CR considering the fading effect [9], [7]. Hence, CSS mode of operation improves the faultlessness of PU present in the radio environment and gives provision to CR devices to use of underutilized spectrum [5].

Thus, increasing the accuracy of detection performance will enhance the achievable throughput to the CR nodes. Consequently, the achievable throughput is varied as a function of sensing time. We have applied Energy detection approach for its computational and experimental simplicity. In the following, the paper is structured into five sections. The sensing preliminaries is discussed in section II, where both stand-alone and cooperative spectrum sensing technique has been explicated. Moreover, the importance of efficient spectrum hole detection is focused here. In section III, the proposed CSS system model along with well-known binary decision fusion rules have been designated. Far ahead, the process of determing achivable throughput of the CR data transmision is mentioned in section IV. The throughput of the CR network has been simulated with respect to the time necessary for spectrum sensing along with Nakagami fading channels and the result has been sumarized in a tabular form in section V. Finaly, some conclusions and future works have been drawn in the Section VI.

II. SENSING PRELIMINARIES

A. *Stand-Alone CR Spectrum Sensing*

The primary task of radio nodes of a CR network is to scan and classify RF characteristics of the neighboring radio environment in the interest of identifying the presence of active PU nodes. The CRs can perform data transmitting and receiving only in the absence of PUs, so the accurate spectrum detection is the primary criteria for CR establishment. The CRs might have no provision to interfere PU transmission. Hence, the CR nodes always have the preparation to free the licensed spectrum if a PU node asks for radio band. In this paper, it is addressed the receiver performance criteria, i.e., the probability of detection (Pd), the probability of false alarm (Pfa), and the probability of miss detection (Pm) to perceive the detection features of the CR network. The detection probability is the possibility of determining the activity of PU at the presence of PU in the environment. Sometimes, there is no active PU in the surrounding, but CRs detect PU by mistake. These possibilities of illusive sensing by the CRs are stated as the probability of false alarm. Besides, CRs can be fallen through identifying the active PU though it is present. This disqualification of a CR node to define the subsistence of licensed PU is called the probability of miss detection [6]. Energy detection based sensing scheme has the highest popularity among the available sensing approaches due to its low computational complexity and it does not necessitate a-priori information of the radio channel. Therefore, this technique is also known as blind spectrum detection.

Usually, all the RF bands are not occupied simultaneously by the licensed PU radios. Energy detection approach measures the average signal energy within a specific radio spectrum and later compares this spectrum energy with a predefined threshold value that is chosen from the probability of false alarm. During the comparison process, the comparator notifies the presence of PUs in the neighboring radio environment when the received signal energy of a specific band is higher than the threshold value. In contrast, lower RF sensing energy compared to threshold indicates the RF opportunity is available for data communication among CR nodes. Consequently, it is considered by the well-known binary hypothetical testing, H0 and H1 to decide the existence of PUs statistically. Thus, H0 represents the absence of PU radios and H1 indicates PU radios are active in the neighboring electromagnetic environment. These statistics are represented mathematically in (1) and (2) where, r(n) signifies the signal received by the CR nodes, q(n) represents available noise present in the radio channel, s(n) is the transmitted signal of PU nodes, and n represents the sampling index [10]. From (3), we calculate the received signal energy where S signifies the total number of samples and E refers to a random variable in H0 with PDF [10]. In (4), probability of false alarm has been evaluated where P0(x) is a Chi-square distribution, and ψ denotes the value of threshold.

$$r(n) = q(n) \tag{1}$$

Equation (1) denotes the absence of PU radios: $\boldsymbol{H_0}$, while PU radio signal actively present ($\boldsymbol{H_1}$) in the following equation

$$r(n) = s(n) + q(n) \tag{2}$$

The expectation of the signal is represented by

$$E = \frac{1}{S}\sum_{n=1}^{S} |r(n)|^2 \tag{3}$$

$$P_{fa} = P_r(E > \psi \mid H_0) = \int_{\psi}^{\infty} P_0(x)dx \tag{4}$$

By exploiting equation (5), the amount of E has been intended under the consideration of $\boldsymbol{H_1}$ with PDF $P_1(x)$ [10].

