Improving Throughput in Sub – Nyquist Spectrum Sensing Using a Cluster Model for Cognitive Radio Networks

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Abstract. The underutilization of radio spectrum has led to the downfall of Fixed Spectrum Allocation (FSA) since mobile frequency bands are getting overloaded due to rise of users all across the world. These drawbacks could be overcome by a concept called Dynamic Spectrum Allocation (DSA) implemented by an intelligent form of communication termed as Cognitive Radio Networks (CRN). CRN finds its applications adopted in military for battlefield surveillance, medical areas for 24x7 patient monitoring and also in TV white spaces. CRN involves SS in an efficient manner to deploy mobile users in TV frequency bands in a wider range through Wideband SS (WSS). WSS provides omnipresent spectrum monitoring for detecting spectral holes in the unutilized TV spectrum. The concept of Sub-Nyquist Sensing in WSS has several advantages in data sampling improving a plethora of application throughputs. The cluster approach in CRN has improved the base station crisis in load handling, throughput performance. In this paper, we focus on improving the traffic Quality of service (QoS) of the users in WSS by employing a cluster CRN network and applying Nyquist Sensing (NS) and Sub-Nyquist sensing (SNS) to find out the significance of SNS in the cluster network.

1. Introduction
Cognitive Radio Network (CRN) is an intelligent form of wireless communication where it becomes aware of the surrounding environment and gets adapted to the changes in the environment [1]. CRN provides efficient spectrum usage by eliminating the underutilization of the spectrum resources. CRN has mainly two users namely Primary Users (PU) or licensed users and Secondary Users (SU) or unlicensed user. Spectrum holes are created in the spectrum when the PU’s activity is not present for a particular sensing duration. These spectral holes can be utilized by the SU to communicate within the available spectrum without causing any interference to the PU [2]. The objective of this paper is to improve the traffic QoS (Throughput) of the users in Wideband Spectrum Sensing (WSS) using a cluster based model to compare the performance of Nyquist and sub Nyquist sensing on the proposed model and obtain an inference on the result.

The standard incorporated by IEEE 802 LAN/MAN Standard Committee (LMSC) is IEEE 802.22 which is used mostly used in remote areas across the globe [3], [4], [5]. It is a standard used for wireless regional networks which makes use of the unused spectrum in the TV white spaces called spectral holes for mobile communication on the limitation that no interference is caused to the licensed users. This standard was formed for the favours of unlicensed users aiming to access the TV spectrum on a non – interference basis. CRN plays a primary role in the spectrum utilization by SU in observing the spectrum to monitor the PU’s activity. This concept of spectrum monitoring is called Spectrum Sensing (SS) [6]. SS is a method of sensing the spectrum for unused frequency bands in the radio spectrum. Not always the PU is active in the radio spectrum and this issue lead to the underutilization of the resources. SS needs to be done continuously to avoid any bandwidth crisis.

SS is classified into Narrowband SS (NSS) and Wideband SS (WSS) on the basis of the bandwidth requirement [7]. NSS aims to sense the bandwidth of a range less than the coherence bandwidth which is around 25 KHz. Many techniques have been employed for NSS which emphasizes the concept of SS. They are Energy Detection, Matched Filter Detection, Cyclostationary Feature Detection and Waveform based Detection [8]. These techniques had failed to improve the spectrum
detection efficiency for many users in a TV white space. For example, one of the major terrestrial TV service provider is Doordharshan which operates on most parts of our country. Currently Doordharshan has 1415 TV Transmitters (TX) operating in India out of which 8 TXs transmit on the VHF Band-I, 1034 TXs transmit on the VHF Band-III and the remaining 373 TXs transmit on the UHF Band-IV. Since very less number of operators operate in the UHF Band, it is quite sparsely used in India and NSS will not be able to sense this much of a spectrum range [9]. To reform this sensing complication, the other type of sensing was introduced in CRN which is the WSS in which sensing is done for larger bandwidth which explores more spectral opportunities. WSS has a plethora of benefits on a dynamically varying spectrum which are reduced sensing time and larger bandwidth access.

