A Cluster Based Selective Cooperative Spectrum Sensing Technique for Cognitive Radio Network

Mamjuda Hussain, Pratyush Tripathi

***Abstract*—Cognitive radio (CR) has been recently proposed as a promising technology to improve spectrum utilization by enabling secondary access to unused licensed bands. A prerequisite to this secondary access is having no interference to the primary system. This requirement makes spectrum sensing a key function in cognitive radio systems. Among common spectrum sensing techniques, energy detection is an engaging method due to its simplicity and efficiency.**

The growing demand of wireless applications has put a lot of constraints on the usage of available radio spectrum which is limited and precious resource. Cognitive radio is a promising technology which provides a novel way to improve utilization efficiency of available electromagnetic spectrum. In this paper, a cluster-based optimal selective CSS scheme is proposed for reducing reporting time and bandwidth while maintaining a certain level of sensing performance. Clusters are organized based on the identification of primary signal to-noise ratio value, and the cluster head in each cluster is dynamically chosen according to the sensing data qualities of CR users.

The cluster sensing decision is made based on an optimal threshold for selective CSS which minimizes the probability of sensing error. A parallel reporting mechanism based on frequency division is proposed to considerably reduce the time for reporting decision to fusion center of clusters. In the fusion center, the optimal Chair-Vashney rule is utilized to obtain a high sensing performance based on the available cluster's information.

***Index Terms*—Cooperative spectrum sensing, Cluster, Selective combination, Parallel reporting mechanism**

I. Introduction

Cognitive radio (CR) is a new way technology to compensate the spectrum shortage problem for wireless environment. The demand of radio spectrum increases proportionally with the increase in number of users, and thus it causes a significant increase in utilization of spectrum. The major hurdle in the current spectrum scarcity is the fixed spectrum assignment. This spectrum shortage problem has a deep impact on research directions in the field of wireless communication. It enables much higher efficiency of spectrum by dynamic spectrum access. It allows unlicensed users to utilize the free portions of licensed spectrum while ensuring that it causes no interference to primary users' transmission. Cognitive radio arises to be enticing solution to the spectral congestion problem by introducing opportunistic usage of the frequency bands that are not heavily occupied by licensed users. FCC defines a cognitive radio as, "A radio or system that senses its operational electromagnetic environment and can dynamically and autonomously adjust its radio operating parameters to modify the system operation, such as to maximize the throughput, mitigate interference, facilitate interoperability, access secondary markets". Hence, one main aspect for cognitive radio is related to autonomously exploiting locally unused spectrum to provide new paths to spectrum access.

Cognitive radio (CR) has been recently proposed as a promising technology to improve spectrum utilization by enabling secondary access to unused licensed bands. A prerequisite to this secondary access is having no interference to the primary system. This requirement makes spectrum sensing a key function in cognitive radio systems. Among common spectrum sensing techniques, energy detection is an engaging method due to its simplicity and efficiency. However, the major disadvantage of energy detection is the hidden node problem, in which the sensing node cannot distinguish between an idle and a deeply faded or shadowed band [1]. Cooperative spectrum sensing (CSS) which uses a distributed detection model has been considered to overcome that problem [2-7].

CSS schemes require a large communication resource including sensing time delay, control channel overhead, and consumption energy for reporting sensing data to the FC, especially when the network size is large. Cluster-based CSS schemes are considered for reducing the energy of CSS [6] and for minimizing the bandwidth requirements by reducing the number of terminals reporting to the fusion center [7]. Cluster schemes can reduce the amount of direct cooperation with the FC but cannot reduce the communication overhead between CUs and the cluster header.

In this paper, we propose a cluster-based selective CSS scheme which utilizes an efficient selective method for the best quality sensing data and a parallel reporting mechanism. The selective method, which is usually adopted in cooperative communications [8], is applied in each cluster to implicitly select the best sensing node during each sensing interval as the cluster header without additional collaboration among CUs. The parallel reporting mechanism based on frequency division is considered too strongly reduce the reporting time of the cluster decision. In the FC, the optimal Chair-Vashney rule (CV rule) is utilized to obtain a high sensing performance based on the available cluster's signal-to-noise ratio (SNR).