$$P_d = P_r(E > \psi \mid H_1) = \int_{\psi}^{\infty} P_1(x)dx \tag{5}$$

B. *Cooperative Spectrum Sensing*

Stand-alone mode of CR spectrum sensing is problematical in some practical cases due to the presence of hidden radios in radio network and existing multipath fading features of the radio channels. Therefore, the reliability of receiver detection probability is questionable in stand-alone mode of spectrum sensing. As a result, cooperative spectrum sensing (CSS) plays a significant role to obtain trustworthy detection performance which can reduce the noise caused by the CRs to PUs. As a result, the false alarm probability is minimized considerably for the CR network. So, the CSS method is proposed to enhance the sensing accuracy by implementing multiple nodes in CRN as a solution of the troubles that aries by dint of the vagueness of noises, multichannel-fading effects and shadowing in the course of sensing of vacant spectrum [1], [5]. Later, the detection performance is further enriched in terms of additional CR nodes. A fundamental scheme of CSS is outlined in Fig. 1. CR nodes 1, 2 and 3 search PU independently in their electromagnetic radio environment and decide weather a PU is remaining or not.Their individual decision may be defective as the fluctuation of channel characteristics. Hence, a local decision has to be prepared by indiviual CR node which provides a binary sensing decision to make the system design simpler.

The individual sensing result from every CR node is then transferred to the fusion center (FC) where the global decision is prepared through exploiting the well-known binary fusion rules.

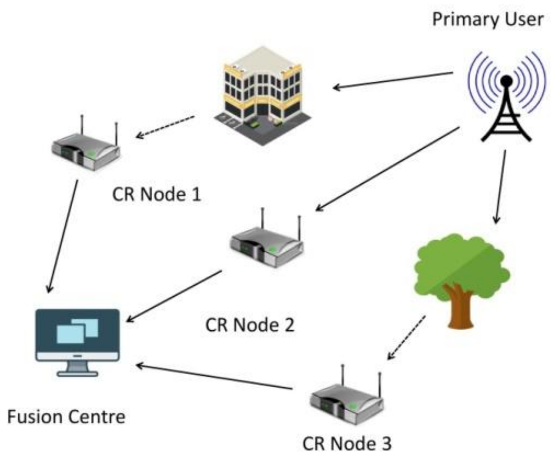

Fig. 1.Illustration of Cooperative spectrum sensing approach.

III. SYSTEM MODEL

Due to simplicity and lower computational cost, Energy detection based sensing is choosen for our proposed cooperative spectrum sensing method. Energy of received signal is calculated and compared with a reasonable threshold value. Every CR node performs the same activity as shown in Fig. 2. There are two hypothesis: H_1 for the presence of PU when received energy (RE) is greater than threshold energy (TE) and H_0 for the absence of PU as RE is smaller than TE. The individual sensing results come out from the CRs are then fused in fusion centre and produced a 1-bit global binary result on the presence of licensed primary radio.

