COOPERATIVE SPECTRUM SENSING METHODOLOGY FOR COGNITIVE RADIOS THROUGH SCHEDULING/ TASKING

by

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Dedicated to the memory of my father

Muhammad Akhtar Hussain, who belonged to the first generation of Telecommunication Engineers that proudly served this country and from whose memory I still draw inspiration.

May Allah bless his soul, Ameen!

Abstract

The rapid advancement in the field of wireless communications that has been expedited by the commercial demand for better services has led to the application of wireless systems in many fields of life. Ranging from military radio communication systems, to cellular systems and wireless sensor networks; purposely emitted radio waves occupy major parts of the frequency spectrum. The past few decades have seen the development of many wireless systems that have been permanently allocated spectrum by regulatory authorities.

Direct and indirect observation of spectrum usage has identified the temporal and spatial availability of spectrum within allocated frequency bands. This implies that although spectrum scarcity is becoming a major problem, however intelligent access to pre-allocated spectrum has the potential to enable usage of licensed spectrum by unlicensed users on the pre-agreed condition of minimum interference.

Cognitive networks promise to solve these problems of spectrum scarcity by accommodating unlicensed (secondary) users in under-utilized segments of the spectrum. Spectrum sensing forms the primary stimulus for a cognitive radio and is vitally important for ensuring that the unlicensed users do not offer intolerable levels of interference to licensed (primary) users. Cooperative

spectrum sensing provides the capability to cognitive networks to overcome problems related to “hidden” primary users. In this research, we have presented a novel strategy that takes advantage of cooperative diversity to establish grouping among cooperating secondary users. This strategy is then extended to group-based spectrum sensing to establish a scheduling/ tasking mechanism. The strategy ensures enhanced agility that will result in a reduction of interference to primary users through their early detection.

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This work would have never materialized, had it not been for the consistent prayers, love, support and encouragement of my family. Thank you for tolerating my absence from home in pursuit of this work.

I thank you all!

List of Acronyms

Acronym	Meaning
AM	Amplitude Modulation
AMPS	Advanced Mobile Phone Service
ASIC	Application Specific Integrated Circuit
ATSC TV	Advanced Television Systems Committee
AWGN	Additive White Gaussian Noise
BPSK	Binary Phase Shift Keying
CDFC	Central Decision Fusion Center
CDMA	Code Division Multiple Access
cov	Covariance
CR	Cognitive Radio
CRN	Cognitive Radio Networks
CSS	Cooperative spectrum sensing
Ctrl Sys	Control System
DARPA	Defense Advanced Research Projects Agency
DEC Alpha	DEC Alpha Server System
DSA	Dynamic Spectrum Allocation
DSP	Digital Signal Processing
EDGE	Enhanced Data Rates for GSM Evolution
EIRP	Equivalent Isotropically Radiated Power
EV-DO	Evolution - Data Optimized
FAB	Frequency Allocation Board, Pakistan
FCC	Federal Communications Commission, USA
FD	Frequency Division
FFT	Fast Fourier Transform
FH	Frequency Hopping
FM	Frequency Modulation
FPGA	Field Programmable Gate Array
GDFC	Group Decision Fusion Center

Acronym	Meaning
GPP	General Purpose Processor
GPRS	General Packet Radio Service
GSM	Global System for Mobiles
HF	High Frequency
I/O	Input/Output
IEEE	Institute of Electrical and Electronics Engineers
IF	Intermediate Frequency
Info	Information
INFOSEC	Information Security
IS	Irregular Sub-band
ITU	International Telecommunication Union
MILCOM	IEEE Military Communications Conference
MODEM	Modulator/Demodulator
NMT	Nordic Mobile Telephone
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OSI	Open Systems Interconnection Reference Model
PDA	Personal Digital Assistant
PSD	Power Spectral Density
PU	Primary user
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
Reconfig	Reconfiguration
RF	Radio Frequency
RKRL	Radio Knowledge Representation Language
RX	Receiver
SCF	Spectral Correlation Function
SCORE	Signal Communication by Orbiting Relay Equipment
SDL	Simple DirectMedia Layer
SDR	Software Defined Radio
SFD	Staggered Frequency Division

Acronym	Meaning
SIS	Staggered Irregular Sub-band
SNR	Signal to Noise Ratio
SoC	System-on-Chip
SQPSK	Staggered Quadrature Phase Shift Keying
SU	Secondary user
Sys	System
TD	Time Division
TDMA	Time Division Multiple Access
TV	Television
TX	Transmitter
UHF	Ultra High Frequency
UML	Unified Modeling Language
UMTS	Universal Mobile Telecommunication System
UNIX	UNIX Computer Operating System
US or USA	United States of America
UWB	Ultra Wide Band
VHF	Very High Frequency
WiMAX	Worldwide Inter-operability for Microwave Access
WSN	Wireless Sensor Network
WSS	Wide Sense Stationary
xG	Next Generation Networks
XOR	Exclusive OR

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Chapter – 1

1. Introduction

1.1 History: In 1864, James Clerk Maxwell presented the *Electromagnetic Theory of Light* and predicted the presence of radio waves. The revolutionary concept of using these waves for communication was practically demonstrated by Oliver Lodge in 1894 and subsequently by Marconi [1]. In 1901, the first trans-Atlantic wireless communication link was demonstrated. Radio broadcast was demonstrated by Reginald Fessenden using amplitude modulation (AM) in 1906. The use of wireless communication in merchant shipping helped save over 700 lives in the *Titanic* disaster of 1912. World War I contributed to the rapid deployment and testing of various radio communication techniques and standards. Developments in this field led to the use of various AM and FM techniques in VHF and HF frequency bands. World War II saw the development of multiplexed and trunked radio access systems. Police and other emergency services joined the bandwagon and large scale metropolitan networks began to appear for these services. In 1946, the first *Public Mobile Telephone System* became operative in five American cities [2]. Spread Spectrum techniques appeared in the same era with the primary objective of enhancing security of wireless communications [3]. With the launch of the SCORE satellite in 1958, radio communications was extended to space [4]. In 1981, the first analog cellular communication system, Nordic Mobile Telephone (NMT), commenced services in Scandinavia [5]. This was soon followed in 1983 by the Advanced Mobile Phone Service (AMPS) in USA [6]. Digital wireless communication led to the development of various 2nd and 3rd generation standards such as GSM, CDMA IS-95, CDMA-2000, UMTS, EV-DO, etc [7]. The quest for higher data rates has ensured that research and development in this field will yield better and more efficient standards. These standards continue to tax the spectral resources, creating a spectrum scarcity situation.

1.2 Spectral Resource Management: Radio or wireless communications gained immense popularity and application due to its inherent advantages of mobility and deployment speed. These advantages were of paramount importance to applications in military, police and emergency services communications. Thus a lot of development in this field was sponsored directly or indirectly by various government agencies. This meant availability of large research endowments as well as ease in regulatory matters. Government regulatory authorities, such as Federal Communication Commission (FCC) in USA have made permanent allocations of large frequency bands to various services. Many of these services include non-commercial systems such as military, police and emergency communications. In Pakistan, the Frequency Allocation Board (FAB) is responsible for such allocations. Additionally, these organizations must conform to any applicable International Telecommunication Union (ITU) regulations as set forth during the biennial World Radio Communication Conferences. The ITU's Radio communication Sector coordinates spectrum use on an international level, seeking to globally harmonize RF spectrum bands and to reduce harmful interference between countries to improve the use of RF services. A typical spectrum allocation cycle is shown in Fig.1 [8].

Whenever a company receives a license to operate in a particular segment of the spectrum, it attains exclusive rights of usage and any unauthorized use of this segment is considered as interference. The prime motivation for purchase of larger than needed segments is to guarantee optimal service to the primary (licensed) users. Another aspect is the availability of spectrum for future expansion of user-base. Another large scale user of the frequency spectrum is terrestrial TV broadcast.

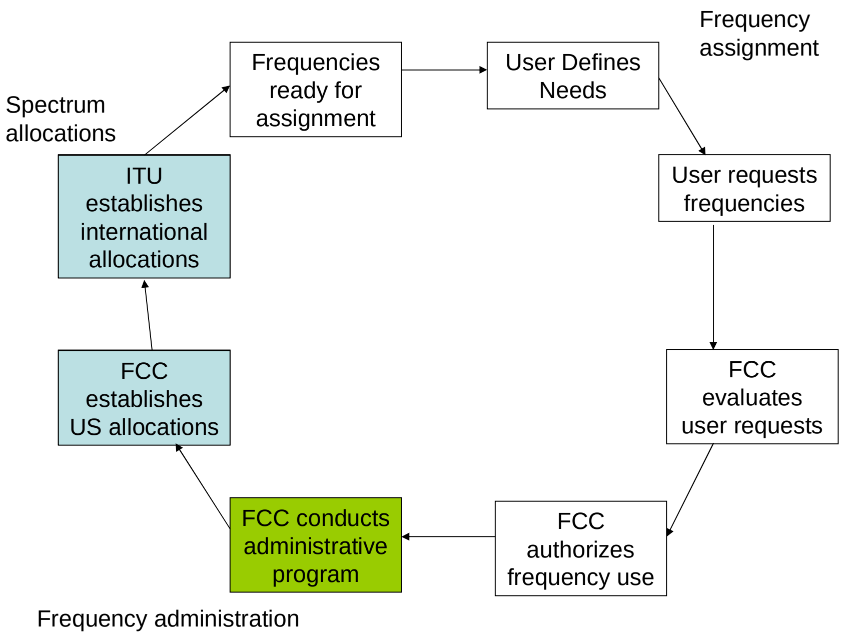


Fig.1. Spectrum Allocation Cycle

With the advent of satellite TV broadcast and IP based cable distribution systems, terrestrial TV seems to be outdated. An analysis carried out by FCC revealed that an average of 50% of allocated spectrum is unused at any given place or time [9]. A more thorough analysis reveals that while 50% of allocated spectrum is unused, a further 30% of the allocated spectrum is under-utilized. Thus it can be safely said that approximately 80% of the allocated spectrum is under-utilized [10]. This implies that existing policies need to be revisited to ensure that spectral resources are optimally utilized.

A review of existing policies on Spectrum Management was conducted by FCC [11]. As a result of this review, FCC recently issued a second report and order in the matter of Unlicensed Operation in TV Broadcast Bands on 14 November 2008 [12]. This document essentially defined the parameters under which unlicensed users would be permitted to operate in TV bands. It categorized these unlicensed users into Fixed devices and Personal/ Portable devices. The ability to sense spectrum occupancy has been considered as a pre-requisite. This ability may be on an individual basis (with a lower cap on permissible EIRP) or centralized/ cooperative.

This re-evaluation of spectrum management policy has opened up new avenues for research into the fields of Dynamic Spectrum Sensing and Access. It has also assured a better management policy that is futuristic, efficient and technology friendly. With this policy, it is now possible to incorporate greater advancements in sensor and ad-hoc networks. The key aspect remains the ability of the nodes (or the network) to sense 'white spaces' or spectrum opportunities for further allocation. Thus the prime stimulus for access to under-utilized spectrum is the ability of Spectrum Sensing.

1.3 Spectrum Deficiency: There is a definite need to understand the gravity of the spectrum deficiency situation. A comprehensive review of the RF environment is often misleading, especially in third-world countries such as Pakistan. A snapshot view of spectral availability obtained through measurements with Spectrum Analyzers reveals large ‘white spaces’. This means that there is virtually no deficiency of spectrum, even in the TV band. However, if we correlate these measurements with the FCC allocations that are also complied by Frequency Allocation Board of Pakistan, we observe that large portions of this band are allocated to licensed users [13]. Thus, in reality, there is a virtual spectral deficiency that does not permit further allocations of the spectrum. Apparently, this is a legal issue. The primary (licensed) users or PUs have been guaranteed spectrum access in their licensed bands. However, the actual occupation of the spectrum is varying on geographical as well temporal basis. Thus the spectral deficiency can be overcome by using techniques that permit intelligent access to spectral resources through interference avoidance, dynamic sensing of opportunities and appropriate allocation. Emerging concepts in this regard include Spread Spectrum [14] (CDMA and UWB), Software Defined Radios [15] and Cognitive Radios [16]. FCC has defined a metric on the basis of aggregate interference temperature and maximum EIRP that is permissible [12]. The concept can be seen in Fig.2 [17].

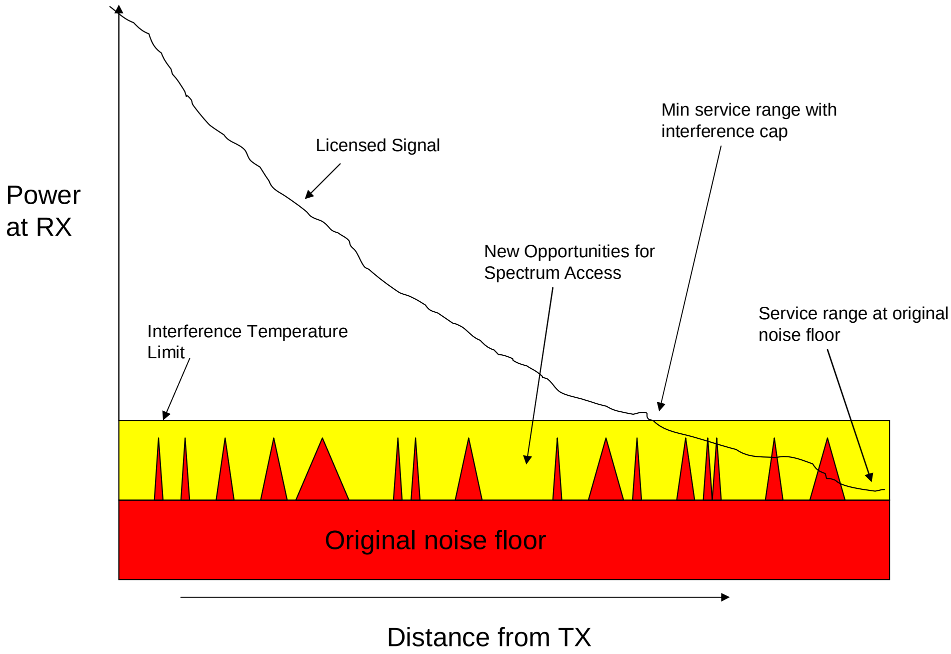


Fig.2. Interference Temperature Model

1.4 The Cognitive Radio Paradigm: The word 'cognitive' or 'cognition' pertains to the mental process of perception, memory, judgment and reasoning [18]. It is essentially a human function, wherein there is a stark contrast to emotional or volitional motivations. Cognitive ability, when applied to a radio device implies that the radio is capable of observing, orientating, planning and acting. This term was originally coined by J. Mitola in an article in 1999 [19] and was elaborated in great detail in his Ph.D. dissertation of 2000 [20]. He described the Cognitive Radio paradigm as [21]:

"The point in which wireless personal digital assistants (PDAs) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to detect user communications needs as a function of use context, and to provide radio resources and wireless services most appropriate to those needs."

With this paradigm in mind, it is logical to conclude that the Cognitive Radio (CR) platform will provide the solution to the problems of spectrum scarcity due to its ability to observe and adapt. A CR platform will be able to detect spectral opportunities coupled with user needs and adapt accordingly. In its entirety, the CR concept is still in its development phase. A lot of ongoing research is related to its various functions, such as spectrum sensing, spectrum management, spectrum mobility and spectrum sharing. With machine learning capabilities, the CR will be able to continuously adapt to changing user needs, RF environments and emission policies, transforming into a truly intelligent communication device.

Due to the importance of this emerging field, many existing research organizations have joined the bandwagon in a bid to capitalize on developments. The SDR Forum is an industry funded research group that has focused on the development of Software Defined Radios (SDR) [22]. In its report, the SDR

Forum describes SDR as the enabling technology for CR [23]. However, the difference between the various involved technologies has been clarified by J. Mitola [20]. Fig.3. describes the dimensions of software radio implementations.

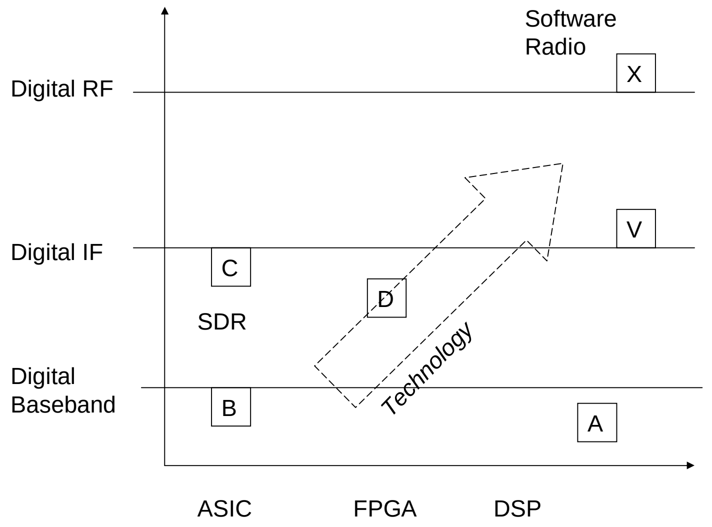


Fig.3. Dimensions of Software Radio Implementations

The implementations from A to D are present-day SDRs. The virtual radio at V is an ideal single-channel SDR based on a DEC Alpha processor running UNIX. Implementation X is the ideal Software Radio with RF digital access. All functions are programmable; however it has implementation issues that are being subjected to research. Thus, SDR is a platform that can utilize a large range of RF bands and air interface modes through software. An ideal software radio would further incorporate all bands and modes required by a user.

Add the ability to learn from all this and adapt accordingly – you would create the blend necessary for a CR.

1.5 Motivation for Research: With the present state of research in this field, it is obvious that this area is one of the hottest areas of research in the field of wireless communications. It has rightly been declared as the gateway to the next generation networks. Pakistan has been at the forefront of technological adoption in the telecommunications arena. Pakistan was the first country in South Asia to get a nation-wide optical fiber backbone. It also achieved the highest rate of consumer growth in cellular communications. Telecommunications is a major stimulus for economic growth and prosperity in any country. Research into enabling technologies for next generation networks is of vital importance in this regard.

It is a well established fact that Software Radios are finding immense applications in military communications. A lot of research in this area has been funded and sponsored by Defense departments around the world. The active participation of IEEE MILCOM conferences in this field is a testimonial to this fact. Battlefield communications are adversely affected by the presence of numerous emitters that are temporary entities, often not under a single command structure. It has been estimated that in the deployment area of a mechanized division spread over 70km by 45 km, more than 10,700 individual emitters would be transmitting in a shared spectrum [24]. This is a network managers' nightmare for military communication planners. Unless more efficient techniques of spectrum management are introduced, military communication planners will have to consider moving well beyond 3 GHz. The SDR has the capabilities to offset this disadvantageous spectral situation. Pakistan Army has been contemplating the development/ induction of SDRs for quite some time. A lot of work has been done in this regard. The CR concept for military network deployment is, logically, the next step in the development of next generation wireless communication systems for the armed forces.

Spectrum sensing is the primary stimulus for this technology. FCC has made it mandatory for all unlicensed devices to incorporate effective mechanisms of spectrum sensing [12]. A lot of work has been done on spectrum sensing techniques. Cooperative spectrum sensing methodologies are still a relatively open area of research. These methodologies take advantage of cooperative diversity to expand the information base as well as to reduce the workload on individual sensing nodes. The prime question is when to cooperate and with whom.

This work focuses on developing a methodology for effective cooperation that addresses the questions related to establishment of a cooperative environment. The effectiveness of this methodology would depend upon the correctness of the fused decision about the presence or absence of a primary user (PU) on a particular frequency. It would also depend upon minimizing the time taken to detect the presence of a PU so that a decision to vacate the frequency by the CR is taken in minimum time. This latter metric is often termed as 'agility'.