II. Spectrum Sensing

Spectrum sensing (SS) is the procedure that a cognitive radio user monitors the available spectrum bands, captures their information, reliably detects the spectrum holes and then shares the spectrum without harmful interference with other users. It still can be seen as a kind of receiving signal process, because spectrum sensing detects spectrum holes actually by local measurement of input signal spectrum which is referred to as local spectrum sensing. The cognitive users in the network don't have any kind of cooperation. Each CR user

Mamjuda Hussain, Department of Electronics & Communication Engineering, M.Tech Scholar, Kanpur Institute of Technology, Kanpur, India

Pratyush Tripathi, Associate Professor, Department of Electronics & Communication Engineering, Kanpur Institute of Technology, Kanpur, , India.

will independently detect the channel through continues spectrum sensing, and if a CR user detects the primary user it would vacate the channel without informing the other CR users.

The goal of spectrum sensing is to decide between the following two hypotheses:
H0: Primary user is absent
H1: Primary user is present in order to avoid the harmful interference to the primary system.
A typical way to detect the primary user is to look for primary transmissions by using a signal detector. Three different signal processing techniques that are used in the systems are matched filter, energy detector and feature detection.

A) Matched Filter

The optimal way for any signal detection is a matched filter [10]. It is a linear filter which maximizes the received signal-to-noise ratio in the presence of additive stochastic noise. However, a matched filter effectively requires demodulation of a primary user signal. This means that cognitive radio has a priori knowledge of primary user signal X[n], such as modulation scheme, pulse shaping, and packet format. Such information must be pre-stored in CR memory, but the inconvenience part is that for demodulation it has to achieve coherency with primary user signal by performing timing and carrier synchronization, even channel equalization. This is still possible since most primary users have pilots, preambles, synchronization words or spreading codes that can be used for coherent detection, for examples: TV signals has narrowband pilot for audio and video carriers; CDMA systems have dedicated spreading codes for pilot and synchronization channels; OFDM packets have preambles for packet acquisition. If X[n] is completely known to the receiver then the optimal detector is:

$$T(Y) = \sum_{n=0}^{N-1} Y[n]X[n] \underset{>H_0}{\overset{<H_1}{}} \gamma \quad (1)$$

Here γ is the detection threshold, and then the number of samples required for optimal detection is:

$$N = [Q^{-1}(P_D) - Q^{-1}(P_{FD})]^2 (SNR)^{-1} = OSNR^{-1}$$

Where PD and PFA are show as the probabilities of detection and false detection. The main advantage of matched filter is that due to coherency it requires less time to achieve high processing gain since only O(SNR^{-1}) samples are needed to meet a given probability of detection. However, a significant drawback of a matched filter is that a cognitive radio would need a dedicated receiver for every primary user class.

B) Energy Detector

One approach to simplify matched filter approach is to perform non-coherent detection through energy detection [10]. The structure of an energy detector is shown in Figure 1.

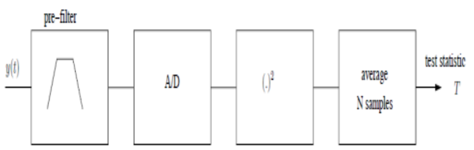

Figure 1: Block diagram of an Energy Detector

It is a sub-optimal detection technique and it has been proved to be appropriate to use it to determine the presence of a signal in the absence of much knowledge concerning the signal. In order to measure the energy of the received signal the output signal of band pass filter with bandwidth W is squared and integrated over the observation interval T. Finally the output of the integrator is compared with a threshold to detect if the primary or licensed user is present or not. However, due to non-coherent processing O(SNR^{-2}) samples are required to meet a probability of detection constraint.
In this case we have:

$$T(Y) = \sum_{n=0}^{N-1} Y^2[n] \underset{>H_0}{\overset{<H_1}{}} \gamma \quad (2)$$