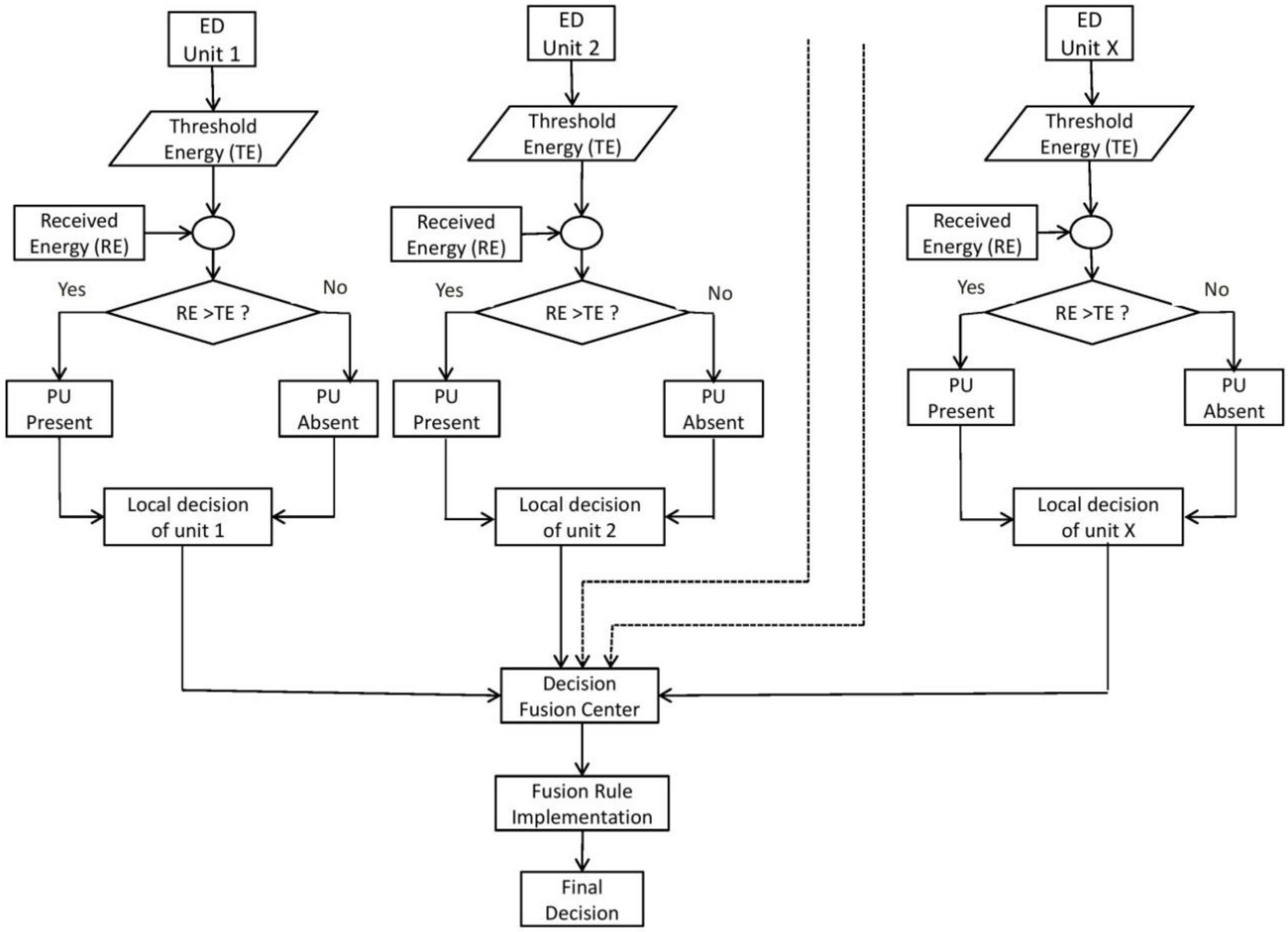

Fig. 2. An elementary pictorial representation of Cooperative Spectrum Sensing for CR network.

The particular sensing results have been composed in [5], [9], exploiting various binary fusion rules for instance AND rule, OR rule, Majority rule, and Chair-Varshney fusion rule that is also labeled as optimal fusion rule. Equation (6) states the logic that has been utilized in FC for hard decision fusion. In this equation, j represents the number of CR nodes which share their local decision as H1 within total number of X nodes and Yd symbolizes the probability of detection for CSS scheme [9].

$$Y_d = \sum_{i=j}^{X} \binom{X}{i} P_d^i (1-P_d)^{X-i} \quad (6)$$

Logical AND operation is carried out when applying binary AND rule. Here, logic-1 is forwarded to FC by all CR nodes. Probability of detection in cooperative spectrum sensing is determined by substituting *j=X* in equation (1) for AND rule which is shown in (7) [10].

$$Y_d = P_d^X \quad (7)$$

According to OR rule, the final decision will be 1 for any local sensing decision as 1. Hence, for OR rule, the probability of detection has been determined by means of (8) where *j=1* [9].

$$Y_d = 1 - \sum (1-P_d)^X \quad (8)$$

In majority rule, as the word 'majority' implies that the final decision will be 1 if in any case half or more than half of the individual decisions acknowledged by the FC is 1. Hence, the probability of detection has been calculated using equation (9) where $j = \lfloor x/2 \rfloor$ [9].