Since the bandwidth detection range is very narrow for NSS, it may be difficult to detect any active transceivers within the radio spectrum. NSS may lead to synchronization issues due to the unavailability of CR users to detect the spectrum. Moreover, NSS cannot be used for higher bandwidth as it provides only a single binary decision for the whole spectrum [10]. Since NSS cannot be implemented for detection of larger spectral opportunities, WSS is the only key.

WSS is another approach which can sense at a larger bandwidth range (300 MHz to 3GHz), WSS can be classified into Nyquist SS (NS) and Sub-Nyquist Sensing (SNS). In [11], Quan et al. proposed a multiband joint detection algorithm that can sense over multiple bands. This algorithm proposes a method of sampling and converting a Wideband signal using an ADC and Fast Fourier Transform (FFT) techniques. Then the Wideband signal is split into several Narrowband signals to explore spectral opportunities using a binary hypothesis rest. Results proved that this algorithm can sense better spectral holes than a Narrowband sensing case. Furthermore Tian and Giannakis proposed a wavelet-based sensing algorithm in [12] where the Power spectral Density (PSD) of the Wideband signal was constructed as a train of sub bands and the PSD is smooth between these sub bands but evinced slight discontinuities among the sub bands. All these algorithms led to a failure due to the sampling limitation called by Shannon’s theorem. In this paper, we deploy a cluster network and apply SNS to improve the throughput performance over a dynamically varying spectrum.

The rest of the paper is organized as follows: Section II presents the literature survey. Section III proposes the system description. Section IV presents the simulation results and inference and Section V concludes the paper.

2. Literature Survey

In [13], Alqawasmeh et al., have developed an energy efficient multi-level cluster based SS technique with low complexities. This model was developed for many CRNs belonging to different sub groups which follow cooperative sensing approach under same radio environment. The grouping of the CR devices are done based on geolocation and based on the hierarchy levels using voting and combination rules between the sub cluster heads. Due to the involvement of sub groups the need for high computation algorithms and complexities are reduced using hierarchy level calculations. The technique was compared with traditional algorithms for different channel conditions and found to provide higher detection probability.

In [14], Jayant P.Pawar and PrashanthV.Ingole have together analysed the DSA scheme in IEEE 802.22 (WRAN) for varying operating interval and PU count in the same channel with constant operation time. They have provided a detailed study on the WRAN standard and calculated the throughput and spectral efficiency for the network and found that on increasing operating interval the throughput and spectral efficiency values increase while it decreases when PU count is increased. The on-off duration of Pus are varied providing move opportunities for secondary users but making spectrum more dynamic. The authors have highlighted the importance and impact of DSA on WRAN with continuously varying parameters.

In [15], Jain P.C has discussed about Wireless Broadband Internet access for WRAN TV white space in VHF and UHF frequency bands. The frequency bands can be deployed for wide range applications. The use of Geo-Location technology and Cognitive Engine with Machine learning algorithm and sensing algorithms made with SDR device helped in establishing broadband services
easily as the signal strength is stronger than Wi-Fi or 4G signals. The Frame work and architecture of Mac defining scheduling time periods and energy and feature detection performed in the Mac layer and the role of BS in Resource management and portioning are detailed. The author provides has provided a detailed view on the functionality and architecture of each component in the WRAN and has proven the sustained use of spectrum by assigning TV white space for internet access in rural area.

In [16], Hongjian Sun et al., have assessed and presented a survey on taxonomy and techniques for WSS in CRN. They provide a comparison on different narrowband techniques and highlight the disadvantages of using these techniques for WSS. The two categories namely NS and SNS in WSS are discussed. The different open research challenges in WSS are detailed. They have demonstrated the importance of OSA in CR and its effect on sensing accuracy. The sparsity level uncertainty is an important issue in next generation networks, which is explained and solved using SNS based WSS.

In [17], Mourad Mabrrok et al., have developed a blind WSS using multi-coset samplers for SNS technique. Lomb Scargle periodogram algorithm is used for detecting active bands. The modified algorithm is easily adaptable to the changes in active bands and switches easily involving least computational requirements. Eigen values for samples are calculated and noise is distinguished from information signals based on these values and the data on the number of active slots are obtained. Using Music like algorithm the location of active slots are obtained and the reconstructed signal is obtained. The modified algorithm achieved low Mean Square Error and Signal to Noise Ratio.