$$N = 2[Q^{-1}(P_{FA}) - Q^{-1}(P_D)]^2 = O(SNR^{-2}) \quad (3)$$

C) Feature Detection

An alternative method for the detection of primary signals is Cyclo-stationary Feature Detection [11] in which modulated signals are coupled with sine wave carriers, pulse trains, repeated spreading, hopping sequences, or cyclic prefixes. This results in built-in periodicity. These modulated signals are characterized as cyclo-stationary because their mean and autocorrelation exhibit periodicity. This periodicity is introduced in the signal format at the receiver so as to exploit it for parameter estimation such as carrier phase, timing or direction of arrival.

These features are detected by analyzing a spectral correlation function SCF. The main advantage of this function is that it differentiates the noise from the modulated signal energy. This is due to the fact that noise is a wide-sense stationary signal with no correlation however modulated signals are cyclo-stationary due to embedded redundancy of signal periodicity.

III. System Description

The CR network, which shares the same spectrum band with a license system, utilizes a cluster-based CSS scheme as shown in Figure 2. The CR network is organized in multiple clusters in each of which the CUs have an identical average SNR of the received primary signal.

This identical SNR assumption can be practical when the clusters are divided according to geographical position, i.e., adjacent CUs in a small area are gathered into a cluster. The header in each cluster is not fixed but dynamically selected for each sensing interval based on the quality of the sensing data at each CU. In detail, the node with the most reliable sensing result will take on the cluster header's roles which include making and reporting the cluster's decision to the FC. In order to reduce the reporting time and bandwidth, only the sensing data of the cluster header, which is the most reliable sensing data, is utilized to make the cluster decision. This method means that the decision of a cluster is made according to the selective combination method. The FC will combine all cluster decisions to make a final decision and broadcast the final sensing decision to the whole network.

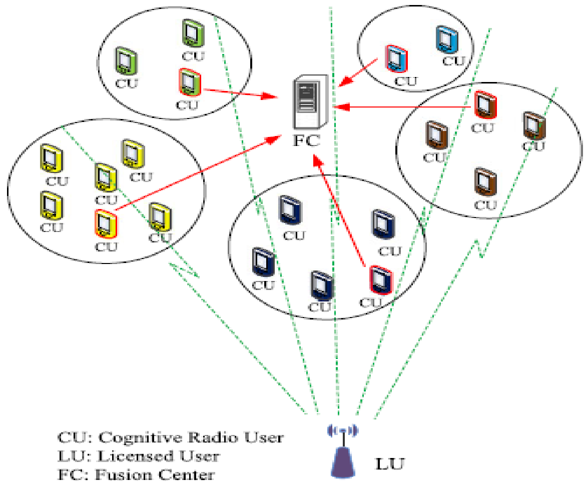

Figure.2: System Model

The fusion rule in the FC can be any kind of hard decision fusion rules such as an OR rule, AND rule, 'K out of N' rule, or Chair-Varshney rule. Without loss of generality, we propose the utilization of the optimal Chair-Varshney rule at the FC since the SNR value of the received primary signal at the CU is available in this proposed scheme.

IV. CCS Mechanism

We suggest a cluster header selection based on sensing data reliability. For each sensing interval, the CU with the most reliable sensing data in a cluster is selected to be the cluster header. Obviously, the reliability of the sensing data can be evaluated by the log-likelihood ratio (LLR) of the sensing result. The LLR value of the received signal energy x_{E_i} is given by:

$$\Lambda_i = \log\left(\frac{f_{X|H_1}\left(x_{E_i}\,|\,H_1\right)}{f_{X|H_0}\left(x_{E_i}\,|\,H_0\right)}\right), \qquad (4)$$

The probability density function (PDF) of x_{E_i} corresponding to each hypothesis. Since the SNRs of the received primary signals in a cluster are identical, the LLR of the i^{th} user in the c_j cluster can be considered to be derived from the same distribution.