$$Y_d = \sum_{i=\lfloor X/2 \rfloor}^{X} \binom{X}{i} P_d^i (1-P_d)^{X-i} \quad (9)$$

In accordance with the Chair-Varshney optimal fusion rule, all the individual decisions are not eqaully significant. Hence, each CR node has a weighted value of probability of detection that based on CR performance parameters and radio channel characteristics. The CR node with better channel state information, better radio features and closer to the PU will get priority to prepare better global decision [11]. The following optimal statistic, named as Chair-Varshney fusion rule which confirms a high-SNR approximation to Λ.

$$\Lambda = \sum_{sign(y_k)=1} \log \frac{P_d}{P_f} + \sum_{sign(y_k)=-1} \log \frac{1-P_d}{1-P_f} \quad (10)$$

In equation (10), the characteristic of Λ is significant as it does not need a-priori information of channel gain while it does require weighted P_d and P_f values for all CR nodes. Though, this scheme undergoes substantial performance loss at low to adequate fading gains of the channel [9].

IV. ACHIEVABLE THROUGHPUT

The amount of data processed by a system with a certain time interval is termed as achievable throughput. There is a variation in throughput with respect to sensing time. To analyze this concept, a framework is considered as shown in Fig. 3 where T is the as total frame length where *t* is conserved for radio spectrum detecting. Therefore, the remaining length of the frame length (*T-t*) can be operated for opportunistic data transmission for CR nodes.

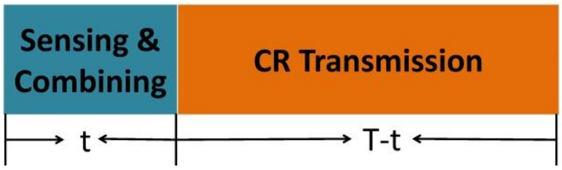

Fig. 3. Framework for cooperative cognitive radio.

To calculate the achievable throughput *T(t)* from sensing ability with cooperation, we can consider the following equation.

$$T(t) = C_0 P(H_0)\left(1-\frac{\lambda}{L}\right)\left(1-Q\left(\alpha+\sqrt{N}\gamma\right)\right) \quad (11)$$

In equation (11) C_0 is the achievable rate of secondary transmitter in the absent of primary user which is equivalent to $log_2(1+SNR_s)$ *where SNRs* is the signal to noise ratio of the CR network, $\alpha = \sqrt{2\gamma+1}\, Q^{-1}(P_d)$ and $Q(x)$ is a monotonically diminishing function. The throughput will decrease, if the time required for spectrum sensing increases. For the lower sensing time, achievable throughput will be higher. Moreover, in this case, as the spectrum sensing is performed with multiple cooperative nodes, the sensing result is comparatively more reliable. Accordingly, if there is less probability to collide data with PU transmission the throughput will certainly increase.

V. SIMULATION AND ANALYSIS

In this section, it is implemented through numerical simulations to appraise the manageable throughput with respect to sensing time of the CRs. Energy detection based sensing scheme is applied in CSS for AWGN and generic Nakagami fading distribution channels. Frame length is chosen for a specific time, i.e. 100ms in the proposed system. To discover better estimation Monte Carlo simulation is performed and Monte Carlo value of 100000 is chosen for simulation purpose. In this analysis, it is calculated the achievable throughput from the detection probability and probability of false alarm by introducing several decision fusion rules for instance AND, OR, Majority and optimal decision fusion rules under AWGN channel. Fig. 4 represents the simulated achievable throughput that varies with sensing time of a CR while applying the optimal fusion rule. For a nine (09) node CSS system, the maximum attainable throughput is 6.061 bits/sec/hz at the starting. In this case, a CR requires the least possible time for spectrum sensing. The achievable throughput decreases as of increasing time for spectrum sensing. The achievable throughput is increased with nine (09) CR nodes due to the enhanced detection performance achieved by the cooperation among CR nodes.