1.6 Goals of Research: This research has been undertaken with the following goals:

1.6.1 Academic Goals:

- To carryout a study of Cognitive Radio Networks as an enabling technology for Next Generation radio networks in a spectrum scarcity scenario.
- To extend the study to the specific area of spectrum sensing in a cooperative environment.

1.6.2 Technical Goals:

- To simulate a suitable spectral environment for testing of cooperative spectrum sensing functions.

- To develop an algorithm that permits scheduling/ tasking of cooperative spectrum sensing functions on the basis of correlation of individually sensed environments.

1.7 Structure of Document: This document has been prepared to present a comprehensive overview of this research. Chapter 1 of the document is an introductory chapter that covers basic concepts related to issue being researched. Chapter 2 focuses on the overall concept of CR with relevant details about the existing work in this field. Chapter 3 describes the proposed methodology for CSS and presents the flow of this algorithm. Chapter 4 explains the simulation details and the results obtained. The last chapter is Chapter 5, which concludes the thesis report while describing some of the future research issues that need to be addressed. A comprehensive bibliography is given at the end.

<u>Chapter – 2</u>

2. The Cognitive Radio (CR)

2.1 Conceptual Development of CR:

2.1.1 The Frequency Hopper: Military radio communications opted for frequency hopping [25] as a mode of achieving a certain degree of resistance to Electronic Counter Measures [26] such as jamming [27]. Initial hopper radios were able to jump over a wide range of frequencies according to pre-designated hopping algorithms or Transmission Security Keys. A failure to establish synchronization at a particular frequency was considered jamming and the link would shift to new frequencies. Due to data transmission, a certain degree of latency was accepted. These hoppers gradually evolved with the help of a small degree of spectrum sensing. Subsequent versions of hoppers were able to modify the hopping sequences according to sensed spectrum occupancy. It has been made possible due to adaptive spectrum exploitation as can be seen in Fig. 4.

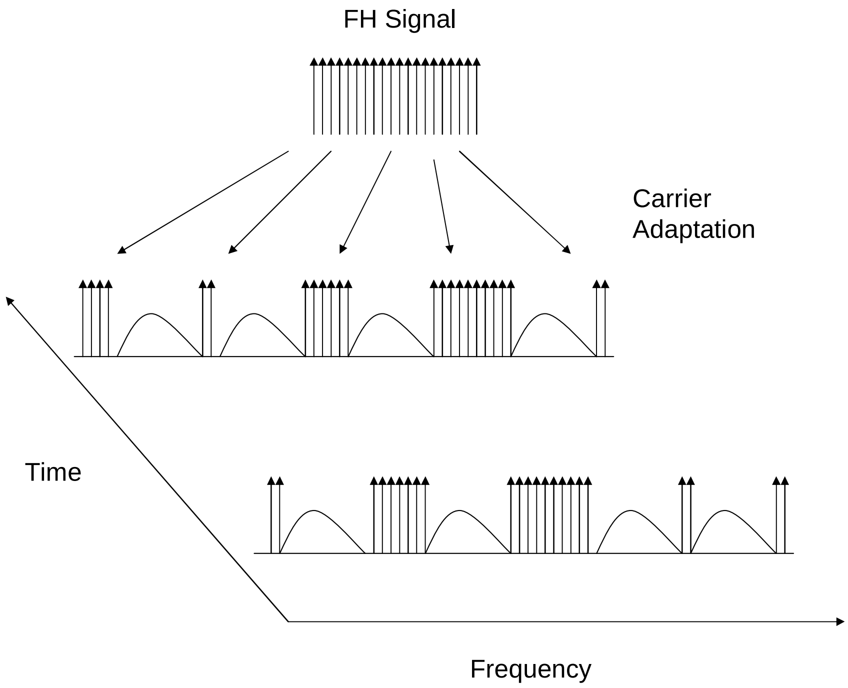


Fig.4. Adaptive Spectrum Exploitation

2.1.2 The Software Defined Radio: Adaptive spectrum exploitation has permitted a frequency hopper radio to sense the spectrum. The era of the SDR has been ushered in due to the capability to adapt a radio terminal's transmissions through software IF stages. The SDR Forum [15] defines an SDR as *"Radio in which some, or all of the physical layer functions are software defined"*. Hardware based radios limit the cross-functionality and can only be modified through physical intervention. This intervention may be in the form of tuning, channel modification or modulation changes. The changes are restricted to the types of hardware modules incorporated in the communication device.

This results in minimum flexibility in terms of supported waveform standards. In contrast, SDR technology provides an efficient solution to this problem, allowing multi-mode, multi-band and/or multi-functional wireless devices that can be enhanced using software. SDR defines a combination of hardware and software where some or all of the physical layer processing is implemented through software on programmable processing technologies. These devices include field programmable gate arrays (FPGA), digital signal processors (DSP), general purpose processors (GPP), programmable System on Chip (SoC) or other application specific programmable processors [15]. The use of these technologies allows new wireless features and capabilities to be added to existing radio systems without requiring additional hardware. The SDR Forum has defined a generalized modular architecture for SDR [28] (Fig.5).

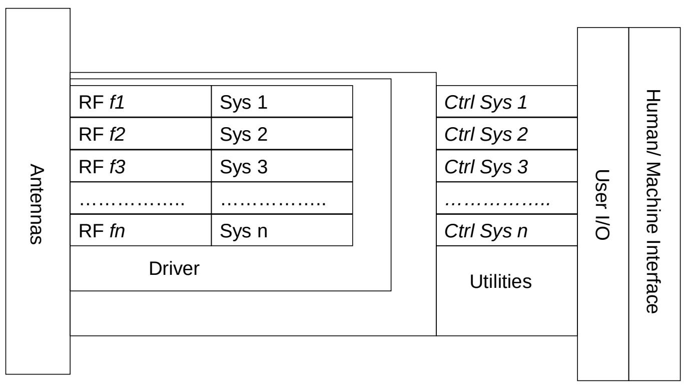


Fig.5. Multiband, Multi-mode SDR Functional Model

In the model, a common baseband processing engine can service multiple RF front ends. Each of these supports a specific air interface. The interface between the baseband processing engine and the RF front end is then switched to connect to the appropriate RF front end supporting this mode of operation.

2.1.3 Development of the CR Concept: Mitola suggested the development of SDR to the next level by personalizing the SDR to meet user needs through a process of adaptation and learning [19]. He further coined the term 'Cognitive Radio' for this new architecture [20]. The SDR forms the basic platform for development of CR. Fig.3 described the evolution of technology, ultimately leading to an ideal software radio. This radio will ultimately have all functions, related to the physical layer, implemented in software. To transform this concept into reality, Mitola focused his work [20] on development of suitable knowledge representation ontology. Through this ontology, he developed definitions of air interfaces and protocols. While analyzing other languages such as SDL and UML, Mitola suggested the use of RKRL (Radio Knowledge Representation Language) for comprehensively describing air interfaces and radio protocols. In order to be effective as a cognitive network, it may be asked from a handset to specify the number of multipath components seen by it. The primary problem is that the network may not have any standard language to pose such a question. The secondary issue is that the handset has the answer in the form of time-domain structure of its equalizer taps but cannot access this information [19]. Thus the handset does not know what it knows! This is not a small issue, if we are considering CR as a major technology for next generation networks. Cognition means being aware, and awareness implies the acquisition of knowledge. Knowledge has to be exchanged to enhance awareness. Exchange of knowledge, logically, requires a common ontology or language that facilitates inter-communication. This can be considered analogous to two people exchanging information verbally. The joint ability to understand what is being exchanged is absolutely essential for both individuals. Mitola's work [20] on development of RKRL received worldwide acceptance and further work on CR was based on the concepts introduced by him. The models underlying CR include RKRL (Radio Knowledge Representation Language), reinforced hierarchical sequences, and the cognition cycle [20]. The architecture is based on neural-network-like nodes that respond to external stimuli and then process the resulting data structures. These structures support a cognition cycle consisting of Observe, Orient, Plan, Decide, and Act phases. This cycle encompasses the radio's interaction with the environment.

After Mitola, the research community embraced the CR concept and a lot of work was done on various aspects. The SDR Forum established a CR Working Group under its Technical Committee to oversee research in this area [29]. The group is sponsored heavily by industrial stakeholders such *General Dynamics*™ C^4 *Systems* [30] and *Cognitive Radio Technologies*™ which offers services for intelligent wireless communication systems [31].

There have also been numerous publications on various aspects of CR under the auspices of IEEE. The effects of incorporation of CR in a network have been analyzed in [32]. The adaptability of CR to user requirements was discussed in [33]. A CR test-bed for analyzing genetic algorithms has been described in [34]. Spectrum sensing issues have been analyzed in great detail in [35]. G.Ganesan et al [36-38] took it a step further by discussing cooperative spectrum sensing. Physical Layer issues were analyzed in detail in [39]. Simon Haykin [40] critically analyzed the major issues associated with CR, namely radio-scene analysis (or spectrum sensing and decision), channel state estimation, transmit power control and dynamic spectrum management.

The conceptual development of CR is ongoing with a lot of work being done on higher layer issues as well physical layer issues. Test-beds are being created and used for developing and analyzing cognitive engine algorithms as well as cross-layer management. With the acceptance of smart multiband radios in many applications around the world, the logical next step is the intelligent CR.

2.2 Cognitive Functions: The major functions of CR [9] are:

2.2.1 Spectrum Sensing: Spectrum sensing serves as the primary stimulus for CR networks. It is the ability of a CR network or node to detect spectrum opportunities so as to allow their usage. Thus spectrum sensing gives a CR its characteristic adaptability. Detection of primary users is an efficient way of assessing spectral opportunities or ‘holes’. A cognitive node (secondary user or unlicensed user) utilizes spectrum when it knows that the primary user (licensed user) is not using the particular segment of the spectrum. This knowledge is possible through spectrum sensing. The further usage of this spectrum is possible through techniques such as Dynamic Spectrum Allocation.

2.2.2 Spectrum Management: This function pertains to the capturing of best available spectrum that meets user communication requirements. It involves the performance of two sub-functions. Firstly, the analysis of the sensed spectrum and secondly, the optimal decision while giving fundamental importance to user requirements.

2.2.3 Spectrum Mobility: Adaptability and dynamism are the hallmarks of CR networks. These are made possible by a continuous process of evaluation of existing decisions and channel feedback to maintain necessary QoS. Spectrum mobility, thus allows a CR node to efficiently migrate to new frequencies or wireless standards to meet these QoS parameters.

2.2.4 Spectrum Sharing: The objective of this function is to allow the provision of fair spectrum scheduling. It is one of the major challenges in open spectrum usage. In a typical CR environment, all CR nodes would try to provide optimal services to their users in 'greedy' fashion [41]. This behavior of CR nodes is understandable because each CR will try to enhance its QoS parameters whenever it sees better opportunity to do so. Game theory has been applied to this problem to analyze it further. The induction of CR technology into a radio network has been analyzed using game theory in [32]. A game-theoretic model has been used by [42] to analyze the non-cooperative behavior of the secondary users in IEEE 802.22 networks. This work was then extended to propose a 'Nash Bargaining Solution' to enhance the efficiency of dynamic spectrum allocation. A price-based iterative water-filling algorithm has been proposed in [43] that allows CR nodes to converge to a Nash Equilibrium [44].

2.2.5 Application of Functions of CR in OSI Model Context: The above mentioned functions can be analyzed in the context of the OSI model to get a broader picture of the CR OSI model. The NeXt Generation program or xG is a technology development project sponsored by DARPA's Strategic Technology Office, with the goals of *"developing both the enabling technologies and system concepts to dynamically redistribute allocated spectrum along with novel waveforms in order to provide dramatic improvements in assured military communications in support of a full range of worldwide deployments"* [45]. DARPA, as a part of its xG networks project, is attempting to implement CR networks. Fig.6 shows the xG network communication functionalities in this regard [9].

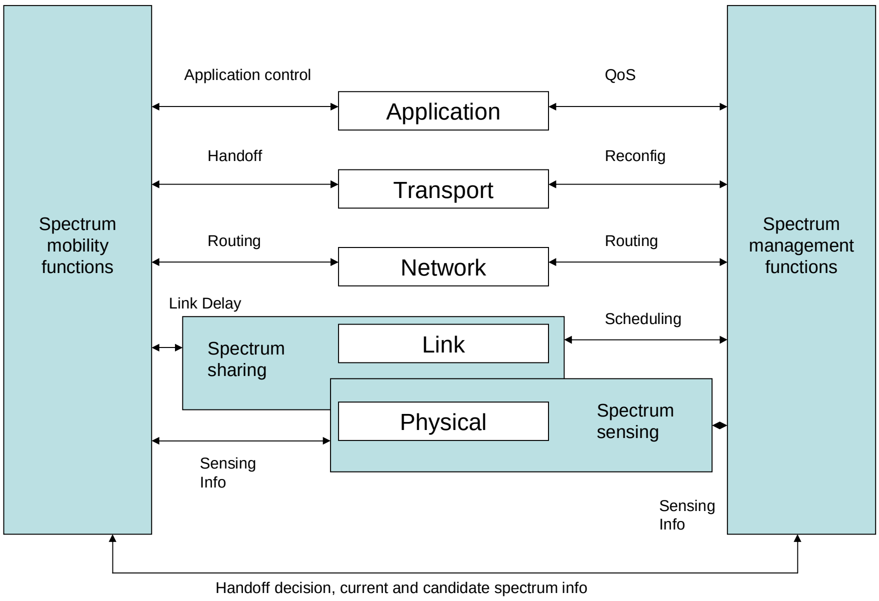
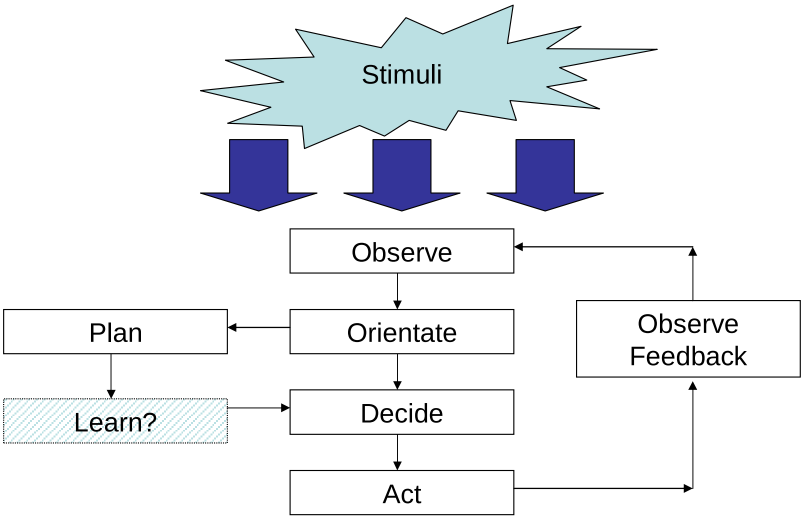


Fig.6. xG Network Communication Functionalities

2.3 Advanced Functions of CR

2.3.1 The Cognitive Lifecycle: The Cognitive engine of a CR undergoes various phases in performance of its various functions [20]. These are shown in Fig.7. During the observe phase, the radio gathers information through various sensors and inputs regarding location, RF environment, temperature, time, etc. In the orientate phase, the radio orients itself by analyzing the possible responses to the various stimuli gathered during the observe phase. It determines priorities associated with each response in this phase. Planning is the process of generation of plans. In this phase, the radio develops models of causality that are embedded in the planning tools. There is a reasonable degree of 'reasoning' in this phase. The decide phase selects the best plan from the candidates developed during the plan phase. The act phase entails the implementation of the decided plan. The radio maintains a certain degree of observation during all these phases. This gives the advantage of 'urgent' or feedback based responses.



Stimuli: Spectrum, Network, Policy, User Requirements, Geo-Location…..

Fig.7. The Cognition Cycle

2.3.2 The CR Ontology: Digital radios of today have considerable flexibility but they lack computational intelligence. To make the lifecycle effective, it is necessary that the results/ decisions of the CR during the various phases are registered as knowledge by the CR. Furthermore, the various functions that a CR performs have to be logically interconnected. This interconnection in the form of information exchange and knowledge acquisition requires the development of ontology. In the world of Computer Science, ontology is defined as a representation of knowledge [46]. This issue was initially addressed in great detail by Mitola [20] when he presented the concept of RKRL for his proposed CR framework. With the help of RKRL, the CR would achieve actual cognition. Fig.8 shows a CR framework [20] that incorporates machine learning and RKRL. A computational model of the radio and its equalizer function would form an essential part of such a model.

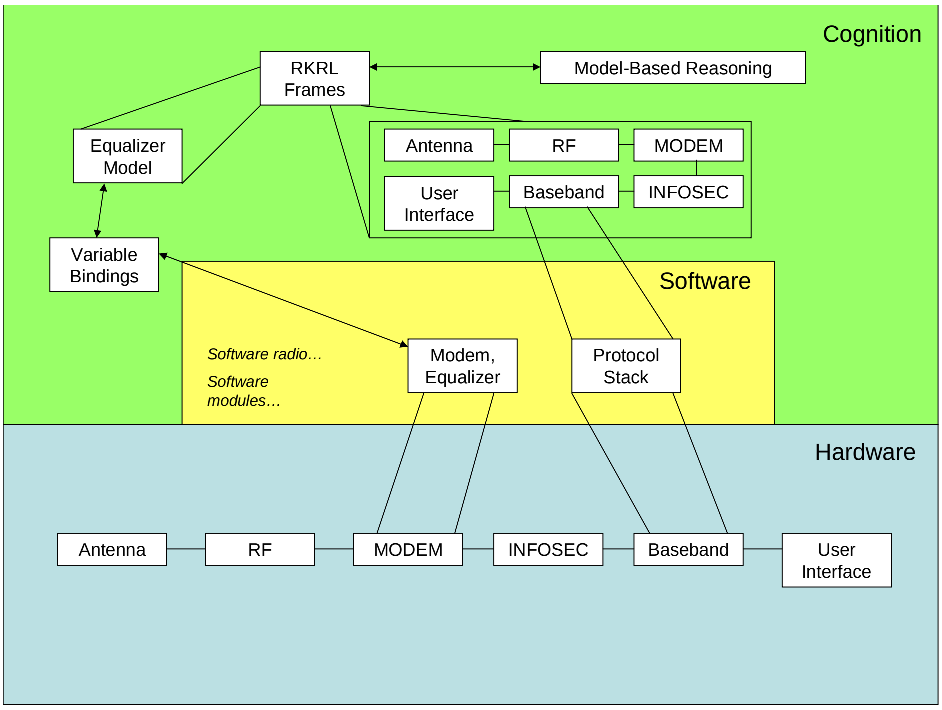


Fig.8. The CR Framework

The issue of knowledge representation for a CR architecture was also discussed in [47]. A CR, by definition, should have a knowledge-driven differential response capability; that is, it should be able to use knowledge of radio technology and policy, representations of the goals, and other contextual parameters to reason about a failed attempt to satisfy a goal and to identify alternative actions that would achieve the goal. In order to satisfy this definition, [47] proposed a general architecture for CR that combined ontology and rules with the processing structures of existing SDR. The architecture was based upon Mitola's proposed structure [20]. Essentially, this architecture extends the existing processing capabilities of SDR to include reasoning, perception and exchange of knowledge. This is still a very active area of research.

2.3.2 Sensory Perception for CR: The concept of sensory perception is what differentiates human beings from animals; and traditionally, this was the capability that was lacking in all types of computational machines. Machine learning and artificial intelligence have totally changed this. Understandably, this is a developing field and its implications in the context of CR are still in stages of infancy. Artificial intelligence and machine learning are very broad subjects and are beyond the scope of this thesis. However, it needs to be understood that learning, perception and awareness are what differentiate CR from SDR. Thus true CR cannot be wholesomely studied without at least a conceptual introduction to this important field of scientific research. I will try to do justice to the related concepts in the succeeding paragraphs.