For each cluster, therefore, the LLR value can be normalized such that it has a zero mean as follows:

$$Y_{i,c_j} = A_{i,c_j} - E[A_{c_j}] \qquad (5)$$

It is obvious that the reliability of the sensing data will be higher if the absolute value of the normalized LLR is larger. We propose utilization of the absolute value of the normalized LLR as the reliability coefficient for selecting the cluster header as well as the selective cluster data.

In order to implicitly select the most reliable sensing data among CUs in a cluster without additional data collaboration, one contention time should be determined for each CU as follows:

$$t_{con} = \exp\left(-k\left|Y_{i,c_j}\right|\right) \qquad (6)$$

Where, κ is a predefined constant such that the contention time is sufficient. Obviously, from this equation, the node with the highest absolute value of the normalized LLR will have the smallest contention time. In contention, each CU must monitor the reporting channel and wait for a quiescent condition before considering itself as a cluster header, i.e., the node with the most reliable sensing data, when the contention time expires. The CU who wins the contention will make a local cluster decision and report the cluster decision to the FC based on its own sensing data as follows:

$$Y_{c_j} \underset{H_0 : D_{c_j} = -1}{\overset{H_1 : D_{c_j} = 1}{\gtrless}} \tau_{c_j}, \qquad (7)$$

Where, Y_{c_j} is equal to the normalized LLR with highest absolute value and τ_{c_j} is the cluster threshold. Next, we consider the problem of choosing the optimal cluster threshold.

For implementing the proposed selective mechanism in a cluster, all CUs in a cluster have to monitor the control channel to determine the cluster header during the contention time. One question raised here is how to arrange the contention time for multiple clusters in the network. Generally, there are two common solutions for this problem. The first approach is to assume that the contention times of the clusters are carried out sequentially over time.

This method requires a strict synchronization among CUs in the network and a long contention time to minimize the collision in contention due to differences in transmission range. Obviously, this method can cause a long reporting time with a high rate of contention collision. The second approach is to assume that the contention times of different clusters are conducted in parallel with different sub-control channels. Since each cluster only reports a 1-bit hard decision to the FC, the sub-control channel can be reduced to a pair of frequencies corresponding to two possible values of a cluster decision.

This means that a node in a certain cluster only monitors two predetermined frequencies during the contention time, and the node who wins the contention will transmit only one predefined frequency to the FC according to its cluster decision. Normally, a control channel bandwidth is sufficient for allocating a reasonable number of frequency pairs to clusters. For example, it is acceptable to divide 50pairs of frequencies for 50 clusters in a 200-kHz control channel. Figure 4.3 shows an example of a sensing frame structure for the proposed parallel report mechanism compared with the conventional fixed allocation direct reporting method.

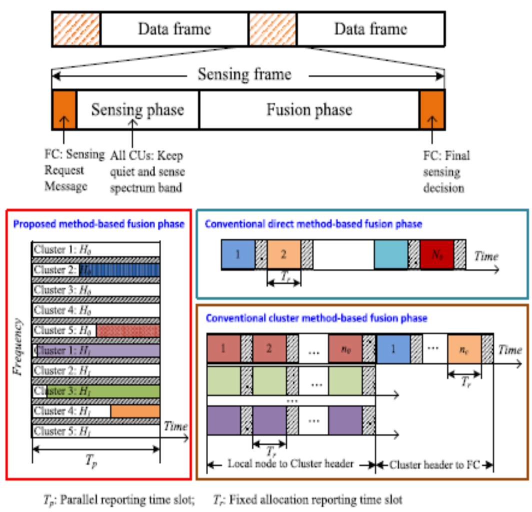

Figure 3: Sensing frame structure

In this method, the problems of strict synchronization and contention collision, which can occur with the previous method, are completely resolved. Indeed, with this parallel contention and reporting mechanism, the synchronization among CUs can be looser since there is only one contention time that is identical to the reporting time.

No collision between two cluster reports will occur since these cluster decisions are transmitted at different frequencies. Even in the case that two CUs in a cluster have the same value of the most reliable sensing data, a collision still will not occur since the two nodes will transmit the same frequency, and at the receiver side, two transmitted frequencies can be considered as two versions of a multipath signal. The remainder problem with this parallel reporting method is that the FC needs to be equipped with parallel communication devices such as an FFT block, which is usually used in an OFDM receiver, or a filter bank block to detect multiple reporting frequencies. However, this requirement is not a big issue.