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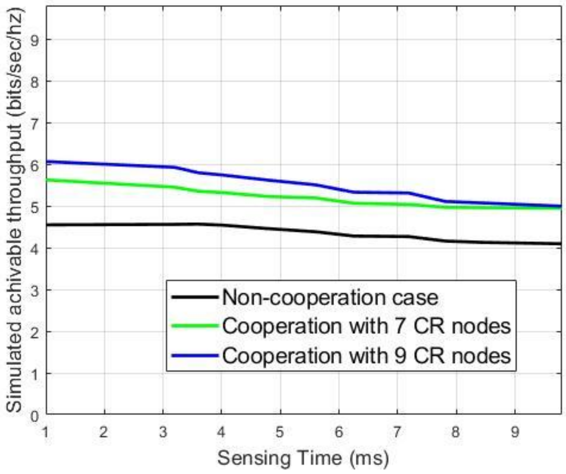

Fig. 4.Achievable throughput for Optimal rule covered by AWGN channel.

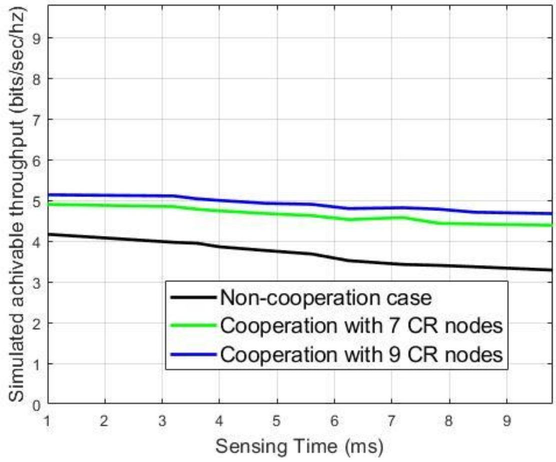

Fig. 5. Achievable throughput for AND rule covered by Nakagami channel

Accordingly, achievable throughput is calculated according to binary OR, Majority and Optimum fusion rules under the effect of AWGN channel. Throughput performance for opportunistic data transmission by applying various fusion rules is shown in Table I. The more the number of CR nodes (i.e. cooperation among the CR nodes) in a radio system, the more the overall system performance. Thus, the radio system with cooperation among 9 CR nodes always shows better performance than the radio system with cooperation among 7 nodes. This is also shown in Fig. 4. The detection performance of a cooperative CR node is always performing better than a stand-alone CR case. Furthermore, binary optimal fusion rule provides the best throughput as summarized in Table I.

Table I Achievable Throughput for various fusion rules covered by AWGN channel

Sensing Time (ms)	Attainable Throughput (bits/sec/hz)			
	AND Rule	OR Rule	Majority Rule	Optimal Rule
1.003	5.638	5.869	5.751	6.061
3.200	5.587	5.755	5.699	5.923
4.800	5.398	5.506	5.506	5.614
5.600	5.343	5.450	5.396	5.503
6.250	5.222	5.274	5.222	5.327

Later, we concentrate our focus on the detection performance of a generic Nakagami fading channel by employing AND, OR, Majority and Optimal fusion rules as shown in Fig. 5, Fig. 6, Fig. 7, and Fig. 8 respectively. In this case, the performance reduces than AWGN, Rayleigh, and Rician fading effects. The highest attainable throughput is obtained by exploiting optimal fusion rule (i.e., 5.481 bits/sec/Hz) which is depicted in Table II.