2.3.2.1 Context, Concept, Reasoning and Knowledge: *Context* is the direct outcome of sensing in any form or from any type of sensor. For example, my sense of vision (with some assistance from my brain that identifies it as snow) tells me that there is snow on the ground. Thus the *context* is that I have observed snow on the ground. An established *concept* is that if there is snow on the ground then it must have snowed recently. The development of this *concept* is as a result of *reasoning*. The absorption of this outcome is the creation of *knowledge* (which is that it has snowed recently).

2.3.2.2 Knowledge Space for CR: Concepts exist in knowledge representation space [20]. The knowledge representation space for cognitive radios includes:

- Radio hardware
- User
- Network
- Subset of Space-Time

There are two levels of knowledge space. One is the Meta-level and the other is the physical space based level. The meta-level includes concepts that are formed on the basis of sensory perception acquired from space-time, location, user-requirements, spectrum situation, network and/or regional policies, etc. The physical level of radio knowledge relates to two sub-aspects. These are knowledge about the physical world and about the radio itself. The presence of information in the cumulative knowledge space implies a certain degree of awareness. This awareness is characteristic of CR.

2.3.2.3 Machine Learning: Machine learning is a subfield of artificial intelligence that is concerned with the design and development of algorithms and techniques that allow computational machines to "learn". In general, there are two types of learning: inductive, and deductive. Inductive machine learning methods extract rules and patterns out of large data sets [48]. Here it would be useful to consider the definitions of *deduction*, *induction* and *abduction* in relation to reasoning and learning [49]. *Deduction* allows deriving *b* as a consequence of *a*. In other words, deduction is the process of deriving the consequences of what is assumed. A valid deduction guarantees the truth of the conclusion if the assumptions used for deriving the deduction are true. *Induction* allows inferring *a* from multiple occurrences of *b* when *a* entails *b*. *Induction* is the process of inferring probable inputs as a result of observing multiple outputs. An inductive statement requires perception for it to be true. For example, the statement 'it is snowing outside' is invalid until one looks or goes outside to see whether it is true or not. Thus, induction requires a substantial experience of sensory perception. *Abduction* allows inferring *a* as an explanation of *b*. Because of this, *abduction* allows the precondition *a* to be inferred from the consequence *b*. *Deduction* and *abduction* thus differ in the direction in which a rule like “*a* entails *b*” is used for inference. As such *abduction* can be considered equivalent to the false logic that affirms the outcome, because there are multiple possible inputs for *b*. Unlike *deduction* and *induction, abduction* can produce results that are incorrect. However, abduction is still useful as a heuristic, especially when something is known about the probability of different inputs that can cause *b*. Machine learning has been used in telecommunications, e.g. in call-admissions control algorithms [50]. The common algorithms in this regard address network applications like call admissions control, and do not address user or environment specific knowledge in the context of a radio. The latter is the focus of CR. In the context of CR, consider a simple case of learning based on environment and user requirements. If a CR user accesses his emails through GPRS/EDGE whenever he is commuting then this repeated action would have initiated a learning process. The CR would have queried possible networks on his commuting route for minimum cost and maximum data throughput. Thus, having negotiated the best possible solution, the CR would provide near-optimal service. On the other hand, if the CR user habitually sends or receives voice calls only while in office (uses the office network for emails), the CR would try to negotiate best possible voice quality with minimum cost for the user. These changing requirements of the user would have been inferred from experience of location, time, network/

spectrum, usage and cost. Thus, in such a scenario, a CR would be able to provide optimal service to its user under most circumstances. The overall effect of this ‘learning’ by the CR is a generalized awareness related to sensory perception and of parameters that can be modified to optimize service. The ability to modify these parameters is a function of a software radio and the higher ability to take conscious decisions in this regard is the cognitive capability of a CR. A further capability, afforded due to the learning process, relates to the ability of the CR to cope with situations that may have not been foreseen at the time of design of the CR.

2.4 Spectrum Sensing: Spectrum sensing serves as the primary stimulus for the cognitive capability of CR networks (CRN). Technological developments have improved spectral efficiency by increasing the number of users in each frequency band. CR promises more efficient spectrum utilization through environmental awareness. By using advanced computational power to sense the existing radio frequency (RF) environment, user requirements and network policies, CR become aware of and can respond to that environment [51]. CR may help improve spectrum management by moving it from the rigid framework of regulations to the flexible realm of mobility and dynamism. In the United States, there are three spectrum management models – command and control, exclusive use, and unlicensed use, often referred to as ‘spectrum commons’ [51]. Under the command and control regime, RF spectrum is divided into frequency bands, in which specific channels are licensed to specific users for specific services. These frequency bands are subject to explicit usage rules governing the designated RF service or transmission type. In the exclusive use regime, a licensee is authorized to use a specific frequency band or channel for whatever service or purpose they desire. These rights are subject to general emission rules that are designed not to interfere with neighboring spectrum users. In return for not interfering with other users, licensees are afforded the freedom to use their spectrum however they choose, much like property rights. In the ‘spectrum commons’ regime, RF devices operate on a first-come, first-serve basis. Devices transmitting in this band are subject to certain emission rules, but are not guaranteed any interference protection rights or the exclusive use of dedicated channels [52]. This is where the spectrum awareness afforded through spectrum sensing comes in. Thus, cognitive devices would be able to operate in areas/ spectrum governed by any of these models, and as such, must be aware of spectrum occupancy and/or be able to download software describing the unique rules of each regime.

Advanced techniques of digital signal processing have permitted more efficient spectrum sensing methods to be employed. In spectrum sensing the needs for signal processing are: firstly, the improvement of radio front-end sensitivity by processing gains, and secondly, primary user identification based on knowledge of the signal characteristics. The spectrum sensing problem is to positively detect the presence of a primary user (or simply spectrum occupancy) on a particular frequency. In this section we discuss advantages and disadvantages of three techniques that are used in this regard [35]. These are energy detection, matched filter and cyclostationary feature detection.

2.4.1 Energy Detection: This is the simplest technique for spectrum sensing. It is considered simple due to minimum complexity. This technique was suggested in [53] and was applied to fading channels in [54]. The concept has been employed in simple radiometry [53]. The problem of spectrum sensing using energy detection can be considered on the basis of the front-end of the receiver employed for the purpose. The radio receives an RF signal $r(t)$. This signal may contain the primary signal at center frequency f_c with bandwidth $(-f_b,f_b)$ Hz. The RF signal is down converted, passed through an ideal low-pass filter and sampled. The bandwidth of the filter is $(-f_{bw},f_{bw})$ Hz. Sampling rate T_s

is $1/2f_{bw}$. We then get the baseband signal $\{x_n\}$. This signal is processed by the energy detector, which gives:

$$x_n = \eta s_n + v_n \tag{2-1}$$

where s_n is the primary baseband communication signal and v_n is the complex noise process. The value of $\eta \in \{0,1\}$ determines the presence or absence of the primary signal s_n. Thus the problem is simplified to a binary hypothesis testing problem:

$H_0 : \eta = 0$; implies primary is absent,

$H_1 : \eta = 1$; implies primary is present.

The primary signal $\{s_n\}$ is unknown and is modeled as a complex-valued zero-mean wide-sense stationary (WSS) process. Alternatively, $\{s_n\}$ can also be modeled as a cyclostationary process (instead of a WSS process) [55]. The challenge in utilizing this simple detection technique is the uncertainty involved in the complex noise process [56] v_n. As the exact noise level is unknown to the detector, therefore it has to be estimated. The estimation error causes an 'SNR Wall' [57]. Small modeling uncertainties are unavoidable in any practical system and so robustness to them is a basic performance metric. The impact of these modeling uncertainties can be quantified by the position of the 'SNR wall' below which a detector will fail to be robust, irrespective of the time for which it observes the channel.

The simplest implementation of an energy detector is through a spectrum analyzer. This is done by averaging the frequency bins of a Fast Fourier Transform (FFT) [58]. The method used is the Welch Periodogram [59] as follows:

The signal is split up into overlapping segments. The original data segment is split up into L data segments of length M, overlapping by D points.

If D = M / 2, the overlap is said to be 50%

If D = 0, the overlap is said to be 0%.

After the data is split up into overlapping segments, the individual L data segments have a window applied to them (in the time domain). Most window functions permit more influence to the data at the center of the set than to data at the edges, which represents a loss of information. To mitigate that loss, the individual data sets are commonly overlapped in time. After doing the above, the periodogram is calculated by computing the discrete Fourier transform, and then computing the squared magnitude of the result. The individual periodograms are then time-averaged, which reduces the variance of the individual power measurements. The end result is an array of power measurements vs. frequency "bin". The implementation [58] of this concept is shown in Fig.9.

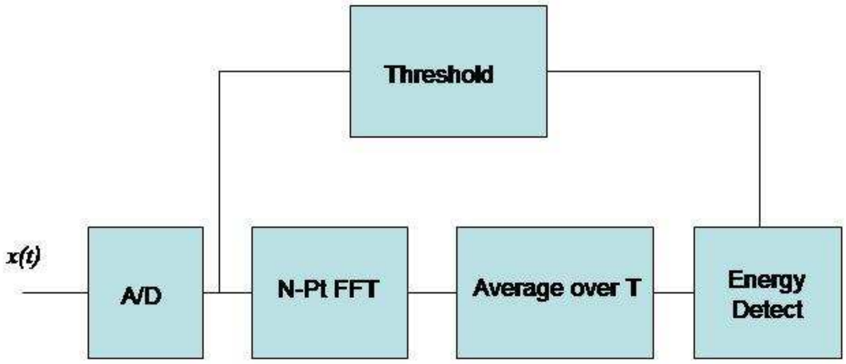


Fig.9. Implementation of an Energy Detector using Welch Periodogram

Processing gain is proportional to FFT size *N* and observation time *T*. Increasing the FFT size improves frequency resolution and correspondingly helps narrowband signal detection. Also, longer observation time reduces the noise power thus improving SNR. However, due to non-coherent processing $O(1/SNR^2)$ samples are required to meet a probability of detection constraint [60].

There are several disadvantages of using energy detectors. Some of these are [35]:

- The threshold used for primary user detection is highly dependent upon unknown or changing noise levels.

- For frequency selective channels, it is very difficult to define the threshold.
- The energy detector does not differentiate between modulated signals, noise and interference.
- It cannot recognize the interference, hence it cannot benefit from adaptive signal processing for interference canceling.
- An energy detector does not work for spread spectrum or hopping signals.
- As spectrum policy for using the band is constrained only to primary users, therefore a cognitive user should treat noise and other secondary users differently. This is not possible in simple energy detection.

In general, it is possible to enhance the efficiency of a detector by analyzing the primary signal characteristics such as modulation type, etc. This results in increased complexity and is highly dependent upon a-priori knowledge about primary signal features. Thus, the most important advantage of the energy detector is its independence of primary signal features diminishing the need for intensive a-priori knowledge.

2.4.2 Matched Filter Detection: The optimal way for any signal detection is a matched filter, since it maximizes received signal-to-noise ratio [61]. However, such a detector requires effective demodulation of a primary user signal. This means that the CR should have comprehensive a-priori knowledge of primary user signal e.g. modulation type, pulse shaping, packet format, etc. Such information might be pre-stored in CR memory, but the cumbersome part is that for demodulation it has to achieve coherency with primary user signal by performing timing and carrier synchronization. This is possible because most primary users have pilots, preambles, synchronization words or spreading codes that can be used. Examples of such signals include a TV signal (pilots for audio/video), CDMA signals (dedicated spreading codes for pilots and synchronization), OFDM/ OFDMA (pilots in each symbol). The main advantage of matched filter is that due to coherency it requires less time to achieve high processing gain since only O(1/SNR) samples are needed to meet a given probability of detection constraint [60]. The most significant drawbacks of a matched filter detector are:

- A CR would require a dedicated receiver for every primary user class.
- Detailed a-priori knowledge of primary user is required. Such knowledge has to be pre-configured or downloadable from some

network control entity. This type of learning has been described by Mitola as ‘rote’ learning [20] and requires control communications through a dedicated control channel.

A sensing method based on matched filtering for identifying the unused spectrum for opportunistic transmission by estimating the RF transmission parameters of primary users has been proposed in [62]. The process of estimation of primary user parameters is an interesting proposition and it has the potential to offset the disadvantage of requiring a-priori knowledge, generally associated with matched filtering. As a case study, the effectiveness of this technique was tested in a simulated environment of WiMAX. The technique makes use of energy detection to estimate the primary user parameters. After estimating the parameters, the technique of [62] shifts to matched filtering. Generally, the estimated features include bandwidth and center frequency. This variation of typical matched filter detection is innovative, however it is computationally intensive. The CR platform is expected to incorporate machine learning algorithms in order to make it fully cognitive. The technique of [62] can support machine learning, ultimately reducing computational intensity through learned optimization.

Matched filtering was further analyzed in [63]. It analyzes the problem of sensing presence of digital TV broadcasts of ATSC [64] standard in the TV VHF/UHF bands. In these types of signals, a synchronization sequence occurs every 24.2 msec. Matched filtering is used to identify and detect the presence of this sequence. This work strengthens the concept that matched filtering requires intensive a-priori knowledge and a separate receiver for each class of primary user.

Detection of primary users through matched filtering is, undoubtedly, the optimal solution at present. However, its effectiveness is diminished by the stringent requirements of having a-priori knowledge about the primary user. Thus the technique is reduced to being a primary user detector rather than a system capable of sensing spectrum occupancy comprehensively.

2.4.3 Cyclostationary Feature Detection: The spectral correlation theory of cyclostationary signals was used in [65] to present a broad treatment of weak random signal detection that clearly reveals the relationships among the variety of detectors. It presented several arguments with supporting results that favor cyclic- feature or cyclostationary detection over energy detection for accommodating the problems associated with unknown and changing noise levels. Modulated signals are in general coupled with sine wave carriers, pulse trains, repeating spreading, hoping sequences, or cyclic prefixes which result in built-in periodicity. Even though the data is a stationary random process, these modulated signals are characterized as cyclostationary, since their statistics, mean and autocorrelation, exhibit periodicity. This periodicity is typically introduced intentionally in the signal format so that a receiver can exploit it for parameter estimation. This can then be used for detection of a random signal with a particular modulation type in a background of noise and other modulated signals. Common analysis of stationary random signals is based on autocorrelation function and power spectral density. On the other hand, cyclostationary signals exhibit correlation between widely separated spectral components due to spectral redundancy caused by periodicity.

Consider a stochastic process *x(t)*. The autocorrelation function of *x(t)* is given as:

$$R_x(t;\tau) = E\{x(t-\tau/2)x^*(t+\tau/2)\} \qquad \textbf{(2-2)}$$

The signal *x(t)* is said to be wide-sense cyclostationary with period T_0 if $R_x(t;\tau) = R_x(t+T_0;\tau)$ for all t, τ [65].

Similarly, the spectral correlation function [35] (SCF) can be written as:

$$S_x^{\alpha}(f) = \lim \underset{\tau \to \infty}{\lim} \underset{\Delta t \to \infty}{\lim} \frac{1}{\Delta t} \int_{-\Delta t/2}^{\Delta t/2} \frac{1}{T} X_{\tau}(t, f+\frac{\alpha}{2}) X_{\tau}^*(t, f-\frac{\alpha}{2}) dt \qquad \textbf{(2-3)}$$

SCF is also termed as cyclic spectrum. Unlike PSD which is real-valued one dimensional transform, the SCF is two dimensional transform, in general complex valued and the parameter α is called cycle frequency. Power spectral density is a special case of a spectral correlation function for α=0 [35].

This very important characteristic of modulated signals is exploited to perform cyclostationary feature detection of primary users. Signal analysis in cyclic spectrum domain preserves phase and frequency information related to timing parameters in modulated signals [65]. Different types of modulated signals (such as BPSK, QPSK, SQPSK) that have identical power spectral density functions can have highly distinct spectral correlation functions. Furthermore, stationary noise and interference exhibit no spectral correlation. Implementation of a spectrum correlation function for cyclostationary feature detection [35] is shown in Fig.10. It can be designed as an add-on of the energy detector from Fig.9.

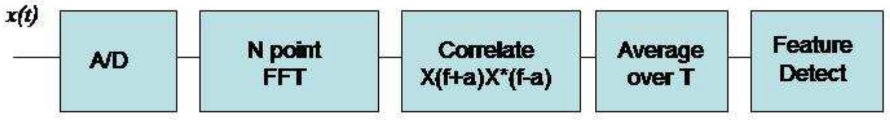


Fig.10. Cyclostationary Feature Detector using SCF

2.5 Cooperative Spectrum Sensing:

Cooperative spectrum sensing (CSS) [37],[38],[66] is an environment where two or more spectrum sensing nodes, that form part of a CR network, combine their spectrum sensing capabilities leading to centralized [67] or decentralized [68] decision fusion. CSS allows individual nodes to gain a more global degree of awareness about spectrum occupancy [69]. It also has the inherent advantages of increased levels of agility as well as greater accuracy due to the ability to detect a primary user (PU) that is obscured to a sub-set of sensing nodes due to channel behavior [70]. Here, agility means the ability of a CR to sense vacant spectrum and quickly shift to it and the corresponding ability to sense a primary user in a particular CR-used band and quickly shift out of it. CSS has to be considered in the context of increased communication overhead [35]. If the inherent advantages of CSS are more important as compared to the cost of overhead then it is a viable trade-off.

2.5.1 Cooperative Diversity & Information Gain:

The concept of cooperative diversity forms the foundation stone for CSS. To understand the full implications of cooperative diversity, we will discuss a real life analogy. CSS nodes can provide information gain to each other due to the diversity in individually sensed spectra. This can be considered analogous to two people having finite fields of view. If they both see a completely overlapping view (Fig. 11a) of the environment then they do not provide any information gain to each other through sharing of information. On the other hand, it is also possible that both individuals have a partially overlapping view (Fig.11b). This implies that they would give a partial information gain to each other. The information gain is directly proportional to the difference in their views indicated by the dotted lines in Fig. 11b and Fig.11c. If the overlapping view is reduced to zero (Fig. 11c), then a maximum information gain is possible by sharing of information between the two individuals.

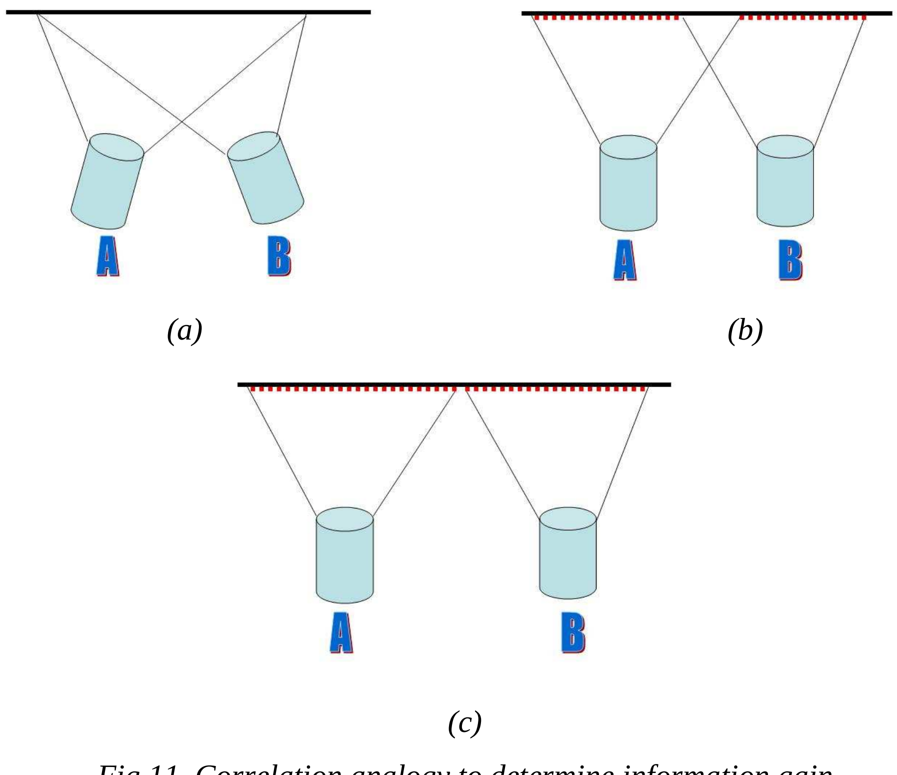


Fig.11. Correlation analogy to determine information gain

Above analogy highlights the fact that correlation between the individually sensed spectra determines the extent of information gain that would be possible as a result of information exchange between sensing nodes. By increasing the number of CSS nodes, it is possible to enhance the agility and accuracy of the fused decision related to spectrum occupancy. However, the information gain is not linearly proportional to the number of sensing nodes because the varying cross-correlation between sensing pairs tends to increase or decrease the cumulative information gain [71]. The level of information gain should define whether two CSS nodes should cooperate or not.