In [18], Ashish Bagwari et al., have deployed cluster based SS approach for wideband. They have surveyed and provided comparison for CR device performance for with and without cluster approach for voice and custom application traffics. The communication between networks using cluster approach was established between 14 CPE devices. The throughput for cluster based approach was higher than network without cluster. Though they have addressed spectrum scarcity issues and need for resources when many CPE devices are used they have failed to improve the detection performance through cluster network.

In [19], Fan Deng et al., have discussed about cluster based compressive WSS in CRN. They have developed a joint detection mechanism in cluster network for cooperative SS using SNS called Cluster based joint compressive sensing (C-JCS) using Maximum Entropy Clustering (MEC). They have used reconstruction algorithms and data fusion idea to improve the efficiency and effectiveness of the method. The approach was compared with Independent compressive sensing and Joint compressive sensing techniques and found to be outperforming the traditional algorithms.

In [20], Rajiv Kumar Berwer and Santhosh Kumar have demonstrated a multi-channel based clustering approach a topology management mechanism for CRN. The method involves two phase where, in the first phase the device or node with maximum degree of priority is identified and selected as cluster head and in the second phase the remaining devices join the cluster heads by sharing information. They have aimed to reduce the message overhead caused in this approach and reduce the design complexities.

3. Proposed Mechanism

3.1. System Model and Cluster based Approach

The whole concept of this mechanism is based on how SS and sampling is done by CRN which is shown in Figure 1.
CRN plays a major role in SS, spectrum decision, spectrum sharing and spectrum mobility. The proposed model comprises of a network with sub networks as clusters in an entire CRN network. A basic network with a single base station has its own complications in terms of the load carried by the base station to transmit and receive signals from various nodes which is very huge and over the time, the connectivity and durability of the base station reduces. Other issues include network congestion in the case of several hundred nodes connected to a single base station, call dropping especially in the voice transmission over larger distances. These models adopt a binary decisive expression to identify the unused spectrum band of licensed users which is given in Equation 1, 2 and 3.

\[
x(t) \rightarrow X(F) \quad (2.1)
\]

\[
H_0: y(k) = w(k) \quad (2.2)
\]

\[
H_1: y(k) = s(k) \times h(k) + w(k) \quad (2.3)
\]

for \(k=1,2\ldots n\).

where \(n\) is the number of received samples, \(w(k)\) is the additive white Gaussian noise, \(s(k)\) indicates the PU signal, \(H_0\) and \(H_1\) are the sensing states for a binary decision indicating that \(H_0\) is a null hypothesis for a free state and \(H_1\) is a valid hypothesis for a busy state in PU’s activity.

The proposed model is a cluster network in CRN for data communication between mobile nodes as it had several advantages over a general CRN network. Figure 1 depicts the cluster model for a communication scenario which consists a total of 14 nodes connected through 3 sub networks called clusters. Here, nodes 1 to 7, 2 to 3, 8 to 14 and 11 to 12 are communicating with each other through the base station using video, CBR, Email and Voice applications respectively. Each nodes are placed at an average distance of 30 metres to avoid any interruptions in their transmission [20]. The mobile nodes here are connected via a half-duplex wireless link whereas the switches and routers are connected via wired links. A cluster model is generally approached when the size of the network increases which would impact sensing the spectrum bands.
In analysing figure 2, we can see that the cluster network clearly overcomes the complications of load on base station, traffic congestion between data packets and interconnectivity which was faced by previous network models. In this network, the data between the nodes for different application are sent from the TX node which reaches the sub network base station and it is forwarded via the L2 switches to the router which connects the entire cluster network which is then eventually sent to the Receivers (RX). For example, the data from video application is sent from Node 1 TX to the central router which then forwards the packets to Node 7 RX. The keep out distance is always set to 100 metres to maintain antenna gain [21]. The whole concept of this cluster network in based on a technique called Cooperative SS (CSS) [22] which has laid the path in improving the spectrum detection capability. There are few challenges faced in SS which reduction in detection capability due to the effect of fading and shadowing changes and detecting very weak PU signal with negative PSD (nearly down to -20dB). These challenges are overcome by CSS in an effective manner as it has a separate Fusion Centre (FC) [23] which collects the sensing results from different CR’s and then obtains a binary decision on the PU’s presence which are then communicated to different CR’s. Thus, CSS has a better detection capability under different conditions which is quite not possible in the previous case.