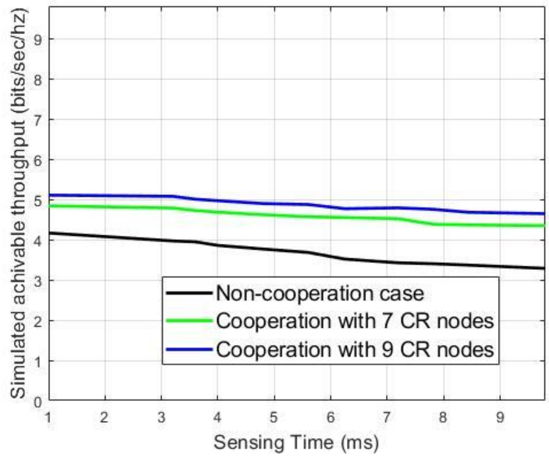

Fig. 6. Achievable throughput for OR rule covered by Nakagami channel

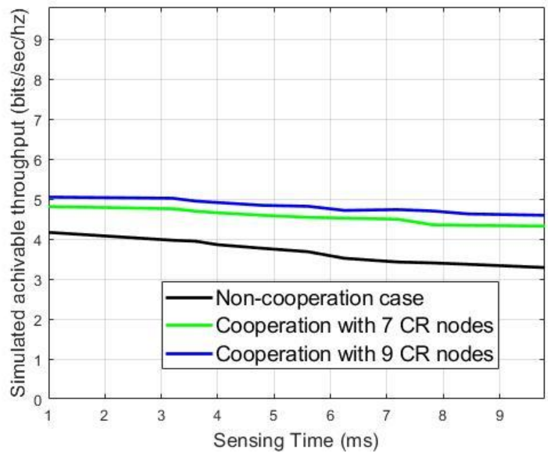

Fig. 7. Achievable throughput for Majority rule covered by Nakagami channel.

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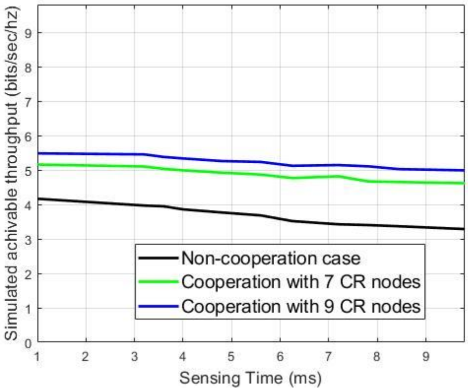

Fig. 8. Achievable throughput for Optimal rule covered by Nakagami channel.

The comparison of throughput results for various decision fusion rules under Nakagami fading channel is summarized in Table II.

Table II: Achievable throughput for different fusion rules covered by Nakagami channel

Sensing Time (ms)	Attainable Throughput (bits/sec/hz)			
	AND Rule	OR Rule	Majority Rule	Optimal Rule
1.003	5.132	5.104	5.046	5.481
3.200	5.104	5.074	5.017	5.451
4.800	4.923	4.895	4.839	5.257
5.600	4.899	4.871	4.816	5.232
6.250	4.794	4.767	4.713	5.120

The maximum achievable throughput is obtained for a stand-alone CR node is 4.215 bits/sec/hz. The highest throughput is 5.211 bits/sec/hz for cooperative case with seven (07) CR nodes applying optimum fusion rule which is 19.1% more than the non-cooperative case under Nakagami fading channel. In a cooperative radio environment, when the number of CR nodes are greater than before from 7 to 9 then achievable throughputs is obtained as 5.481 bits/sec/hz which is 30% more than the previous non-cooperative case. Therefore, it is decided that overall throughput is enhanced as per our expectation.

VI. CONCLUSION

RF spectrum is one of the fundamental requirements to establish communication technologies and it is advantageous to develop and establish a flexible communication service such as CR networks. In this paper, efficient spectrum sensing approaches for CRs in a cooperative environment are suggested exploiting various well-known decision fusion rules. The performance of Chair-Varshney optimal fusion rule outperforms among all the fusion rules while considering Nakagami fading distribution of the radio channel. Likewise, the number of CR nodes in the cooperative scenario has been changed to observe the variation in detection performance. The more the number of CR nodes in CSS mode, the greater the detection performance. As a result, the enhanced probability of detection of CR nodes has increased the throughput of the CR networks. Nevertheless, the sensing-throughput fluctuates with respect to the fading distribution of the electromagnetic radio paths. In this research paper, spectrum sensing has been done with CSS approach for effective sensing decisions to fulfill the opposite objective of PU nodes and CR nodes. As a result, the attemptable throughput for effective CR data transmission is enhanced while considering the PUs transmission is not hampered. In the future, it is established the optimal number of CR nodes in a CSS environment for which CR data transmission is maximized.

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