V. SIMULATION RESULTS

The simulation of the proposed cluster-based selective CSS scheme is conducted under the following assumptions:

- The LU signal is a DTV signal as in [9].
- The bandwidth of the PU signal is 6 MHz, and the AWGN channel is considered.
- The local sensing time is 50 µs.
- The probability of the presence and absence of PU signal is 0.5 for both.
- The network has N_0 nodes and can be divided into NC clusters. Each cluster includes n0 nodes.

We evaluate the sensing performance of the selective method in the cluster with three different received primary signal SNRs of −14, −12, and −10 dB when the number of nodes in the cluster changes from 1 to 100. The probability of error will decrease along with the increase in the number of nodes in the cluster.

However, the decreasing rate of probability of error is low when the number of nodes in the cluster is large, especially when $N_0 > 10$. Therefore, the selective method only provides high sensing efficiency when the number of nodes is in the range of 20. Second, we assume that the network includes five clusters with different SNR values corresponding to −20, −18, −16, −14, and −12 dB. The error probabilities of the global CV rule-based conventional direct reporting scheme, the cluster and global CV rule-based conventional cluster reporting scheme, and the proposed CSS scheme are then observed according to different values of cluster size. As illustrated in Figure 4, the error probabilities of all CSS schemes decrease along with the increase of the cluster size. The direct conventional CV rule based CSS scheme provides the best sensing performance.

The proposed CSS scheme outperforms the cluster and global CV rule-based conventional cluster CSS scheme when the cluster size is small, i.e., $N_0 < 8$. When the cluster size is large, i.e., $N_0 > 8$, the sensing error probability of the proposed method is slightly higher than that of the conventional cluster scheme, which utilizes a CV rule at both cluster headers and FC. However, it is noteworthy that the cost of this better performance with the conventional cluster and direct schemes compared with the proposed scheme are the extremely large amount of overhead, energy consumption, and reporting time for collecting all decisions from all nodes in the network.

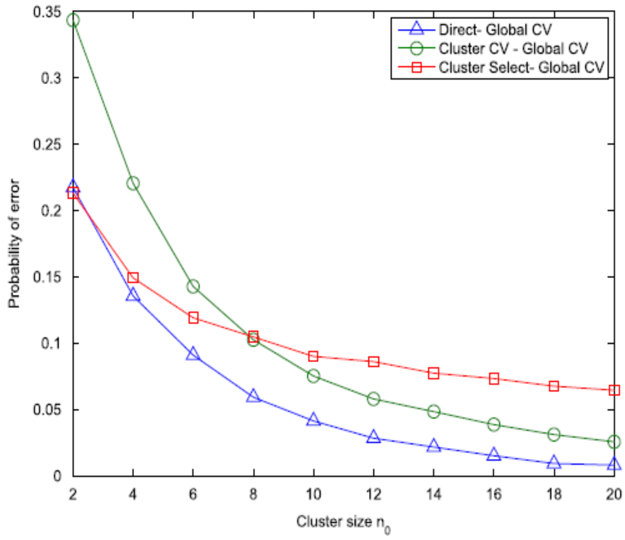

Figure 4 Probability of sensing error of the proposed and conventional CSS schemes.