3.2. WRAN Architecture

CRN had its own network topology formulated by IEEE as IEEE 802.22 Wireless Regional Area Networks (WRAN). WRAN has a fixed point to multipoint air interface system and the significance of shifting towards WRAN is the reason that it has a fixed wireless network connectivity even in the sparsely populated remote regions with a range of 1-100 Kms [24]. The main reason of incorporating the IEEE 802.22 than any other 802 standards it has higher data rate, channel bonding, better range and a complex spectrum management due to CSS which makes the bands invulnerable against third-party attacks. WRAN is primarily employed in the TV white spaces for several transmissions like Analog Television (power level of -94 dBm), Digital Television (power level of -116 1dBm), and Wireless microphones (power level of -107 dBm) [25].

3.3. Implementation of wideband SS

The other part we focus on this paper is about WSS. WSS makes SS less complex due to its wider range of spectrum detection (300MHz to 3GHz). WSS is classified as Nyquist SS (NS) and Sub-Nyquist SS (SNS). Nyquist sampling provides sampled data at a rate which very much higher than the Nyquist rate which is twice the maximum frequency of the input signal. These high sampling rate
requirements, a high rate ADC with high resolution and reasonable power consumption is to be modelled [26].

Figure 3. Sweep-tune detection

Even though this model has a very simple structure and high dynamic range in SS, the implementation of this ADC is very difficult due to expensive real-time digital signal processing. Another method to tackle this high sampling rate issue is to use heterodyne sweep-tune sampling as shown in Figure 2 [27], [28] where a Local Oscillator (LO) and a Band Pass Filter (BPF) is used to down-convert and filter the Wideband signal and the existing spectrum techniques could be applied.

3.4 Significance of SNS

However, NS techniques are not feasible due to multiple channel requirement and design accuracy sensitivity. These drawbacks can be overcome by applying SNS where sampling is done at a lower rate than Nyquist rate. High performance ADC’s are not required for this technique since sensing is done even with partial measurements. The two important types of SNS are compressive wideband sensing and multichannel wideband sensing. Compressive wideband sensing is a major technique employed in SNS due to the sparseness of the signal in the spectrum. Some of the algorithms proposed for SNS include cyclic feature detection, distributed compressive sensing for multihop CRN and Analog to Information Converter (AIC) [29], [30]. We implement SNS in our network to reduce the data transmission traffic which improves the throughput performance. In the next section we will look into the simulation scenarios and results and provide an inference on the latter.

3.5 Algorithm

The network incorporates NS or SNS based sampling techniques on a Wideband signal sent from TX 1 of sub network 1 to RX7 of sub network 2. In every PU on/off duration and sensing time interval the spectrum is sensing using SS automation and SS Function and spectrum manager which tracks the location of the PU and it is used to calculate spectrum through binary hypothesis. Together with the RX and spectrum information the spectrum probability of detection is made more precise. So, therefore it provides an accurate information on the available spectrum. The algorithm for the entire work is given below as follows.

1) Input – TX – CPE 1, CPE 2, CPE 8, CPE 11
   RX – CPE 7, CPE 3, CPE 14, CPE 12
   Application – Video, CBR, Email, Voice

2) Function – CPE 1 – CPE 7 (Video application)
   Bit rate – Frame per Sec.: 40; Pixel per Frame: 10000

3) CPE 2 – CPE 3 (CBR application)
   Bit rate - Packet size: 500; Inter-arrival time: 20000 microsecond

4) CPE 8 – CPE 14 (Email application)
   Bit rate - Packet size: 500; Inter-arrival time: 20000 microsecond

5) CPE 11 – CPE 12 (Voice application)
   Bit rate – Email size (bytes): 30000
6) Sampling: SNS
7) Spectrum Monitoring SSF (Enabled)
8) QoS: Best Effort (BE) service
9) Antenna Height: 1 metre
10) Keepout Distance: 100 metres (detect every time)

4. Results and Discussions

4.1 Introduction to NetSim

The entire work has been carried on NetSim v12.0 simulation tool or software. NetSim is a network simulator which is used to create a network and study the behaviour and performance of the network. NetSim v12.0 comes under the NetSim standard version. The simulation scenarios for a clustered and non-clustered CRN are shown in Figure 3-4. The system settings are set before any scenario is plotted and these settings are managed by the license server which is the hub to all other system settings and connected via a USB dongle.