2.5.2 Hidden Node Problem: This is often the most discussed issue with regards to spectrum sensing. This problem was discussed in great detail in [66] and has also been analyzed subsequently. The hidden-node problem arises because of shadowing (Fig.12).

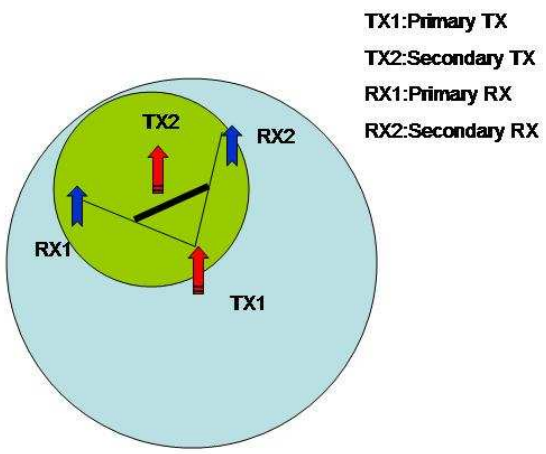


Fig.12. Hidden node problem

Fig.12 shows the classical case of the hidden node problem. There is a possibility that secondary users may be shadowed away from the primary user's transmission however, there may be some primary receivers close to the secondary users that are not shadowed from the primary transmitter. In Fig.12, the secondary transmitter TX2 is shadowed from the primary transmitter TX1. In the event of stand-alone sensing, this node would be unable to detect the presence of TX1. If it chooses to use the part of the spectrum occupied by TX1, then it would create problems for RX1 and RX2 that are not shadowed from both TX1 and TX2. Hence, TX2 may interfere with the primary receiver's reception. Having users cooperating provides us with a possible solution to the hidden-terminal problem, since this problem would arise only if all the secondary users are shadowed away from the primary. If the secondary users are spread over a distance that is larger than the correlation distance of the fading, it is unlikely that all of them are under a deep fade simultaneously. Thus, CSS potentially resolves the issue of 'hidden node'.

2.5.3 Correlation Metrics: Correlation between the sensed spectra, plays a very important role when it comes to evaluating the effectiveness of any cooperation scheme for CSS. While correlation has been discussed in great detail in the past, very little analysis on its use for effective cooperation schemes has been considered. A critical analysis of correlation metrics in the context of CSS, was carried out in [72] as a part of their measurement campaign. The statistics gathered in various joint measurements of the spectrum were analyzed in this campaign. Two units were used; one of them was mobile (on a trolley) while the other was a static unit. Each unit consisted of a spectrum analyzer with rugged laptops. The units were verbally time synchronized to analyze the correlation between the measurements made by each unit. Measurements were taken in dense urban as well as suburban environments. It was established that CSS can improve the detection reliability and lower the sensitivity requirements on single sensors. It was further validated that correlated spectrum measurements will lower the cooperation gain and that such correlations decrease with increasing distance [72]. Various techniques for correlation were analyzed, which are summarized in the succeeding paragraphs.

2.5.3.1 Basic Correlation: The cross-correlation between two processes U and V is given by:

$$R(U,V) = \frac{1}{L}\sum_{t=1}^{L} U_t . V_t \qquad \textbf{\textit{(2-4)}}$$

where U and V are the two vectors of length L. The problem with this evaluation methodology is its dependence on the duty cycle [72]. Here, duty cycle implies the time for which a primary transmitter keeps transmitting. The effect it has on the correlation can be understood from the fact that the correlation also depends on the resemblance in terms of consistency in time. Thus a lower absolute power received on a particular frequency by two sensing nodes for a longer duration would have a higher correlation as compared to a higher absolute power for shorter duration. Thus this metric fools the statistics by depicting greater correlation between sensed spectra. Another factor is the AWGN noise present in the entire spectrum. Since all cooperating nodes would be sensing approximately the same levels of noise on all frequencies at all times, therefore most of the correlation would be attributed to this noise and very little to the actual sensing of primary users. This can be seen in Fig.13.

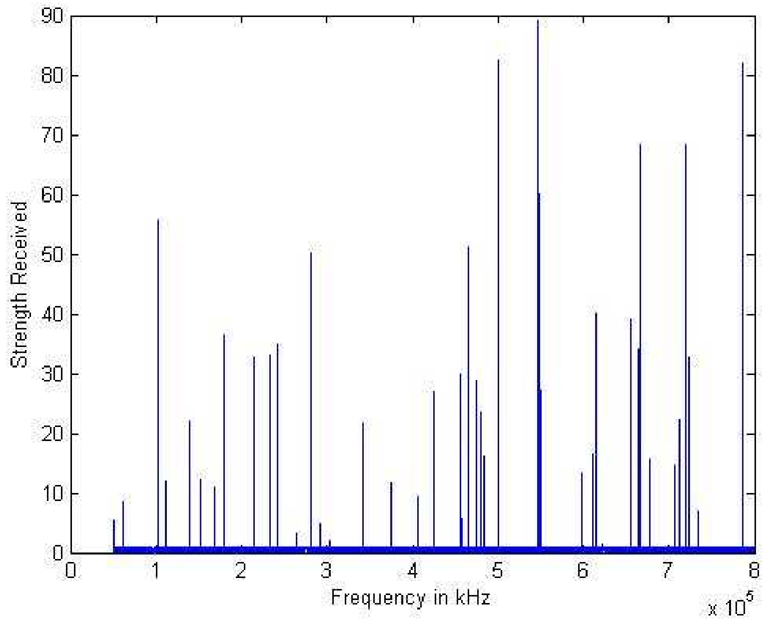


Fig.13. Sensed spectrum including AWGN. A large chunk of correlation would be associated with the AWGN visible at the bottom of the spectrum.

A higher duty cycle can result in high cross-correlation whereas the absolute power may not be that correlated. This also highlights the need to have proper time-synchronization. Timing errors would contribute to unnecessary correlation increases or decreases. In some cases, the presence of one primary user detected by a secondary user may be refuted by another secondary user.

2.5.3.2 Covariance: One way of reducing the dependence on the absolute power is by subtracting the average received power. Thus, the resulting covariance *cov(U,V)* is written as [72]:

$$\mathrm{cov}(U,V) = \frac{1}{N_s}\sum_{t=1}^{N_s}(U_t - \overline{\mathbf{U}}).(V_t - \overline{\mathbf{V}}) \qquad \textbf{\textit{(2-5)}}$$

where $\overline{\mathbf{U}}$ and $\overline{\mathbf{V}}$ denote the average received power by the two secondary users. The covariance can also be normalized to attain more relevant results [72]:

$$\rho(U,V) = \frac{1}{N_s}\sum_{t=1}^{N_s}\frac{U_t - \overline{\mathbf{U}}}{\sigma_U}.\frac{V_t - \overline{\mathbf{V}}}{\sigma_V} \qquad \textbf{\textit{(2-6)}}$$

where σ_U and σ_V are the standard deviations of the received power vectors. The covariance, thus obtained is independent of the absolute value of the received power vectors because of the correction by the mean. However, this may also be counter-productive. Consider, for example, a base station in a CDMA-based network, which will constantly use the broadcast channel to announce its presence to new handsets trying to join the network. Resultantly, the measured received power shows noise-like characteristics over time although on a much higher level. The correction by the mean, in this case, would filter out the higher power level and a CDMA base station signal would look like noise. Thus, simple covariance with mean subtraction (with or without normalization) is sub-optimal.

2.5.3.3 Binary Covariance: In a dynamic spectrum access scenario, we are interested in the decision about the presence or otherwise of the primary user. The conveyance of this decision is binary data, because it either is ‘1’ indicating presence or ‘0’ indicating absence of a primary user. This considerably simplifies the problem. Combination of binary vectors corresponding to the usable frequency vector is a good option for reducing the complexity. Such a combination process is based on hard-decisions made by the individual sensing nodes. Although it has been shown that soft-decision making may perform better in some situations [73],[74], we perform decision fusion using logical *OR*-combining. Information gain, in this case is achieved from those samples in which the sensed results are different for the individual sensing nodes. In simple words, if CSS node A detects the presence of a primary user at a particular frequency whereas CSS node B does not detect the primary user at the same frequency then CSS node A would be in a position to give information gain to CSS node B. The logical *OR* function evaluates binary vectors to perform such a comparison. This is evident from the following:

0 *OR* 0=0

1 *OR* 1=1

0 *OR* 1=1

1 *OR* 0=1

The logical *AND* function is also useful, because it brings out similarities between sensed decision vectors. It evaluates samples as follows:

0 *AND* 0=0

1 *AND* 1=1

0 *AND* 1=0

1 *AND* 0=0

The most useful measure of binary covariance is obtained from the logical *XOR* function because it highlights the differences between binary vectors.

0 *XOR* 0=0

1 *XOR* 1=0

0 *XOR* 1=1

1 *XOR* 0=1

The *XOR* metric is used for evaluating the differences between vectors whereas *AND* is used for counting similarities in detected primary users. For this purpose, [72] defines the *AND-Ratio* and *XOR-Ratio* for frequency index *f*. The *AND-Ratio* is given as:

$$\alpha(f) = \frac{1}{N_s}\sum_{t=1}^{N_s}\Omega_A(t,f)\wedge\Omega_B(t,f) \qquad \textbf{\textit{(2-7)}}$$

whereas the *XOR-Ratio* is given as:

$$\xi(f) = \frac{1}{N_s}\sum_{t=1}^{N_s}\Omega_A(t,f)\oplus\Omega_B(t,f) \qquad \textbf{\textit{(2-8)}}$$

In these expressions, N_s is the number of samples at the frequency index *f*, Ω_A is the sensed result (binary) at frequency index *f* and sample time *t* out of the total N_s samples taken by sensing node *A*. The same is correspondingly true for sensing node *B*. The ratios $\alpha(f)$ and $\xi(f)$ describe the probability that a sample is either detected by both CSS nodes or by only one of them. A high value for $\alpha(f)$ indicates that cooperation would not improve sensing significantly because most samples were detected by both nodes. A high value for $\xi(f)$, on the other hand, describes the situation with multiple samples that were detected by a single node, and thus, situations where cooperation would improve the sensing reliability at the other node. In simple terms, a high value of $\alpha(f)$ implies that cooperation would not yield a relatively high information gain, whereas a high value of $\xi(f)$ implies that a higher information gain is expected through cooperation. It was also established in [72] that sensing nodes that are closer to each other would be expected to yield lower information gain through cooperation and conversely, nodes that are farther apart would give higher information gain to each other.

2.5.3.4 Weighted Correlation Metric: The *AND-Ratio* and the *XOR-Ratio* consider solely the binary energy detection result. Therefore, a comparison of the received power is not taken into account. The above ratios are also susceptible to varying primary system duty cycles [72]. For example, if the received power at both CSS nodes is very close but the detection threshold is exactly in between, the binary energy detection will falsely indicate that the measurement results of the CSS nodes are different. This problem can be corrected by considering the weighted binary correlation. Let the difference in received power be:

$$\Delta P_{rx}(t, f) = \left| P_A(t, f) - P_B(t, f) \right| \tag{2-9}$$

The objective is to have the following behavior for the correlation metric:

- If $\Delta P_{rx}(t, f)$ is very large and both measurements trigger detections, the specific AND event should contribute less to the similarity-metric compared to the case with small $\Delta P_{rx}(t, f)$.

- If $\Delta P_{rx}(t, f)$ is small but only one of the measurements triggers a detection, the specific XOR-event should lower the similarity metric much less compared to the case of large $\Delta P_{rx}(t, f)$ and only one detection.

To achieve this behavior, [72] applied the following weighting functions:

$$W_{AND}(\Delta P_{rx}(t, f)) = e^{-\frac{1}{2}\left(\frac{10\log_{10}(\Delta P_{rx}(t,f))}{10\log_{10}(C_{AND})}\right)^2} \quad \textbf{\textit{(2-10)}}$$

where C_{AND} is the normalization constant. Similarly, the *XOR* weighting function is defined as:

$$W_{XOR}(\Delta P_{rx}(t, f)) = e^{-\frac{1}{2}\left(\frac{10\log_{10}(\Delta P_{rx}(t,f))}{10\log_{10}(C_{XOR})}\right)^2} \quad \textbf{\textit{(2-11)}}$$

where C_{XOR} is the *XOR* normalization constant. These constants have been chosen in accordance with the standard deviations, as already described. Applying these weights to a combination of the binary metrics gives the weighted *AND-OR* metric as follows:

$$\Phi(f) = \frac{\sum_{t=1}^{N_s} W_{AND}.ANDRatio_{A,B}(t, f)}{\sum_{t=1}^{N_s} ANDRatio_{A,B}(t, f) + W_{XOR}.XORRatio_{A,B}(t, f)} \quad \textbf{\textit{(2-12)}}$$

This relationship is a ratio of the weighted *ANDRatio* to the weighted *ORRatio* because the denominator sums up to a weighted *OR* (sum of *AND* and

XOR). This weighted correlation metric describes the similarity behavior comprehensively, irrespective of the type of communication [72] (GSM, CDMA, UMTS, etc.).

2.5.4 Decision Fusion: The main objective of cooperation is information gain. This information gain is possible, only through a process of decision fusion. Decision fusion implies the combining of individually sensed results to achieve a relatively higher degree of global awareness about the spectrum. In the context of CR in CSS, there are essentially two types of decision fusion. Firstly, hard-decision fusion implies the combining of sensed decisions. Secondly, soft-decision fusion combines the received power at each frequency with the corresponding received power of another node to achieve an aggregate decision. Majority rules can be applied to hard-decisions whereas soft-decisions require applications of thresholds combined with majority rules [72]. The issue of decision fusion has been critically analyzed in wireless sensor networks in the past. Depending upon the volume of data to be fused, there are numerous ways to achieve the desired level of accuracy in the results. In the context of wireless sensor networks (WSNs), the decision fusion rules for multi-hop networks have been analyzed in [75]. Channel-aware decision fusion rules have been developed for resource-constrained WSNs where binary decisions from local sensors may need to be relayed through multi-hop transmission in order to reach a fusion center. The estimated binary decision, based on channel impairment estimation, is transmitted to the next node until it reaches the fusion center.

In the context of CRN, in which multiple CSS nodes are cooperating, [76] analyzed the integration of spectrum sensing schemes with decision fusion algorithms. The effects of varying the number of participating neighbors on fusion values have been studied in detail. In [77] and [78], optimum fusion rules have been investigated under the assumption of conditional independence. Many research papers, such as [68],[79] and [80], have also analyzed the problem of distributed detection with constrained communication resources. The results in these papers, however, are mostly obtained based on the assumption of lossless communication. This assumption is not realistic for many WSNs where the transmitted information has to endure both channel fading and noise/interference. This motivates the study of the fusion of local decisions corrupted by channel fading/noise impairment. The optimal thresholds, both at the fusion center and the local sensors by assuming a simple binary symmetric channel between sensors and the fusion center were derived in [81].

There is no doubt that the problem of decision fusion for CSS nodes can be modeled on grounds similar to WSNs, however, recent work on the combination of CSS with data fusion is more relevant. The issue was simplified in [82] by considering simple counting rules for decision fusion. Spectrum sensing places extreme sensitivity requirements on individual CR nodes. Local decision fusion as a low complexity method can improve the detection performance by simply increasing the number of times of observation and decision. The procedure involved makes use of multiple observations to strengthen or modify its belief. The fusion rules of local decision were analyzed in [82] and their properties and conditions were deduced under the assumption that all the decisions are independent and follow the same probability distributions. These properties and conditions can be used to increase the detection probability and to lower the false alarm probability. The performance of such a local detector can be optimal when choosing appropriate decision number and fusion rule [82].

The most important advantage of an effective decision fusion rule is that it has the potential to overcome the sub-optimal nature of the actual sensing technique employed. It has already been highlighted that energy detection is sub-optimal. By having a counting rule decision fusion algorithm, we achieve a belief strengthening mechanism to confirm or deny local decisions. This reduces the probability of false alarm in detection of primary users [82]. Thus, even if we do not use matched filter or cyclostationary feature detection (which are more optimal than energy detection), we can still achieve optimal results by using an effective decision fusion mechanism of energy detection decisions that takes full advantage of the cooperative diversity to arrive at the correct decision about spectrum occupancy.

The aspect of having centralized or decentralized decision fusion can be studied on the basis of the application. Decentralized decision fusion has often been considered in the context of multi-hop WSNs. The same can be applied to CSS in CRN. In this regard, multiple CSS nodes would ‘broadcast’ their sensing results in hard or soft form (depending upon communication constraints). These would be carried through multiple hops on various cooperating CSS nodes, ultimately leading to a situation of ‘global awareness’ about spectrum occupancy. With regard to centralized decision fusion, each CSS node transmits its sensing results to a central decision fusion center where the results are fused using simple counting rules. The latter strategy is more favorable for CRN as opposed to WSNs. Accordingly, the advantages of a centralized fusion scheme are:

- Maximum advantage of cooperative diversity is achieved.
- Network complexity is reduced as each CSS node is not required to fuse decisions.
- Communication overhead emanating from multi-hop is reduced.
- ‘Greedy’ network entities are avoided.
- Can be implemented in accordance with pre-designed network hierarchies.

The advantages of a decentralized fusion scheme are:

- Local decisions are quickly achieved.
- Local decisions allow greater flexibility in terms of spectrum allocation.
- Ad-hoc nature of networks can be supported.

2.5.5 Concept of Grouping/ Clustering: In general, the decision fusion hierarchy can be considered for forming any sort of grouping within CSS nodes. The main objectives for forming grouping could be:

- For optimizing decision fusion.
- To achieve redundancy in terms of sensed data.
- To cluster together, those CSS nodes that do not provide much information gain to each other.

Cluster-based CSS in CRN was suggested in [83] to overcome the problems associated with information loss due to channel impairments resulting in errors in decision fusion. By separating all the secondary users into a few clusters and selecting the most favorable user in each cluster to report to the common receiver, the proposed method can exploit the user selection diversity so that the sensing performance can be enhanced. For this purpose, [83] considered that the reporting channel (channel between cognitive users and the common receiver) experiences Rayleigh fading and proposed a cluster-based cooperative spectrum sensing method to overcome channel impairments. By employing such a technique, the reporting error due to the fading channel can be reduced. Moreover, both hard and soft decision fusion were applied to the clustering method to analyze results. It was also assumed that clustering had been done by upper layers. No further investigation into the actual formation of clusters was done. Thus, the first two objectives as listed above were achieved, i.e. redundancy in data communication (reporting channel) and optimal data fusion through majority counting. The third objective, related to optimization of cooperation to achieve maximum information gain, was not addressed.