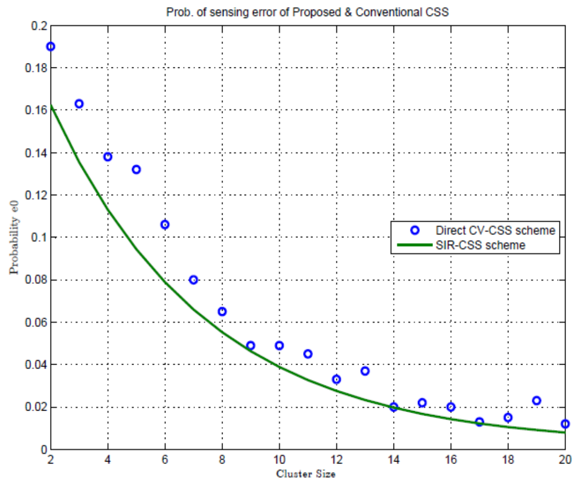

Figure 5: Graphical Representation on Direct CV-CSS scheme and SIR-CSS scheme

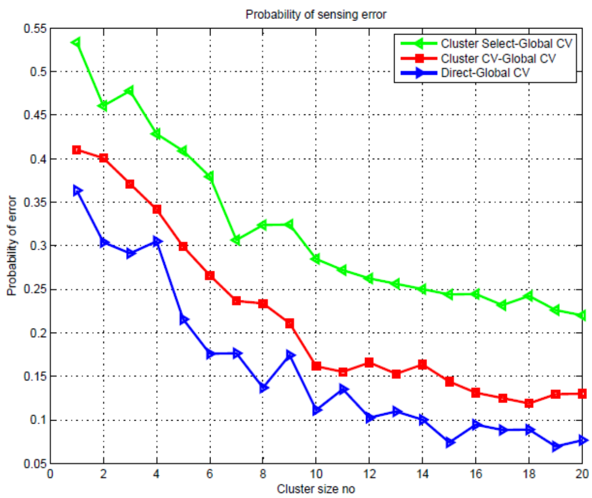

Figure 6: Probability of sensing error of the proposed and conventional CSS schemes

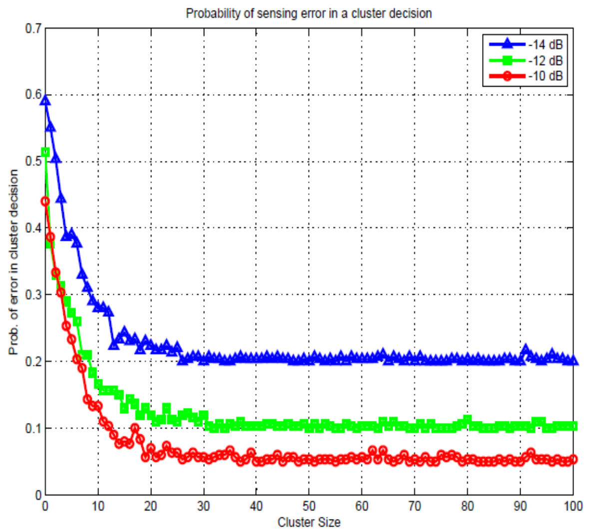

Figure 7: Graphical Representation on Probability of sensing error in cluster decision (dB)

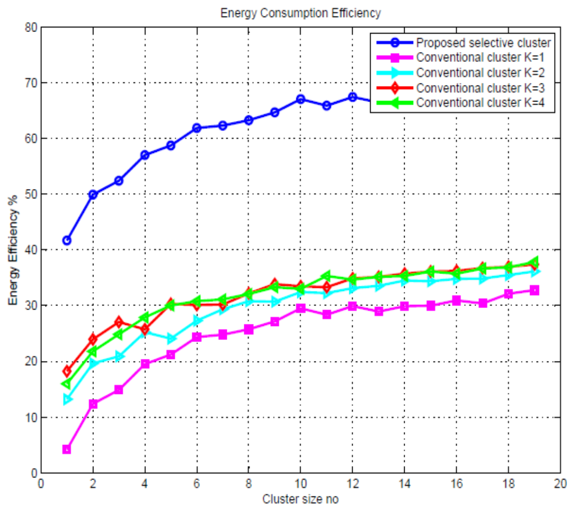

Figure 8: Energy consumption efficiency of the proposed and conventional cluster-based CSS schemes