4.2 Simulation Scenario

![Figure 4. Illustration of a non-cluster based approach for Cognitive Radio Networks setup using NetSim software](image)

![Figure 5. Illustration of a cluster-based approach for Cognitive Radio Networks setup using NetSim software](image)
### Table 1. Simulation Setup

| METRIC                              | VALUE            |
|-------------------------------------|------------------|
| Min Frequency                       | 490 MHz          |
| Max Frequency                       | 496 MHz          |
| Simulation Time(milli-second)       | 10000.0          |
| Modulation Scheme                   | QAM-64           |
| Nodes                               | 1 to 7, 2 to 3, 8 to 14 and 11 to 12 |
| Application                         | 1 to 7 – Video, 2 to 3 – CBR, 8 to 14 – Email, 11 to 12 - Voice |
| No of Nodes                         | 14               |
| Transmission Power                  | 4 Watt           |
| Multiple Access Technique           | OFDMA            |
| Coding Rate                         | 5/6              |
| QoS                                 | Best Effort      |

### 4.3. Comparison of Cluster and Non-Cluster CRN

**APPLICATION METRICS**

**Table 2.** Packet transmission results for non-cluster CRN

| App ID  | Source ID | Dest ID | Packet Transmitted | Packet Received | Payload Transmitted | Payload Received | Throughput (Mbps) |
|---------|-----------|---------|--------------------|-----------------|---------------------|------------------|------------------|
| 1(video)| 1         | 7       | 998                | 996             | 99800               | 99600            | 0.07             |
| 2(CBR) | 2         | 3       | 6986               | 1503            | 698600              | 150300           | 0.12             |
| 3(Email)| 8         | 14      | 1005               | 996             | 100500              | 99600            | 0.06             |
| 4(Voice)| 11        | 12      | 2700               | 486             | 270000              | 48600            | 0.09             |

**Table 3.** Packet transmission results for cluster CRN

| App ID  | Source ID | Dest ID | Packet Transmitted | Packet Received | Payload Transmitted | Payload Received | Throughput (Mbps) |
|---------|-----------|---------|--------------------|-----------------|---------------------|------------------|------------------|
| 1(video)| 1         | 7       | 6986               | 1451            | 698600              | 149250           | 0.11             |
| 2(CBR) | 2         | 3       | 7000               | 1648            | 700000              | 164800           | 0.13             |
| 3(Email)| 8         | 14      | 6995               | 1715            | 699500              | 171500           | 0.14             |
| 4(Voice)| 11        | 12      | 6945               | 1917            | 694500              | 191700           | 0.17             |
Figure 6. Video throughput comparison for a clustered and non-cluster CRN

Figure 6 shows the video throughput for a clustered and non-clustered CRN. The graph depicts that clustered CRN outperforms the non-clustered CRN by a difference of 4% due to the factor of uninterrupted video data transmission.

Figure 7. CBR throughput comparison for a clustered and non-cluster CRN

Figure 7 shows the video throughput for a clustered and non-clustered CRN. The graph shows that clustered CRN outperforms the non-clustered CRN by a percentage of 2% due to the fact that CBR data relates to our local SMS which we send in our daily life 2% is a major improvement for several message transmissions.
Figure 8. Email throughput comparison for a clustered and non-cluster CRN

Figure 8 shows the video throughput for a clustered and non-clustered CRN. The graph shows that clustered CRN outperforms the non-clustered CRN by a percentage of 7% which indicates a smooth transmission of Email packets.

Figure 9. Voice throughput comparison for a clustered and non-cluster CRN

Figure 9 shows the video throughput for a clustered and non-clustered CRN. The graph shows that clustered CRN outperforms the non-clustered CRN by a percentage of 8% due to very less chances of packet loss which leads to avoidance of call dropping.