In [84], CSS algorithms that were inspired by multiple access algorithms were proposed. The concept was quite revolutionary, since it proposed a new way of looking at CSS. CSS has the advantage of better accuracy over non-cooperative schemes. One of the critical problems in CSS is the delay between sensing and decision. Wideband spectrum sensing is another challenge due to its complexity. To solve these problems, [84] proposed new cooperative spectrum sensing techniques inspired by multiple access methods: Time-division (TD), frequency-division (FD), staggered frequency-division (SFD), frequency hopping (FH), irregular sub-band (IS), and staggered irregular sub-band (SIS) cooperative spectrum sensing. Cooperative users are first divided into groups. In TD-CSS, the groups of CSS nodes detect the presence of primary users in turns to reduce delay. To tackle the difficulties of wideband spectrum sensing, FD-CSS assigns different groups to different spectrum bands. SFD-CSS can solve time delay and wideband spectrum sensing issues at the same time by making each group sequentially detect different frequency in different order. FH-CSS performs better than FD-CSS if the channel information is unknown. Finally, asymmetric band access concepts can be applied to CSS to allow different groups to focus on frequency bands with irregular sub-band bandwidth using IS-CSS or SIS-CSS. The most important advantage is the increased agility made possible due to multi-tasking of CSS nodes to different bands as is done in the FD or SFD schemes. While [84] proposed very effective schemes for CSS, they also suggested the formation of groups/ clusters. The FD scheme distributes the frequency band among sensing nodes to enable sharing of workload. This sharing is done in groups. The proposed techniques are very innovative and promise improved agility. In [84], however, the authors had not verified the claimed results through simulation. Furthermore, no criterion for establishment of grouping had been suggested.

2.6 Agility Gain: Agility is defined as the ability of a cognitive radio to sense vacant spectrum and quickly shift to it [36]. It also indicates the time taken by a CR to vacate spectrum after it detects a primary user. Agility is measured in terms of time and its threshold is closely related to the maximum time for which a primary user (PU) can tolerate interference from a secondary user (SU) [36][85]. An important requirement of a CR architecture is to detect the presence of primary or licensed users as quickly as possible. For this reason cognitive users should continuously sense the spectrum. Consider a network with two cognitive radio users *CR1* and *CR2* operating in a fixed TDMA mode for sending data to some base station. Suppose that a primary (licensed) user starts using the band. Then the two cognitive users need to vacate the band as soon as possible to make way for the primary user. However, the detection time becomes significant if one of the users, say *CR1* is in the boundary of decodability as shown in Fig.14. The signal received from the primary user is so weak that *CR1* takes a long time to sense its presence. The time is further increased if it uses a belief strengthening mechanism through majority counting rule for decision fusion. Cooperation between the cognitive users can reduce the detection time of the "weaker" user (*CR1*) thereby improving the agility of the overall network.

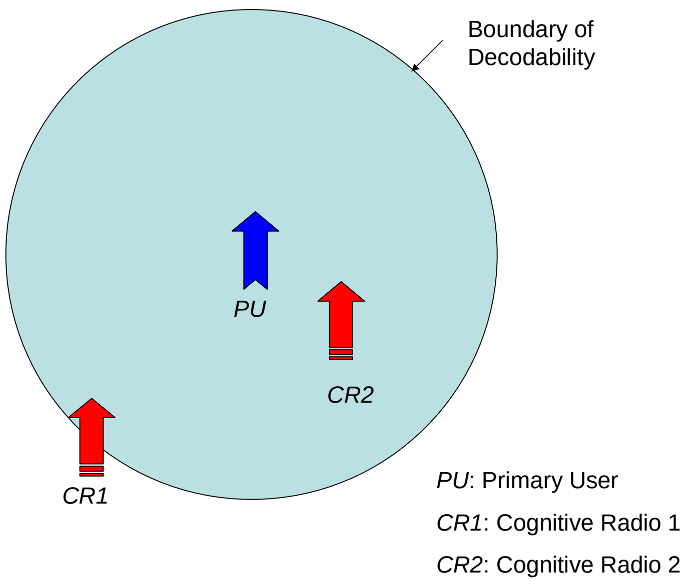


Fig.14. Advantage of Cooperation for Weaker CR

In a cooperation scheme, the agility gain can be computed as given in [36]. Let T_n be the number of time slots taken by user *CR1* in a non-cooperative network to detect the presence of the primary user. We can model this detection time as a Geometric random variable [36].

$$\Pr\{T_n = k\} = (1 - p_n^{(1)})^{k-1} p_n^{(1)} \qquad \textbf{\textit{(2-13)}}$$

Here, $p_n^{(i)}$ is the probability of detection by user *CRi* in a single slot in a non-cooperative environment. This probability [86] is given as:

$$p_n^{(i)} = \alpha^{\frac{1}{P_i+1}} \qquad \textbf{\textit{(2-14)}}$$

where P_i is the received power at the i^{th} CR from the particular primary user and α is the false alarm probability determined uniquely for *CRi* on the basis of the sensing technique used by it.

The total time taken by both *CR1* and *CR2* to vacate the band is [36]:

$$T_{non} = 2\left(\frac{1}{p_n^{(1)}} + \frac{1}{p_n^{(2)}} - \frac{1}{p_n^{(1)} + p_n^{(2)} - p_n^{(1)} p_n^{(2)}}\right) \qquad \textbf{\textit{(2-15)}}$$

If $p_c^{(i)}$ is the probability of detection of *CRi* in a cooperative scheme, then the total time taken in cooperation [36] is given by:

$$T_{coop} = \frac{2 - \frac{p_c^{(1)} + p_n^{(2)}}{2}}{p_c^{(1)} + p_n^{(2)} - p_c^{(1)} p_n^{(2)}} \qquad \textbf{\textit{(2-16)}}$$

Agility gain has been defined [36] as the ratio of time taken in non-cooperation to time taken in cooperation. Thus, it is:

$$\mu_{n/c} \triangleq \frac{T_n}{T_c} \qquad \textbf{\textit{(2-17)}}$$

The same result has been extended to a multi-user environment in [36].

Agility gain quantifies the effectiveness of a network with regards to interference avoidance for the primary users. This is a basic issue for CRN, and it has been stressed by FCC as well [12].

Chapter – 3

3. Proposed Methodology for CSS

3.1 Introduction: CSS has the potential to offset the problems associated with spectrum sensing, the foremost being the 'hidden node' problem. It can also produce greater accuracy in sensing decision due to belief strengthening algorithms when the same results are received from multiple CSS nodes. Another advantage of CSS is that agility can also be enhanced through machine learning processes that are inherently supported by CR. These advantages and the potential applications of CR technology have motivated this research. The concept of grouping of CSS nodes was introduced in the previous chapter. Grouping of CSS nodes was proposed in [84] to support algorithms inspired by multiple access techniques. However, the criteria for establishment of grouping were left to higher layers. These criteria were of critical importance because the effectiveness of these grouping-based algorithms depends entirely on the procedure involved in creation of groups. Grouping of CSS nodes was also proposed in [83], however the objective for creation of groups was to have redundancy in the sensed results (same results received from multiple nodes) in order to mitigate the effects of fading in the reporting channels. The above mentioned proponents of grouping ignored the criteria for its establishment and hence did not tap the full potential of such techniques. These issues have been addressed in this research.

In this chapter, we present a novel technique that takes advantage of cooperative diversity to establish grouping among cooperating secondary users. This technique is then extended to group-based spectrum sensing to establish a tasking mechanism. The technique ensures enhanced agility that ultimately results in a reduction of interference to primary users through their early detection. The presentation of this technique is in phases for ease of understanding and implementation.

3.2 Spectral Environment: An intensive large-scale measurement campaign was carried out to assess spectral environments for studying CSS applications [72]. The statistics gathered in various joint measurements of the spectrum were analyzed in this campaign. Two units were used; one of them was mobile (on a trolley) while the other was a static unit. Each unit consisted of a spectrum analyzer with rugged laptops. In order to make the correlation statistics accurate, the two units needed time synchronization. For this purpose, mobile cellular phones were used to verbally synchronize the units. This was considerably inaccurate, imposing restrictions on the use of similar laboratory equipment.

In order to analyze and develop techniques for CSS implementation in a networked environment, it becomes necessary to compare the advantages of using simulations or empirical measurements. Empirical measurements yield the most realistic results; however, certain practical aspects/constraints related to an effective measurement campaign have to be considered while making a choice to use measurements or simulated data. These practical aspects/constraints include:

3.2.1 Equipment Composition: The minimum equipment composition of each CSS test node should include a spectrum analyzer, a rugged laptop and a data communication terminal with time synchronization applications. The test node should be self-contained for power requirements and mobility.

3.2.2 Quantity: The number of such nodes should be sufficiently large to establish reasonable statistics about the environment. Two or three such nodes would be too less.

3.2.3 Time Synchronization: Each of the spectrum analyzers should have the ability to be time synchronized with its peers and should have equivalent configuration.

3.2.4 Comprehensive Tests: Empirical measurements do not permit the testing of the worst-case scenarios, since these can only be artificially simulated.

Thus comprehensive testing of any CSS technique is not possible on empirical measurements.

Due to non-availability of devices that comprehensively meet these requirements, simulation is the best available option for development and testing of CSS management algorithms and techniques. This aspect creates a bound on the extent of realism that can be applied to the testing scenario.

To overcome these issues, we created a spectral environment that is closest to reality while ensuring that worst-case scenarios are also tested. This is achieved by having maximum randomness in the positions of the primary users (PUs) and secondary users (SUs) within a square area. Considering a trunked radio environment, a random assignment of frequencies was made to each PU from within a specified band. The assigned frequencies are non-repetitive. By computing the distance from each PU to each SU and using this distance to calculate received power, we were able to create vectors of received power corresponding to each usable frequency for each SU. By adding AWGN noise floor figures, we were able to create received spectra for all SUs. A sample of such a spectrum is shown in Fig.15.

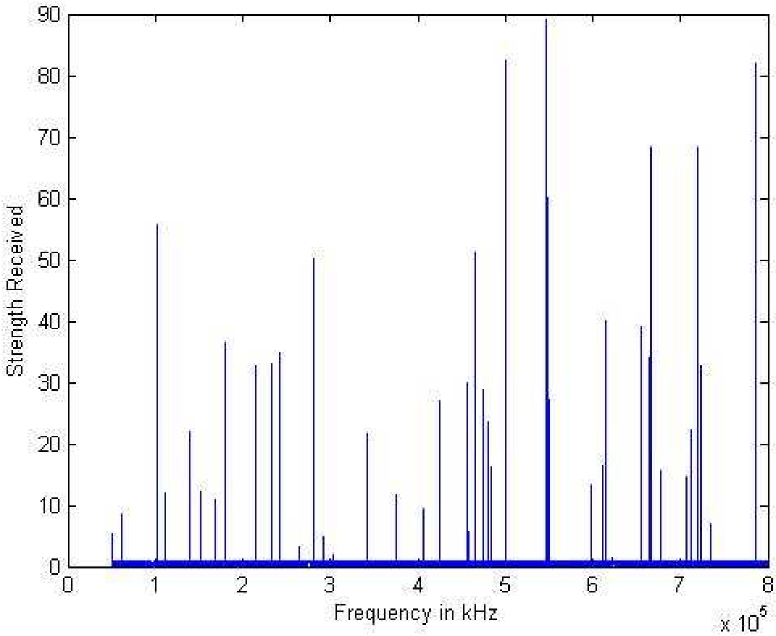


Fig.15. Simulated spectrum

We thus create a received power matrix P_{nm} where n corresponds to the number of SU and m corresponds to the number of PU.

$$P_{nm} = \begin{bmatrix} P_{11} & P_{12} & P_{13} & P_{14} \ldots\ldots & P_{1M} \\ P_{21} & P_{22} & P_{23} & P_{24} \ldots\ldots & P_{2M} \\ P_{31} & P_{32} & P_{33} & P_{34} \ldots\ldots & P_{3M} \\ . & . & . & . & . \\ P_{N1} & P_{N2} & P_{N3} & P_{N4} \ldots\ldots & P_{NM} \end{bmatrix} \qquad \textit{(3-1)}$$

3.3 Individual Sensing Phase: In the first phase of our technique, each CSS node senses the entire spectrum of concern using energy detection. For this purpose, we perform hypothesis testing considering a threshold γ that is higher than the maximum AWGN level (normally taken as -114 dBm as per [12]). In the event of a detected PU at a particular frequency, we have Hypothesis-1:

$$H_1 : P_{nm} \geq \gamma \equiv '1' \qquad \textbf{\textit{(3-2)}}$$

In the event of no PU at a particular frequency, we have Hypothesis-0:

$$H_0 : P_{nm} < \gamma \equiv '0' \qquad \textbf{\textit{(3-3)}}$$

This results in the creation of vectors with each element (either ‘0’ or ‘1’) corresponding to the sensing decision at each frequency. To understand this, consider the following:

If P_{nm}=-23 dBm, which is greater than γ (-114 dBm), then we replace the corresponding element of P_{nm} with ‘1’. However, if we have P_{nm}=-125 dBm, which is lesser than γ (-114 dBm), then we replace the corresponding element of P_{nm} with ‘0’. We have thus created a matrix P_s consisting of binary sensing results with all elements being either ‘1’ or ‘0’.

Depending upon the population of PUs and the frequency band being considered, we would expect to have a sparse [87] matrix, wherein the occurrences of ‘1’ are much greater than those of ‘0’. Such a matrix can be easily compressed using zero-counting algorithms for reduction of data size. Each SU sends its corresponding vector to a central decision fusion centre (CDFC). It is assumed that the reporting channel is sufficiently reliable.

3.4 Binary Correlation Phase: The encoded vectors are transmitted to a pre-designated central decision fusion centre (CDFC) in a centralized cooperation environment. Under normal circumstances, the CDFC would combine the results after decompressing all the vectors. However, in our technique, we do not wish to create a global picture at this stage. Instead, we compute the binary correlation between the sensed results of each pair of SU. The technique selected for the purpose is similar to the binary correlation evaluation criterion that was employed in [72]. The original technique of binary correlation, as previously described in Chapter 2, has been considerably modified to suit our data set. Primarily, we have not used a time index. Instead, we have just used a frequency index. This is because we have communicated just one observation on each frequency by each SU. Belief strengthening is done by multiple observations from different SUs at the same time. We therefore created the following AND_{Sum} and XOR_{Sum} instead of ratios:

$$AND_{Sum}(a,b) = \sum_{f=F_1}^{F_2} SU_a(f) \wedge SU_b(f) \qquad \textbf{\textit{(3-4)}}$$

where a and b correspond to the two SUs for which correlation is being calculated. The frequency index is f which ranges from F_1 to F_2, in discrete predefined intervals.

Similarly, the XOR_{Sum} can be computed using the following relationship:

$$XOR_{Sum}(a,b) = \sum_{f=F_1}^{F_2} SU_a(f) \oplus SU_b(f) \quad \textbf{(3-5)}$$

A high value of AND_{Sum} implies that a high degree of correlation exists between the pairs. Thus cooperation would not give a significant information gain. On the contrary, a high value of XOR_{Sum} implies that cooperation would result in a significant information gain. A binary covariance matrix is created from these two sums. This matrix is a square form matrix that depicts the binary covariance between each pair of SUs. This matrix depicts the distance in terms of covariance between each pair of SU. It is used for carrying out clustering analysis. To understand the concept of a square form distance matrix, consider the data of distances between cities of Pakistan, obtained from Google Earth [88], given in Table 1:

	Karachi	Lahore	Peshawar	Quetta	Islamabad	Multan
Karachi	0	1045	1110	610	1149	730
Lahore	1045	0	380	720	267	315
Peshawar	1110	380	0	613	145	420
Quetta	610	720	613	0	660	430
Islamabad	1149	267	145	660	0	421
Multan	730	315	420	430	421	0

Table 1: Distance between various cities of Pakistan shown in a square form matrix.

In a similar fashion, the covariance distances obtained between each pair of SU can be shown in a square form matrix as under:

$$XOR_{nn} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14}\ldots\ldots & C_{1N} \\ C_{21} & C_{22} & C_{23} & C_{24}\ldots\ldots & C_{2N} \\ C_{31} & C_{32} & C_{33} & C_{34}\ldots\ldots & C_{3N} \\ . & . & . & . & . \\ C_{N1} & C_{N2} & C_{N3} & C_{N4}\ldots\ldots & C_{NN} \end{bmatrix} \qquad \textit{(3-6)}$$

where C_{nn} are obtained from XOR_{Sum} for corresponding pairs of SUs. Since XOR_{Sum} is zero for the same SU (i.e. $n=n$), therefore C_{nn}=0 for $n=n$ on the diagonal. Such a matrix can be easily used for clustering analysis, as will be shown in the next section.

3.5 Grouping Phase: In this phase, the CDFC performs grouping/ clustering on the basis of the XOR_{nn} matrix. We use the hierarchical clustering algorithm [89] because of the size and suitability of our data set. The hierarchical clustering algorithm relies on the Johnson algorithm [90] in this case and proceeds as follows:

The algorithm erases rows and columns in the proximity matrix as old clusters are merged into new ones. The $N*N$ proximity matrix is $D = [d(i,j)]$. The clusterings are assigned sequence numbers *0,1,......, (n-1)* and *L(k)* is the level of the *kth* clustering. A cluster with sequence number *m* is denoted *(m)* and the proximity between clusters *(r)* and *(s)* is denoted *d [(r),(s)]*. The algorithm is composed of the following steps:

- Begin with the disjoint clustering having level $L(0) = 0$ and sequence number $m = 0$.
- Find the least dissimilar pair of clusters in the current clustering, say pair *(r)*, *(s)*, according to $d[(r),(s)] = min\ d[(i),(j)]$ where the minimum is over all pairs of clusters in the current clustering.
- Increment the sequence number: $m = m + 1$. Merge clusters *(r)* and *(s)* into a single cluster to form the next clustering *m*. Set the level of this clustering to $L(m) = d[(r),(s)]$
- Update the proximity matrix, *D*, by deleting the rows and columns corresponding to clusters *(r)* and *(s)* and adding a row and column corresponding to the newly formed cluster. The proximity between the new cluster, denoted as *(r,s)* and old cluster *(k)* is defined as $d[(k),(r,s)] = min\ d[(k),(r)], d[(k),(s)]$ **(3-7)**
- If all objects are in one cluster, stop.

When we apply this procedure to our distance square form matrix given in Table 1, we proceed in the following manner:

- In the first step, cluster level L=0. All cities are in separate groups.

- The nearest pair of cities is Islamabad and Peshawar, at distance 145. These are merged into a single cluster called "Islamabad/Peshawar". The level of the new cluster is L(Islamabad/Peshawar) = 145 and the new sequence number is m = 1.
- Then we compute the distance from this new compound object to all other objects. In single link clustering the rule is that the distance from the compound object to another object is equal to the shortest distance from any member of the cluster to the outside object. So the distance from "Islamabad/Peshawar" to Lahore is chosen to be 267, which is the distance from Islamabad to Lahore, and so on.
- This clustering is summarized in the hierarchical clustering tree shown in Fig.16.

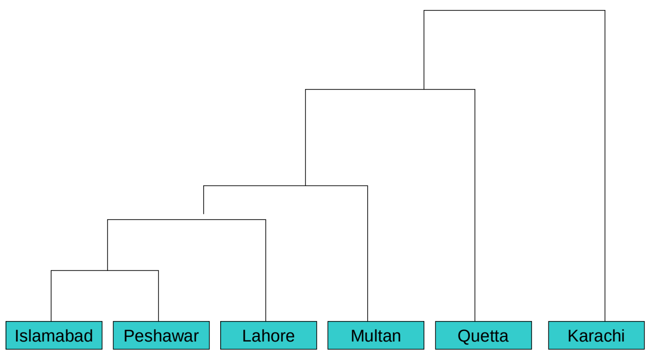


Fig.16. Hierarchical Tree for Sample Data of Table 1

When we apply this technique to our binary covariance data from XOR_{nn}, we obtain grouping carried out in a similar format. The hierarchical tree for such a data set in which 30 SUs were considered is given in Fig.17 and the corresponding grouping is shown in Fig.18.