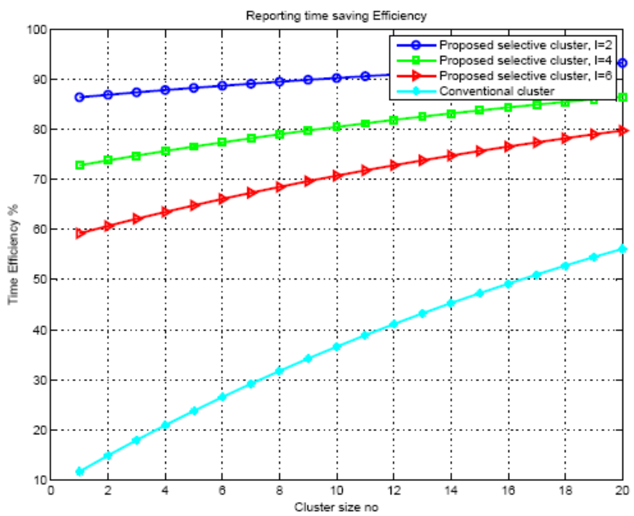

Figure 9: Graphical Representation on Reporting time saving efficiency of the proposed and conventional cluster-based CSS schemes

VI. Conclusion

We have proposed a cluster-based CSS scheme which includes the selective method in the cluster and the optimal fusion rule in the FC. The proposed selective combination method can dramatically reduce the reporting time and energy consumption while achieving a certain high level of sensing performance especially when it is combined with the proposed frequency division-based parallel reporting mechanism.

References

[1] D Cabric, SM Mishra, RW Brodersen, Implementation issues in spectrum sensing for cognitive radios. Conf. Record of the 38th Asilomar Conf. on Signals, Systems and Computers. 1, 772–776 (2004)

[2] L Chen, J Wang, S Li, in 4th International Symposium on Wireless Communication Systems. An adaptive cooperative spectrum sensing scheme based on the optimal data fusion rule (IEEE Piscataway, 2007), pp. 582–586.

[3] N Nguyen-Thanh, I Koo, An efficient ordered sequential cooperative spectrum sensing scheme based on evidence theory in cognitive radio. IEICE Trans. Commun. E93.B(12), 3248–3257 (2010).

[4] L Hesham, A Sultan, M Nafie, F Digham, Distributed spectrum sensing with sequential ordered transmissions to a cognitive fusion center. IEEE Trans. Signal Process. 60, 2524–2538 (2012)

[5] S Maleki, G Leus, Censored truncated sequential spectrum sensing for cognitive radio networks. IEEE J Selected Areas Commun. 31, 364–378 (2013).

[6] L De Nardis, D Domenicali, MG Di Benedetto, in 4th International Conference on Cognitive Radio Oriented Wireless Networks and Communications 2009 (CROWNCOM '09). Clustered hybrid energy-aware cooperative spectrum sensing (CHESS) (IEEE Piscataway, 2009), pp. 1–6.

[7] S Hussain, X Fernando, Approach for cluster-based spectrum sensing over band-limited reporting channels. IET Commun. 6, 1466–1474 (2012)

[8] B Vo Nguyen Quoc, TQ Duong, D Benevides da Costa, GC Alexandropoulos, A Nallanathan, Cognitive amplify-and-forward relaying with best relay selection in non-identical Rayleigh fading. IEEE COML. 17(3), 475–478 (2013).

[9] J. Mitola and G. Q. Maguire, "Cognitive radio: Making software radios more personal," IEEE Pers. Commun., vol. 6, pp. 13–18, Aug. 1999.

[10] H Urkowitz, Energy detection of unknown deterministic signals. Proc. IEEE. 55(4), 523–531 (1967).

[11] E Karami, AH Banihashemi, in 2011 Ninth Annual Communication Networks and Services Research Conference (CNSR). Cluster size optimization in cooperative spectrum sensing (IEEE Piscataway, 2011), pp. 13–17.

Mamjuda Hussain, M.Tech Scholar, Department of Electronics & Communication Engineering, Kanpur Institute of Technology, Kanpur, India.

Pratyush Tripathi, Associate Professor, Department of Electronics & Communication Engineering, Kanpur Institute of Technology, Kanpur, India.