4.4 Comparison of NS and SNS Cluster CRN

APPLICATION METRICS

| App ID | Source ID | Dest ID | Packet Transmitted | Packet Received | Payload Transmitted | Payload Received | Throughput (Mbps) |
|--------|-----------|---------|--------------------|-----------------|--------------------|-----------------|------------------|
| 1(video)| 1         | 7       | 6986              | 1451            | 698600             | 149250          | 0.11             |
| 2(CBR) | 2         | 3       | 7000              | 1648            | 700000             | 164800          | 0.13             |
| 3(Email)| 8        | 14      | 6995              | 1715            | 699500             | 171500          | 0.14             |
| 4(Voice)| 11       | 12      | 6945              | 1917            | 694500             | 191700          | 0.17             |
Table 5. Throughput results for SNS based clustered CRN

| App ID | Source ID | Dest ID | Packet Transmitted | Packet Received | Payload Transmitted | Payload Received | Throughput (Mbps) |
|--------|-----------|---------|--------------------|-----------------|---------------------|------------------|-------------------|
| 1(video)| 1         | 7       | 2761               | 2760            | 276100              | 276000           | 0.20              |
| 2(CBR) | 2         | 3       | 2945               | 2940            | 294500              | 294000           | 0.23              |
| 3(Email)| 8        | 14      | 2775               | 2770            | 294000              | 273500           | 0.22              |
| 4(Voice)| 11       | 12      | 2700               | 2700            | 270000              | 270000           | 0.21              |

Figure 10. Video throughput for a NS clustered CRN and SNS clustered CRN

The throughput comparison plot for NS clustered CRN and SNS clustered CRN is plotted in the Figure 10. The graph indicates that the SNS clustered CRN exceeds NS clustered CRN by a factor of 9%. This is due to the sparse allocation of video packets which helps in faster transmission. These mantissa values are very accurate because of the reason that throughput values of the throughput plot within the given time (ms) are more than around 2000. As they need to be accumulated within the given space, the entire plot takes very specific accurate values listed among them to be shown in the graph.

Figure 11. CBR throughput for a NS based clustered CRN and SNS based clustered CRN
The throughput comparison plot for NS clustered CRN and SNS clustered CRN is plotted in the Figure 11. The graph indicates that the SNS clustered CRN exceeds NS clustered CRN by a factor of 10% due to the CBR performance in SNS sampling.

![Throughput plot for Voice Traffic](image)

**Figure 12.** Voice throughput for a NS based clustered CRN and SNS based clustered CRN

The throughput comparison plot for NS clustered CRN and SNS clustered CRN is plotted in the Figure 12. The graph indicates that the SNS clustered CRN exceeds NS clustered CRN by a factor of 9% due to the lossless transmission of voice data throughout the entire transmit duration.

![Throughput plot for Email Traffic](image)

**Figure 13.** Email throughput for a NS based clustered CRN and SNS based clustered CRN

The throughput comparison plot for NS clustered CRN and SNS clustered CRN is plotted in the Figure 13. The graph indicates that the SNS clustered CRN exceeds NS clustered CRN by a factor of 5%. This improvement is entirely based on the sampling rate set for SNS during simulation.

These results which are plot in the Figures 6-13 clearly indicates that a cluster CRN has its own throughput refinement over the previous versions and applying SNS technique in these samples upgrades the throughput to a higher level.
5. Conclusion and Future Scope
In this work, we aim to improve the traffic QoS of the users in the cluster CRN operating in wideband spectrum. The performance of the network is evaluated and compared for Nyquist and Sub Nyquist based Sampling for WSS in terms of throughput. NSS makes a single binary decision for the entire spectrum failing to recognize the individual spectral opportunities over a wide frequency band and because of this it is essential to go for WSS as it is capable of achieving higher opportunistic throughput by potentially exploiting more spectral opportunities over a wideband. The cluster model discussed consists of a set of 14 nodes which makes a 3 cluster network and it also has 2 switches and a router. Some of the important parameters set for this network are the path loss model which is log normal and the Downlink: Uplink ratio which is set to 1:1. Clustered CRN network provides an enhanced throughput than non-clustered CRN and SNS based clustered CRN also has an improved throughput performance when compared to NS based clustered CRN. NS based clustered CRN is more beneficial for higher throughput and improved spectrum utilization.

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