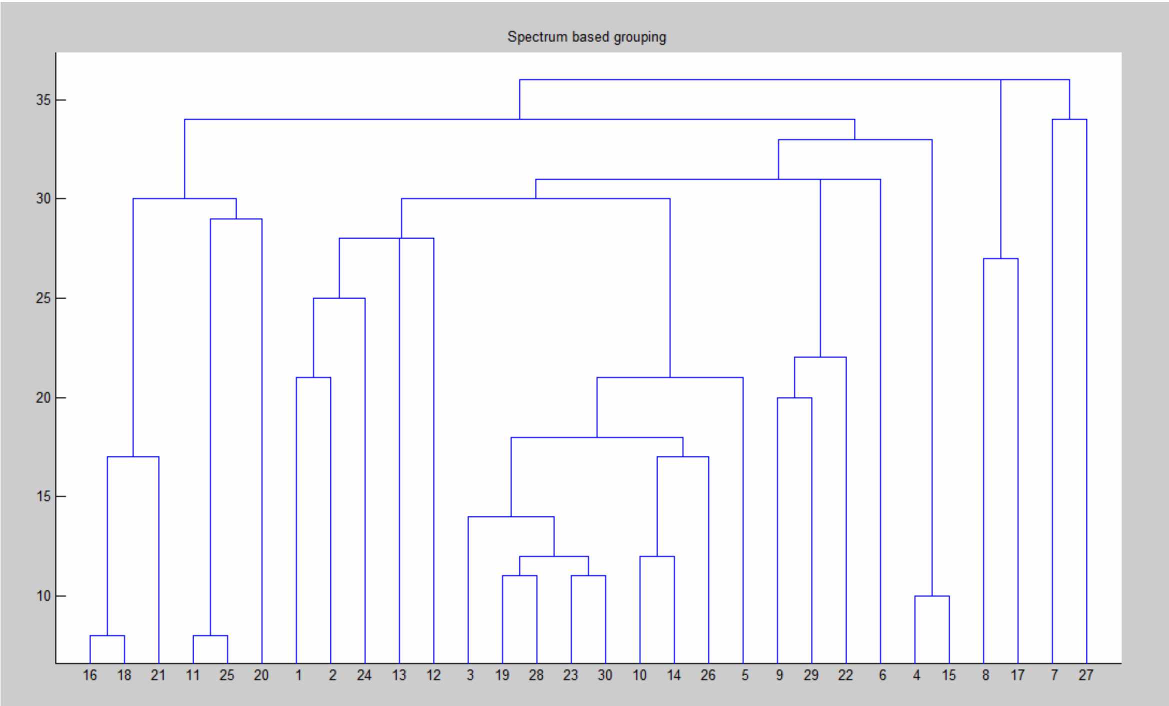


Fig.17. Hierarchical Tree for clustering of 30 SUs

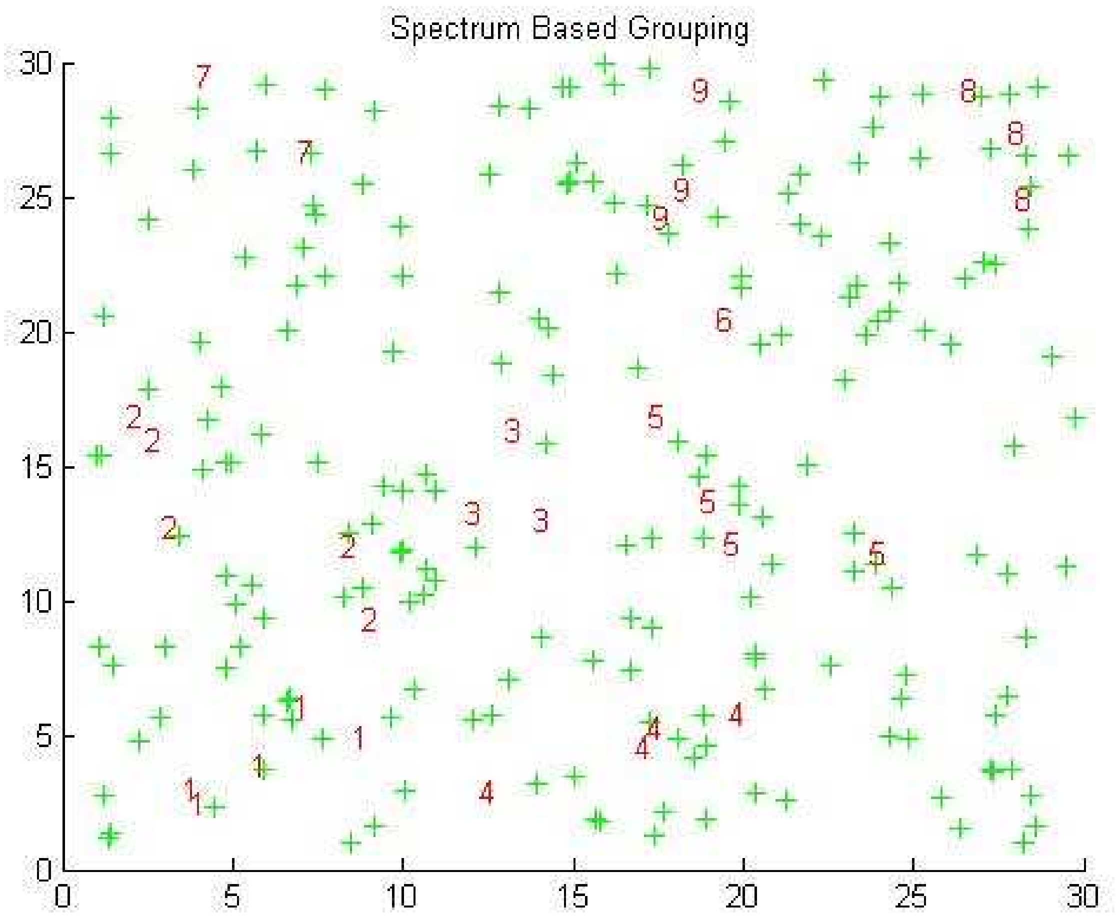


Fig.18. Grouping of 30 SUs. SUs are numbers whereas + are the PUs.

3.6 Tasking of Grouped CSS Nodes: The grouping, as performed in the previous section, has resulted in the clustering together of highly correlated CSS nodes. The threshold used in this case is dependent upon the total number of SUs and dictates the maximum number of groups to be 30% of the total number of SUs. The actual objective of grouping is to enable the employment of a tasking mechanism within groups. The grouping mechanism, itself, has ensured that maximum information gain is obtained through sharing of aggregated sensed spectra between groups. We therefore propose the following tasking mechanism for grouped CSS nodes:

- A group decision fusion centre (GDFC) is defined for each group.
- The GDFC is informed about the members of its group by the CDFC.
- Each GDFC divides the entire spectrum to be sensed into equal parts according to the number of group members thus creating equal sub-bands within the group.
- These non-overlapping sub-bands are sensed by the tasked SU according to the instructions of the GDFC.
- Each GDFC fuses the results obtained from each member SU and passes the aggregated result to the CDFC.
- The CDFC fuses the results from each GDFC to obtain a global picture of the sensed spectrum.

The tasking mechanism can be understood from the hierarchy shown in Fig.19.

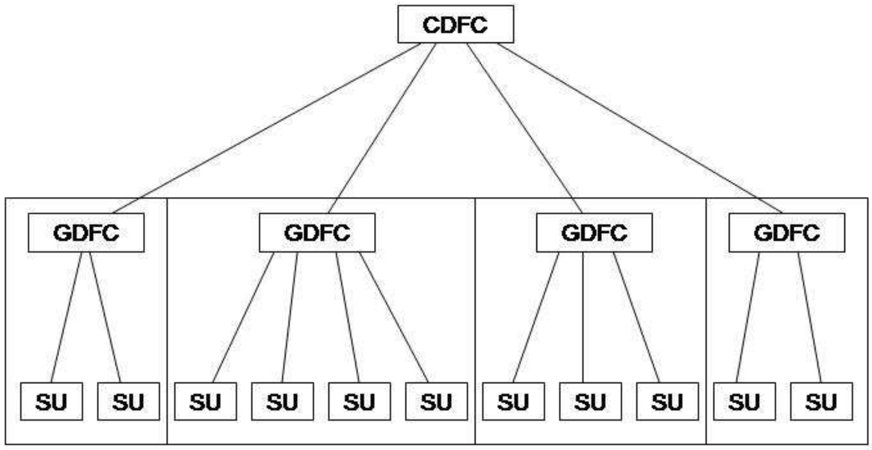


Fig.19. Hierarchy for tasking and decision fusion of CSS nodes

3.7 Advantages of Proposed Methodology:

Formal results, based on simulations, will be used to discuss the achieved advantages in the next chapter. However, basing on the mathematical model of the proposed methodology, certain characteristics have emerged that are overriding advantages of this technique. These are summarized below:

3.7.1 Greater Agility: Consider ΔT_s to be the average time taken by an individual CSS node to sense the entire spectrum ΔF of interest. Let there be *n* CSS nodes under the control of the CDFC, all of them being treated as peers. In the event that cooperation is restricted to result fusion only, then we have a typical centralized or peer-based CSS environment. If it takes time t_f to fuse the decision at CDFC/ GDFC then the total time taken to arrive at a decision is given by:

$$T_{peer} = t_f + \Delta T_s \qquad \textbf{\textit{(3-8)}}$$

Now consider the scenario in which all the CSS nodes are working in an FD tasking scenario. In such a case, the entire spectrum of interest ΔF is divided into n CSS nodes. Thus each CSS node takes $\Delta T_s / n$ time to sense the spectrum. Fusion of decision takes approximately the same time t_f. Thus the total time taken to arrive at a decision in an FD tasking scenario is given by:

$$T_{FD} = t_f + \frac{\Delta T_s}{n} \qquad \textbf{\textit{(3-9)}}$$

In our technique, a grouping mechanism is in place. Let the average group size including the GDFC be κ such that κ is less than n and greater than one. Thus the total time taken to arrive at a decision in our technique is given by:

$$T_{Group} = t_f + \frac{\Delta T_s}{\kappa} \qquad \textbf{\textit{(3-10)}}$$

Since $\kappa \le n$, therefore we have:

$$T_{peer} \ge T_{Group} \ge T_{FD} \qquad \textbf{\textit{(3-11)}}$$

This is a very important conclusion that proves that our technique should take lesser time as compared to the peer-based cooperation among CSS nodes. The only situation in which the two can be equal is when no grouping can be established due to minimum correlation, which is highly unlikely. The agility gain is also measured in terms of the ability of a CSS node to detect the appearance of a new PU. In the case of a peer-based CSS configuration, the maximum time that would be taken to detect a new PU would be ΔT_s. Using our technique, this time is reduced to $\Delta T_s / \kappa$ where $\kappa \geq 1$. It may be noted here that the result obtained using the FD technique is even lesser than our technique using grouping. Apparently, the FD technique is giving a higher agility gain; however, as our next result will show, it is doing so at the cost of accuracy.

3.7.2 Better Accuracy: The probability of detection of a new PU depends upon the probability of a CSS node being present within the area of detect-ability of the PU. For a peer-based CSS technique, consider the average area of detect-ability of a PU to be A_d (Fig.20). If the total area of concern to us is A_{total} then the probability that a CSS node is in the relevant detect-ability area is p_{peer}.

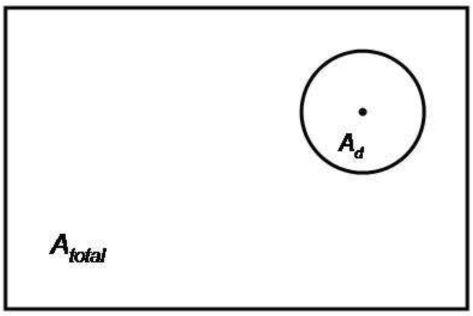


Fig.20. Probability of Detection of a new PU

p_{peer} is given by:

$$p_{peer} = \frac{A_d}{A_{total}} \qquad \textbf{\textit{(3-12)}}$$

In the FD technique all nodes have been tasked with *n* non-overlapping sub-bands. The probability that a particular CSS node is sensing the sub-band of interest is *1/n*. The probability of a CSS node being present in the relevant area of detect-ability is A_d / A_{total}. Thus the probability that the correct CSS node is present within the area of detect-ability is p_{FD} and is given by:

$$p_{FD} = \left(\frac{A_d}{A_{total}} \right) \frac{1}{n} \qquad \textbf{\textit{(3-13)}}$$

In our technique, we have employed binary correlation to establish grouping. If we achieve a relatively higher value of AND_{Sum} then the probability that the correct CSS node from a group is within the area of detect-ability is p_{group} and is given by:

$$p_{group} \approx \frac{A_d}{A_{total}} \qquad \textbf{\textit{(3-14)}}$$

3.7.3 Near Optimal Information Gain: Information gain is determined by the XOR_{Sum}. In the peer-based network, due to high binary correlation (that would exist between some of the CSS nodes) the XOR_{Sum} would be much lower than desired. The maximum XOR_{Sum} is possible when no two CSS nodes detect the same PU. This is only possible when not more than one CSS node is available inside the detect-able area of any PU. In such a rare distribution of SUs, the chance of missing a PU is unacceptable. Similarly, the chance of missing a PU in the FD scenario is even higher and this would also result in loss of desired information. Our technique addresses the problems of both peer-based as well as FD tasking scenarios. The grouping based on binary correlation addresses the problem of agility by tasking of sub-bands within groups. When the sensed results are aggregated at the GDFC, it is observed that the XOR_{Sum} between groups is much higher than both the other techniques. This implies a drastic increase in information gain. By having groups consisting of CSS nodes with high binary correlation, it is ensured that the chances of missing a PU are minimal. Thus we have achieved a near-optimal information gain in our technique.

Chapter – 4

4. Simulation Details & Results

The computer used for achieving the results given in this chapter was HP Compaq Presario ® C700 laptop with genuine Windows Vista. It had a 1 GB RAM and a dual core Intel Pentium ® T2310 processor running at 1.46 GHz. The MATLAB ® version was 7.3.0.

4.1 Spectrum Simulation: The objective was to simulate a spectrum that depicts a reasonable level of spectrum occupancy in order to comprehensively test the proposed methodology. It was also necessary to maintain a certain degree of realism while ensuring the possibility of occurrence of worst case scenario without design. Accordingly, maximum randomness was incorporated in the placement of SUs and PUs, and in the assignment of frequencies. The randomness was within the bounds of the MATLAB software used. PUs and SUs are considered to be randomly placed in a square area of 30x30 km^2. This parameter is modifiable in the original code. The MATLAB function for the placement of these is as under:

```
function [PUx PUy SUx SUy PUxy SUxy]=placeSUPU(numPU,numSU,ar)
%Created by Maj Rizwan Akhtar, MSEE-13, College of Signals, NUST.
%Randomly place the PUs and SUs in a 30km squared area.
PUx=random('unif',1,ar,1,numPU);
PUy=random('unif',1,ar,1,numPU);
scatter(PUx, PUy, 'd','b'), hold on
% Create the Secondary Users (Cognitive sensing nodes)
SUx=random('unif',1,ar,1,numSU);
SUy=random('unif',1,ar,1,numSU);
scatter(SUx, SUy, '+','r'),hold off, title('PUs-Blue Diamonds ; SUs-Red Plus')
% Combined Position Matrices
PUxy=[PUx;PUy]';
SUxy=[SUx;SUy]';
```

This results in the creation of position matrices *PUxy* and *SUxy*. In our initial tests, we have assumed 30 SUs and 200 PUs in the given area of 30x30 km^2. Therefore, *PUxy* is a 200x2 matrix. The first column is the x-position and the second column is the y-position. The rows correspond to the number of PU. Similarly, *SUxy* is a 30x2 matrix. The resultant matrices are plotted in a scatter form and are shown in Fig.21. The blue diamonds are PUs and the red '+' are SUs.

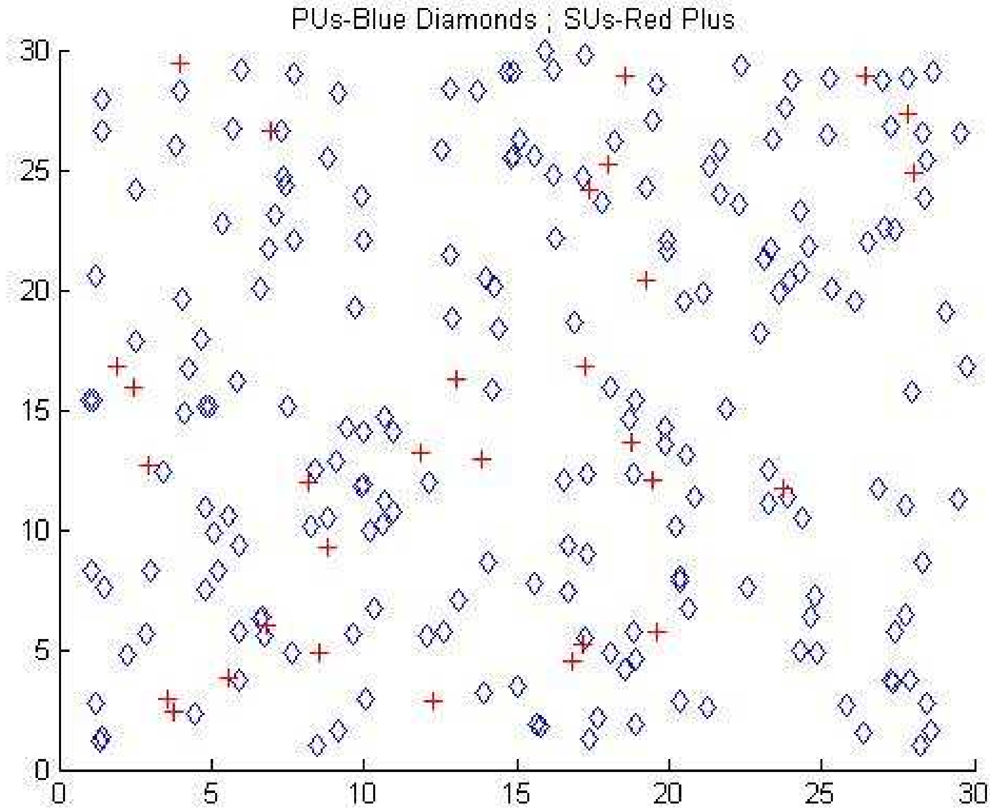


Fig.21. Random placement of PUs and SUs in a 30x30 km^2 area.

We then compute the Euclidean distance between each SU and each PU. We use the following relationship:

$$d_{nm} = \sqrt{(x_n - x_m)^2 + (y_n - y_m)^2} \qquad \textbf{(4-1)}$$

Here, we have assumed that *n* corresponds to the SUs and *m* corresponds to the PUs. Therefore, *n=1,2,3……30* and *m=1,2,3……200*. Thus the distance matrix is created, which is 30x200. We have called it *DistSP* in the simulation.

$$DistSP = \begin{bmatrix} d_{1,1} & d_{1,2} & d_{1,3} & d_{1,4}\ldots\ldots & d_{1,200} \\ d_{2,1} & d_{2,2} & d_{2,3} & d_{2,4}\ldots\ldots & d_{2,200} \\ d_{3,1} & d_{3,2} & d_{3,3} & d_{3,4}\ldots\ldots & d_{3,200} \\ . & . & . & . & . \\ d_{30,1} & d_{30,2} & d_{30,3} & d_{30,4}\ldots\ldots & d_{30,200} \end{bmatrix} \qquad \textbf{\textit{(4-2)}}$$

The MATLAB function used to compute the *DistSP* matrix is given below:

```
function [DistSP DistSPm]=DistSUPU(SUx, SUy, PUx, PUy, numSU, numPU)
%Created by Maj Rizwan Akhtar, MSEE-13, College of Signals, NUST.
DistSP=[];
idx1=1;
idx2=1;
for w=1:1:numSU;
   for v=1:1:numPU;
      DistSP(idx2,idx1)=sqrt(((SUx(idx2)-PUx(idx1))^2)+(SUy(idx2)-PUy(idx1))^2);
      idx1=idx1+1;
   end
   idx2=idx2+1;
   idx1=1;
end
DistSP; %SU are in rows and PU are in columns
DistSPm=1000*DistSP; %Convert the DistSP into meters
```

The frequency band to be sensed is 50 MHz to 100 MHz. This is modifiable from the main file. We will sense the band at intervals of 25 kHz. This channel spacing is modifiable. A smaller channel spacing would result in greater resolution. However, since we are working in the lower part of the TV band, we expect to see broad band transmissions of terrestrial TV as well as some individual radios. Therefore, the channel spacing realistically ensures that no usable part of the spectrum is being missed out.

We then create a vector of usable frequencies that contains the lowest frequency to the highest frequency in steps of 25 kHz. In our simulation, we have created the vector *vFreq*. With the above mentioned parameters, it is 1x2001 in size.

The MATLAB function used to create this vector is:

```
function [vFreq]=FreqVector(LowFreq, HighFreq, BandSpace)
%Created by Maj Rizwan Akhtar, MSEE-13, College of Signals, NUST.
vFreq=[]; %Empty Frequency Spectrum created
%Creation of the vFreq vector:
idx=1;
for v=LowFreq:BandSpace:HighFreq
   vFreq(idx)=v;
   idx=idx+1;
end
vFreq; %Final Frequency Spectrum
```

We then assign these frequencies randomly to the PUs, using a uniform distribution from the *vFreq* vector already created. It is ensured that each PU has a distinct frequency. This creates a vector *PUFreq* containing the frequencies being used by each PU arranged in the same order as the matrix *PUxy*. The function used for this purpose is:

```
function [PUFreq]=FreqAsgn(vFreq, numPU)
%Created by Maj Rizwan Akhtar, MSEE-13, College of Signals, NUST.

PUFreq=[]; %Empty PUFreq vector created
idx=1;
idxrange=length(vFreq);
idxasgn=randint(1,numPU,[1,idxrange]);
for y=1:numPU
   PUFreq(idx)=vFreq(idxasgn(idx));
```

```
  for x=1:idx-1
    if PUFreq(idx)==PUFreq(x)
      PUFreq(idx)=vFreq(idxasgn(idx)+1);
    end
    if PUFreq(idx)==PUFreq(x)
      PUFreq(idx)=vFreq(idxasgn(idx)-2);
    end
  end
  idx=idx+1;
end
PUFreq;
```

We then compute the received power at each SU from each PU on the basis of distance and the frequency assigned. We consider the standard free-space path loss [91] as follows:

$$P_r(d_{nm},\lambda) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L_f} \quad \textbf{\textit{(4-3)}}$$

where $P_r(d_{nm})$ is the received power, P_t is the transmitted power of the PUs, G_t is the transmitter antenna gain (for the PU), G_r is the receiver antenna gain (for the SU), λ is the wavelength obtained from the allocated frequency to the concerned PU, d_{nm} is the relevant distance from the D matrix and L_f is the system loss factor. For purposes of simulation, we have assumed P_t as 5 Watts, G_t is 1, G_r is 1 and L_f is also 1. This results in the creation of a matrix of received power that is 30x200 in size.

$$P = \begin{bmatrix} P_{1,1} & P_{1,2} & P_{1,3} & P_{1,4}\cdots\cdots & P_{1,200} \\ P_{2,1} & P_{2,2} & P_{2,3} & P_{2,4}\cdots\cdots & P_{2,200} \\ P_{3,1} & P_{3,2} & P_{3,3} & P_{3,4}\cdots\cdots & P_{3,200} \\ . & . & . & . & . \\ P_{30,1} & P_{30,2} & P_{30,3} & P_{30,4}\cdots\cdots & P_{30,200} \end{bmatrix} \quad \textbf{\textit{(4-4)}}$$

The MATLAB function used to create the received power matrix is:

```
function [Pr]=RxPower(PUFreq, numSU, PUGt, SUGr, DistSPm, L, c, Pt)
%Created by Maj Rizwan Akhtar, MSEE-13, College of Signals, NUST.
%Convert PUFreq into Hz from kHz
PUFreq=1000*PUFreq;
%Compute the wavelength PUlambda by dividing freq by c
PUlambda=c./PUFreq;
idx5=1;
for g=1:1:numSU
   Pr(idx5,:)=(Pt.*PUGt.*SUGr.*PUlambda.^2)./((4*pi)^2.*DistSPm(idx5,:).*L);
   idx5=idx5+1;
end
Pr; %Received Power at SUs with rows corresponding to SU and columns corresponding to
each PU.
%We now apply equalization:
idx6=1;
for k=1:1:numSU
   Pr(idx6,:)=Pr(idx6,:)./PUlambda.^2;
   idx6=idx6+1;
end
Pr;% Received Power after applying equalization
```

Equalization in the above mentioned function has been applied to cater for large bands. If we are sensing relatively smaller bands, such as 50MHz, then this part of the function can be converted to remarks. The resultant matrix is *Pr*.

The next step is to create association between the received power and the corresponding elements of the frequency vector *vFreq* on the basis of the frequency assigned to each PU. This is the final step in the creation of the spectrum.

```
function [PUFreqMHz PUFreqkHz PrSU vFreq]=CreateSpectrum(PUFreq, numSU, vFreq,
numPU, Pr)
% Created by Maj Rizwan Akhtar, MSEE-13, College of Signals, NUST.
PUFreqMHz=PUFreq/1000; %Creates a vector of PU freq in MHz
PUFreqkHz=PUFreq; %Creates a vector of PU freq in kHz
PrSU=zeros(numSU,length(vFreq));
for s=1:numPU
   for t=1:length(vFreq)
      if vFreq(t)==PUFreqkHz(s)
         PrSU(:,t)=Pr(:,s);
      end
   end
end
```

Having performed this step, we have simulated the spectrum in the given band. The matrix *PrSU* is 30x2001. Each row of this matrix corresponds to an SU. This is the individually sensed spectrum of each SU.

4.2 Simulation of Proposed Methodology: Having simulated the spectrum, we then proceed to simulate our proposed methodology. The first phase, as already explained in the previous chapter, is individual sensing. The outcome of this phase is energy detection on the received spectrum. This performs simple hypothesis testing to ascertain the presence or absence of a valid PU signal. It is carried out on each element of the matrix *PrSU*. As a result of this step, we achieve a binary matrix in which '1' indicates the presence of a PU and '0' indicates its absence. The MATLAB function that performs this is:

```
function [Sensed SenseCount toc1]=GlobalSensing(numSU, vFreq, PrSU, PrThresh)
% Created by Maj Rizwan Akhtar, MSEE-13, College of Signals, NUST.

tic
Sensed=zeros(numSU,length(vFreq));
for d=1:numSU
   for e=1:length(vFreq)
      if PrSU(d,e)>PrThresh
         Sensed(d,e)=1;
      end
   end
end
for g=1:numSU
   SenseCount(g)=sum(Sensed(g,:));
end
SenseCount
```

```
'Global Spectrum Sensing'
toc1=toc
```

Through this function, we were able to compare each element of *PrSU* with the predefined threshold for sensing, which was assumed to be -114 dBm. We also proceeded to count the number of PUs sensed by each SU and the total time taken in this ‘global’ or peer-based sensing process. Till this stage, the entire sensing process is non-cooperative.

In the next step, we carried out pair-wise binary covariance of the sensed results of all the SUs. The procedure for simulation was in accordance with the outline given in the previous chapter. We were able to create the *ANDMatrix* and the *XORMatrix*. Together these define the correlation and the covariance, respectively, for binary data. We used the following function to perform the binary covariance:

```
function [ANDMatrix XORMatrix]=BinaryCovariance(numSU,TC)
% Created by Maj Rizwan Akhtar, MSEE-13, College of Signals, NUST.

for k=1:numSU
   for l=1:numSU
      ANDMatrix(k,l)=sum(TC(k,:)&TC(l,:));
      XORMatrix(k,l)=sum(xor(TC(k,:),TC(l,:)));
   end
end
```

The *XORMatrix* had zeros on the diagonal (row=column). As such, it is a square form matrix and can be used for grouping. For this purpose, we have used the built-in clustering function of MATLAB version 7.3.0. First we identified the *XORMatrix* as a square form matrix to MATLAB. Then we used the single *linkage* function as per the Johnson algorithm [90]. We then used the *cluster* function of MATLAB to perform clustering with *maxclust* parameter set to 30% of the total number of SUs. This identifies the point at which the hierarchical tree is to be cut. The function used for this purpose is:

```
function [X1 X2 Group1 I1]=Grouping(SUxy, XORMatrix, maxgp, PUx, PUy)
%Created by Maj Rizwan Akhtar, MSEE-13, College of Signals, NUST.
%Grouping on the basis of received spectrum
X1=squareform(XORMatrix);
X2=linkage(X1);
Group1 = cluster(X2,'maxclust',maxgp);
SUxy'
Group1'
figure,dendrogram(X2),title 'Spectrum based grouping'
I1=inconsistent(X2);
%Create plot (Spectrum Based Grouping)
figure,axis ([0 30 0 30])
scatter(PUx, PUy, '+','g'),title ('Spectrum Based Grouping')
for i=1:maxgp
    idx=find(Group1==i);
    x=SUxy(idx,1);y=SUxy(idx,2);
    text(x,y,num2str(i),'color','r'),hold on
end
hold off
```

This *grouping* function also created two separate figures. The first is the dendrogram, which is a depiction of the grouping in the form of a hierarchical tree. For the parameters described above, the dendrogram that was created is in Fig.21. The x-axis of the plot identifies the SU number and the y-axis represents the covariance distance that was used to create the grouping.

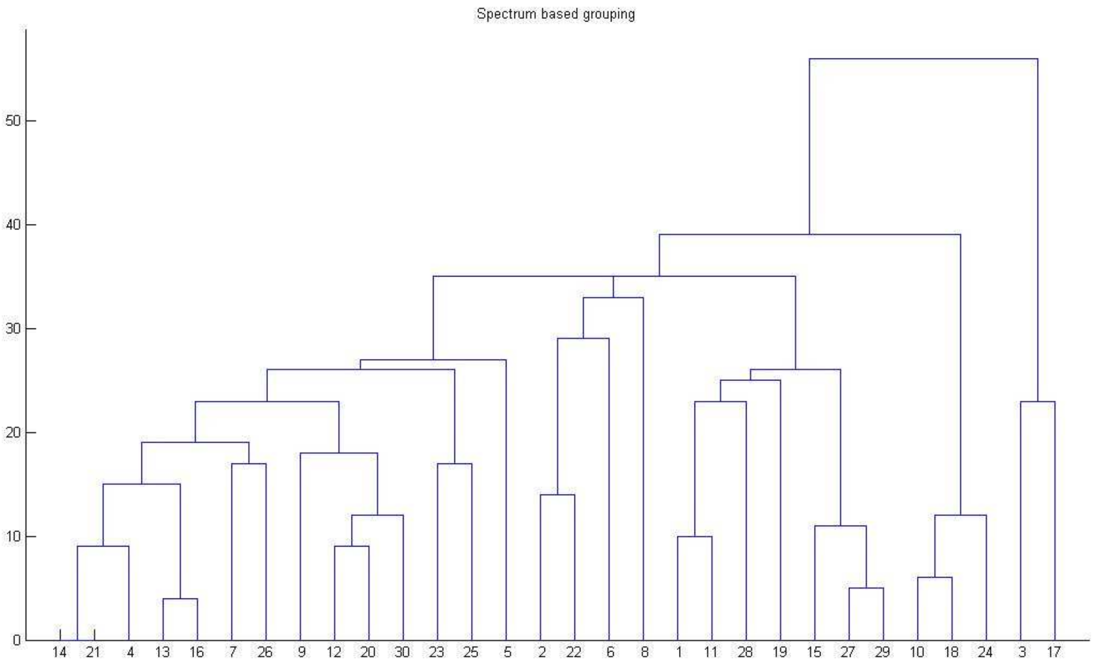


Fig.22. Hierarchical Tree Dendrogram

On the basis of this dendrogram, the *cluster* function created groups of SUs. The grouping can be seen in Fig.23. The green '+' indicate the PUs whereas the numbers signify the grouping of the SUs.

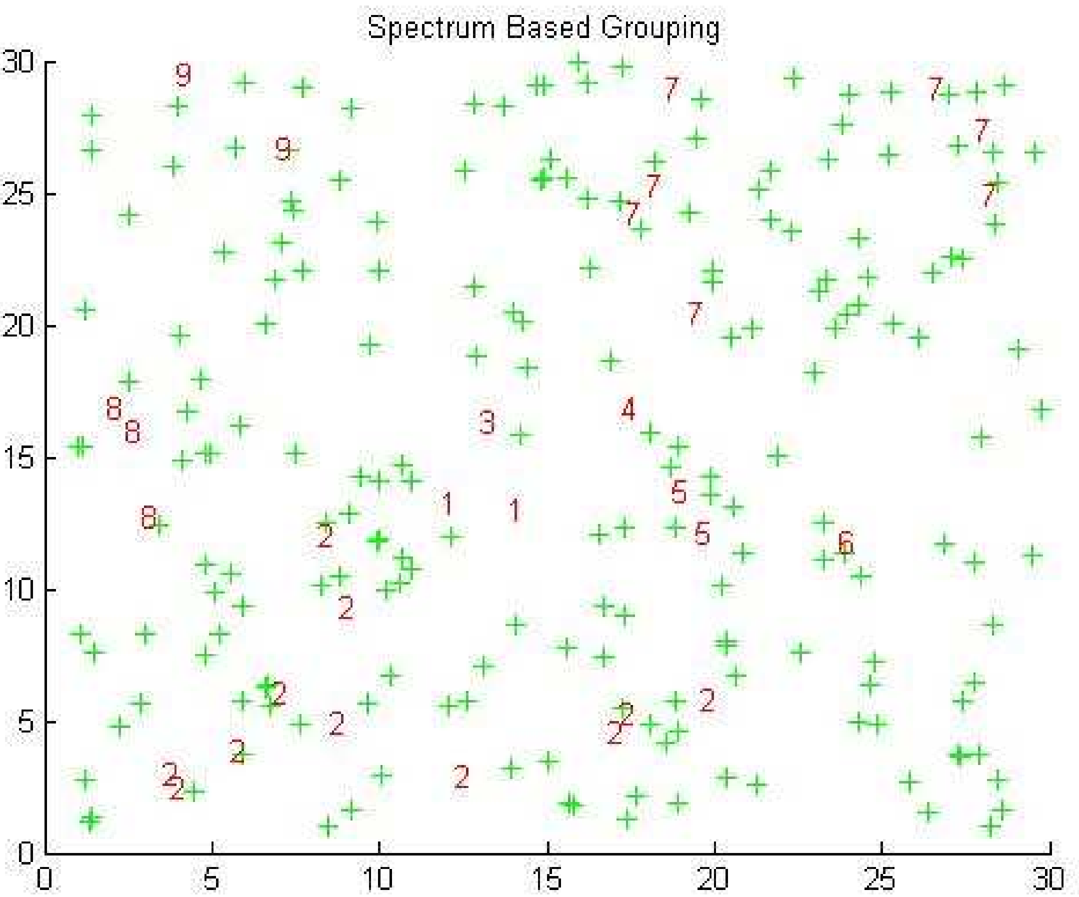


Fig.23. Grouping of SUs

The next phase was the tasking of groups. For this purpose, we selected two groups. The first was the largest one and the second was the group that had an average size. Since the members of a group had highest correlation in terms of sensed spectra, therefore each member within the group was tasked non-overlapping parts of the frequency band to be sensed. Thus the frequency band of 50 MHz was split into sub-bands. The size of each sub-band was 50MHz/M, where M was the number of members in the respective groups. To do this, we first defined the new band to be sensed. Then we showed the performance of group based CSS on the new smaller band. The sensing process was also timed. In the end, the number of sensed PUs by each SU is also counted. The MATLAB function that was written to perform this function is:

```
function [NewBand NewLow NewHigh NewLen NewSensed NewSenseCount
toc2]=groupCSS(HighFreq,LowFreq,maxMembers,numSU,PrSU,PrThresh)
% We consider the largest group to show optimum FD CSS
NewBand=round((HighFreq-LowFreq)/maxMembers)
%We define the lower freq limit for CSS FD in the largest group assigned to
%the first CSS node:
NewLow=LowFreq
%We define the higher freq limit for CSS FD in the largest group assigned
%to the first CSS node:
NewHigh=floor(NewLow+NewBand)
%Now we create the new frequency band (smaller)
idx=1;
for v=NewLow:25:NewHigh
   NewFreq(idx)=v;
   idx=idx+1;
end
NewFreq;
NewLen=length(NewFreq);
%We now perform CSS FD on this new band
tic
NewSensed=zeros(numSU,NewLen);
for d=1:numSU
   for e=1:NewLen
      if PrSU(d,e)>PrThresh
         NewSensed(d,e)=1;
      end
   end
end
 'FD CSS'
toc2=toc
for g=1:numSU
   NewSenseCount(g)=sum(NewSensed(g,:));
end
```

The final process of our technique is the fusion of the results. An error (missed PUs) is also computed in terms of percentage.

4.3 Results: The MATLAB simulation designed to implement our proposed methodology, also included comprehensive analysis functions. The objective was to verify the mathematical results. The results included:

4.3.1 Analysis of Grouping: The proposed methodology is based on grouping of SUs. Therefore, an analysis of the effectiveness of the grouping is of paramount importance. The function written for this purpose, carried out analysis of results obtained in twenty repetitions of our methodology. Each repetition entailed fresh random placements of PUs and SUs as well as frequency assignments. The MATLAB function created for this purpose is:

```
%Analysis File
%Maj Rizwan Akhtar, MSEE-13
clear all
close all
clc
Repetitions=20;
for ct=1:Repetitions
   [maxMembers minMembers medianMembers meanMembers NewHigh NewLow
CSSTime FDCSSTime FDCSSAvgTime C1 ErrorSensed]=rizthesis();
   MaxGpSize(1,ct)=maxMembers;
   MinGpSize(1,ct)=minMembers;
   MedianGpMembers(1,ct)=medianMembers;
   AvgGpMembers(1,ct)=meanMembers;
   NewBand(1,ct)=NewHigh-NewLow;
   Cophenet(1,ct)=C1;
   ErrorPercent(1,ct)=ErrorSensed;
   GlobalSenseTime(1,ct)=CSSTime;
   GroupSenseTime(1,ct)=FDCSSTime;
   AvgGroupSenseTime(1,ct)=FDCSSAvgTime;
end
MaxGpSize
MinGpSize
MedianGpMembers
AvgGpMembers
NewBand
Cophenet
```

```
ErrorPercent
GlobalSenseTime
GroupSenseTime
AvgGroupSenseTime
figure,bar(MaxGpSize, 'DisplayName', 'MaxGpSize', 'YDataSource', 'MaxGpSize');
figure(gcf),title('Size of Largest Group')
figure,bar(AvgGpMembers, 'DisplayName', 'AvgGpMembers', 'YDataSource',
'AvgGpMembers'); figure(gcf),title('Average Group Size')
figure,bar(NewBand, 'DisplayName', 'NewBand', 'YDataSource', 'NewBand');
figure(gcf),title('Scanned Band in KHz by Group Members')
figure,bar(Cophenet, 'DisplayName', 'Cophenet', 'YDataSource', 'Cophenet');
figure(gcf),title('Cophenet Correlation Coefficient')
figure,bar(ErrorPercent, 'DisplayName', 'ErrorPercent', 'YDataSource', 'ErrorPercent');
figure(gcf),title('Percentage of Missed PUs')
figure,bar(GlobalSenseTime, 'DisplayName', 'GlobalSenseTime', 'YDataSource',
'GlobalSenseTime'); figure(gcf),title('Time Taken for Peer Based CSS')
figure,bar(GroupSenseTime, 'DisplayName', 'GroupSenseTime', 'YDataSource',
'GroupSenseTime'); figure(gcf),title('Time Taken for Group Based CSS of Max Group Size')
figure,bar(AvgGroupSenseTime, 'DisplayName', 'AvgGroupSenseTime', 'YDataSource',
'AvgGroupSenseTime'); figure(gcf),title('Time Taken for Group Based CSS of Avg group
Size')
```

Our analysis included:

4.3.1.1 Cophenet Analysis: In the hierarchical cluster tree, any two SUs in the original data set are eventually linked together at some level. The height of the link represents the distance between the two clusters that contain those two SUs. This height is known as the cophenetic distance between the two SUs. One way to measure how well the cluster tree generated by the *linkage* function reflects the data set is to compare the cophenetic distances with the original distance data generated by the binary covariance. If the clustering is valid, the linking of SUs in the cluster tree should have a strong correlation with the binary covariance between pairs of SUs. The *cophenet* function compares these two sets of values and computes their correlation, returning a value called the cophenetic correlation coefficient. The closer the value of the cophenetic correlation coefficient is to 1, the more accurately the clustering solution reflects the data. To verify this, we created an analysis function that performed twenty repetitions of the methodology. Each repetition involved a fresh random placement of all the PUs and SUs as well as their frequency assignments. The results of the cophenet analysis are in Fig.24.

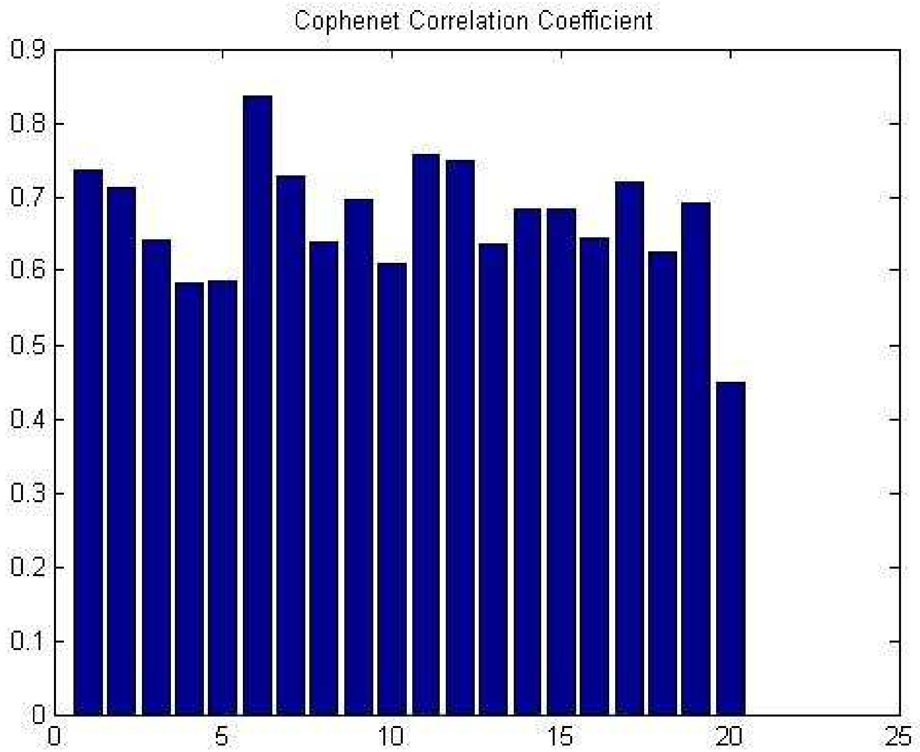


Fig.24. Cophenet Analysis in 20 Repetitions

It was observed that the cophenet correlation coefficient was mostly above 0.6, indicating a reasonably good degree of grouping.

4.3.1.2 Maximum Group Size: Using the same analysis function, we observed the maximum size of groups. The maximum group size ranged from 6 to 15 members. In the case of 15 members, the cophenet was below 0.5, therefore this was not effective grouping. In all other cases (19 out of 20), the maximum group size was quite realistic affording a reasonable utilization of the grouping to achieve effective FD CSS. The result is in Fig.25.

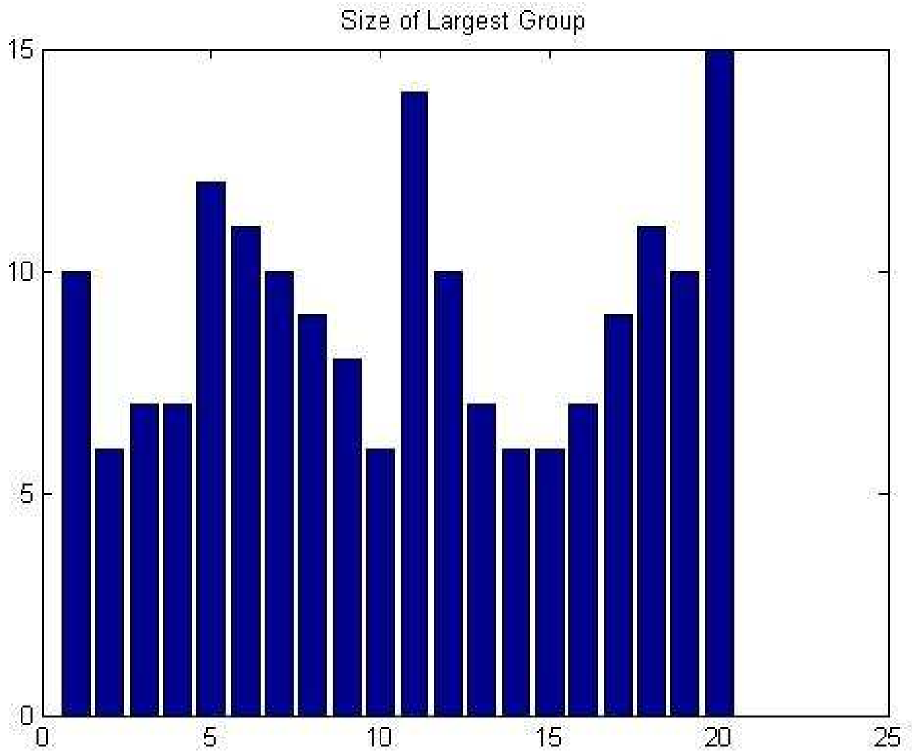


Fig.25. Size of Largest Group

4.3.1.3 Average Group Size: In all cases, the average group size was observed to be 3. This was because of the clustering algorithm, which had a maximum cluster cutoff based on 30% of the total number of SUs. The average group size observed in 20 repetitions is shown in Fig.26.

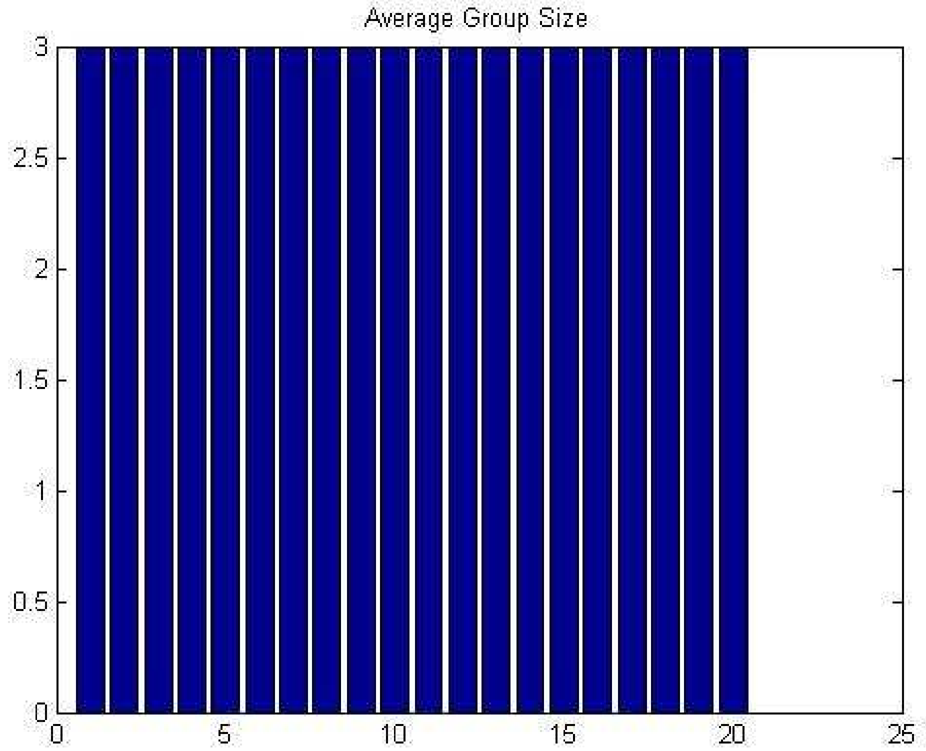


Fig.26. Average group size in 20 repetitions

4.3.2 Agility Gain: Since the frequency band was divided into sub-bands for FD CSS within groups, therefore we were able to achieve an enhancement in agility. The new, smaller bandwidth that was sensed in twenty repetitions is shown in Fig.27. Agility in terms of sensed frequency band is assessed by comparing the time taken in a peer based CSS scheme (Fig.28) with our FD CSS (Fig.29) methodology. The time taken in a group of average size is in

Fig.30. It can be observed that we were able to achieve an agility gain in terms of reduction in sensing time. The FD CSS time for the largest group was approximately 10% of the time taken for peer based CSS. Similarly, the FD CSS time for the average sized group was 23% of the time taken for peer based CSS.

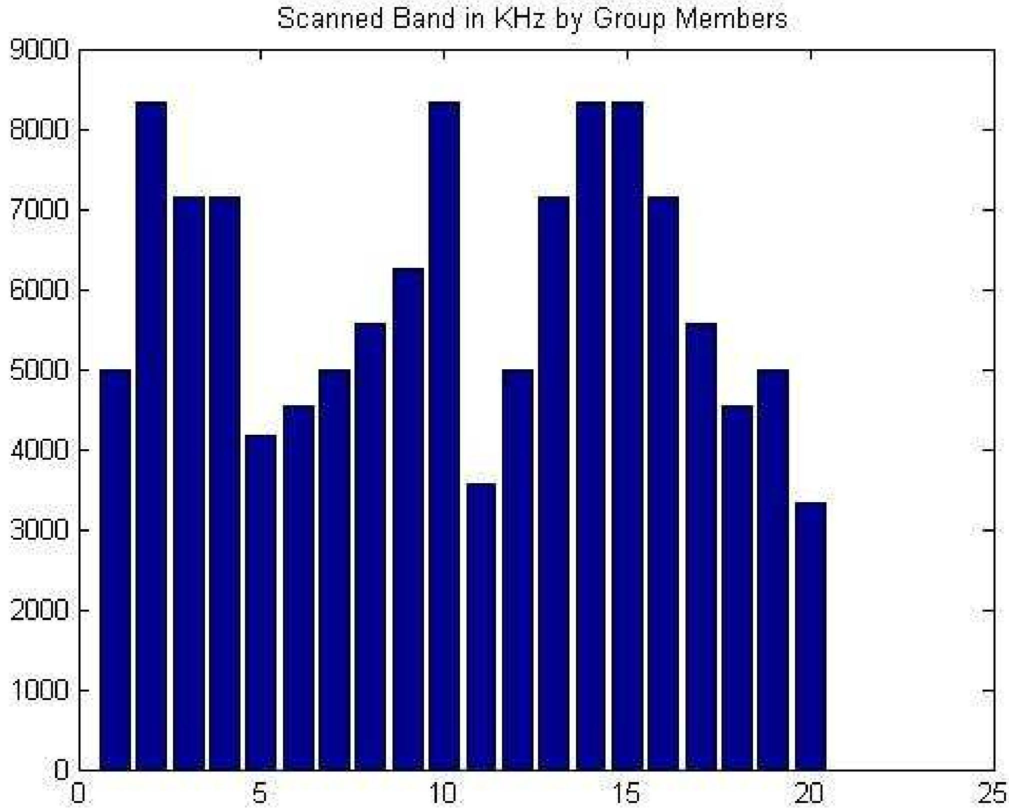


Fig.27. Sensed bandwidth in kHz by each member of largest group

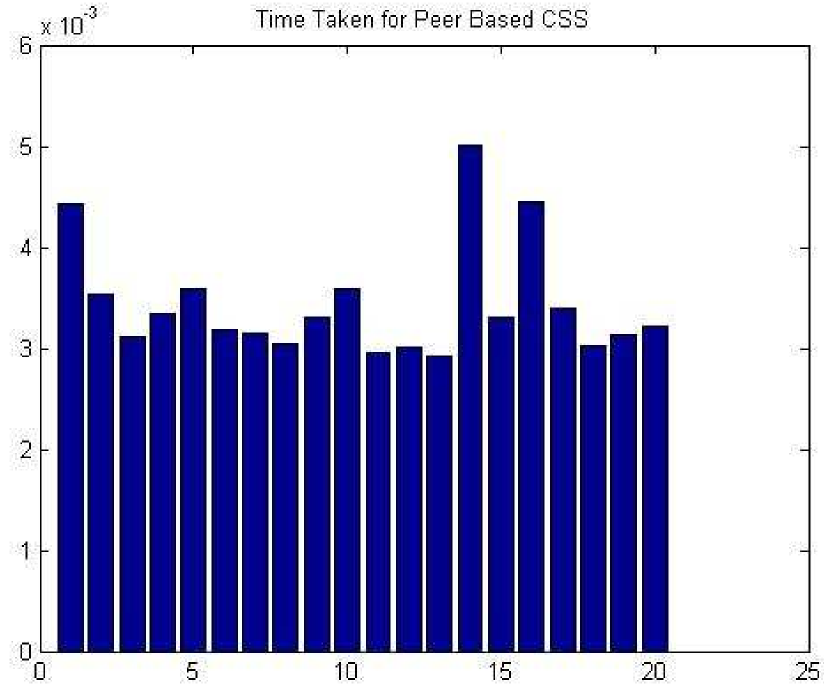


Fig.28. Time taken for peer based CSS (without grouping)

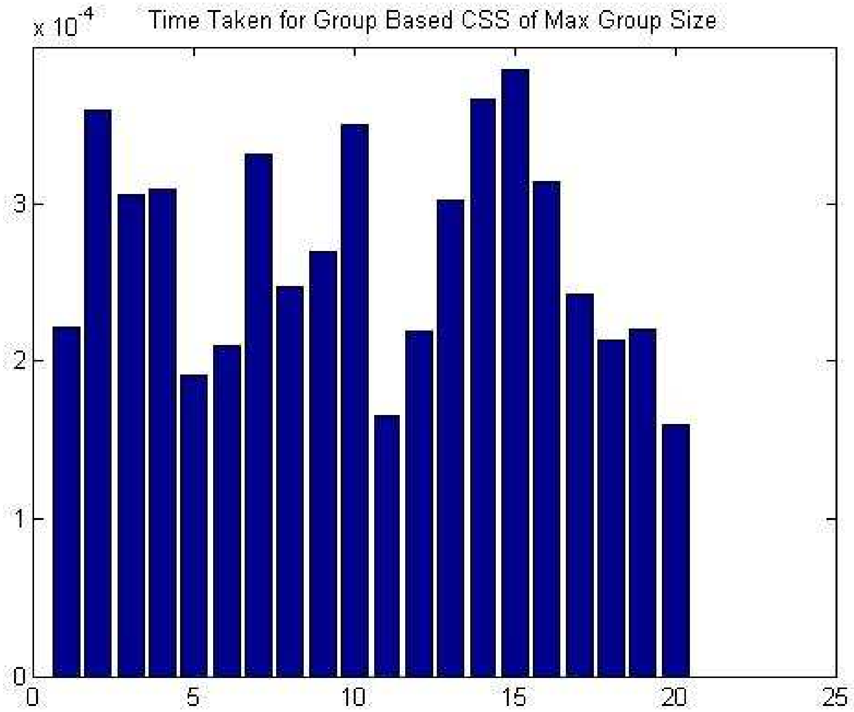


Fig.29. Time taken for our group based FD CSS methodology with largest group

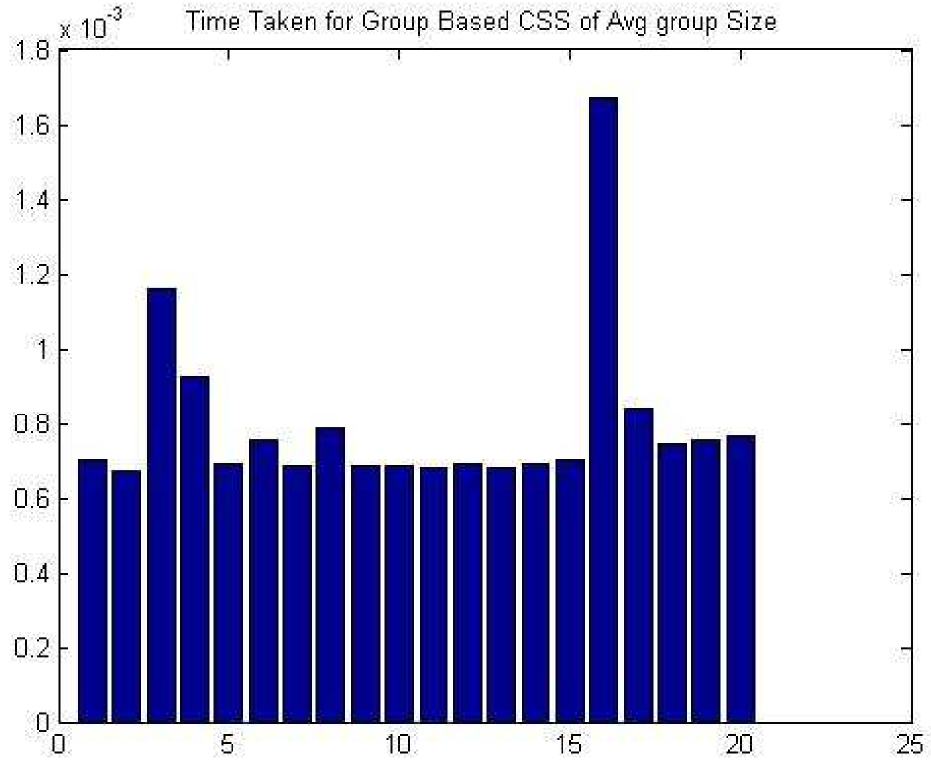


Fig.30. Time taken for our FD CSS scheme with an average group size of 3 members

4.3.3 Sensing Error: In order to establish the accuracy of our proposed CSS methodology, we analyzed the percentage of missed PUs and compared it with the peer based sensing. We were able to achieve a very low percentage of missed PUs (Fig.31) and this percentage was comparable to the sensing error in peer based sensing. The missed PUs were mostly outliers and were missed in both cases. The results in this regard were:

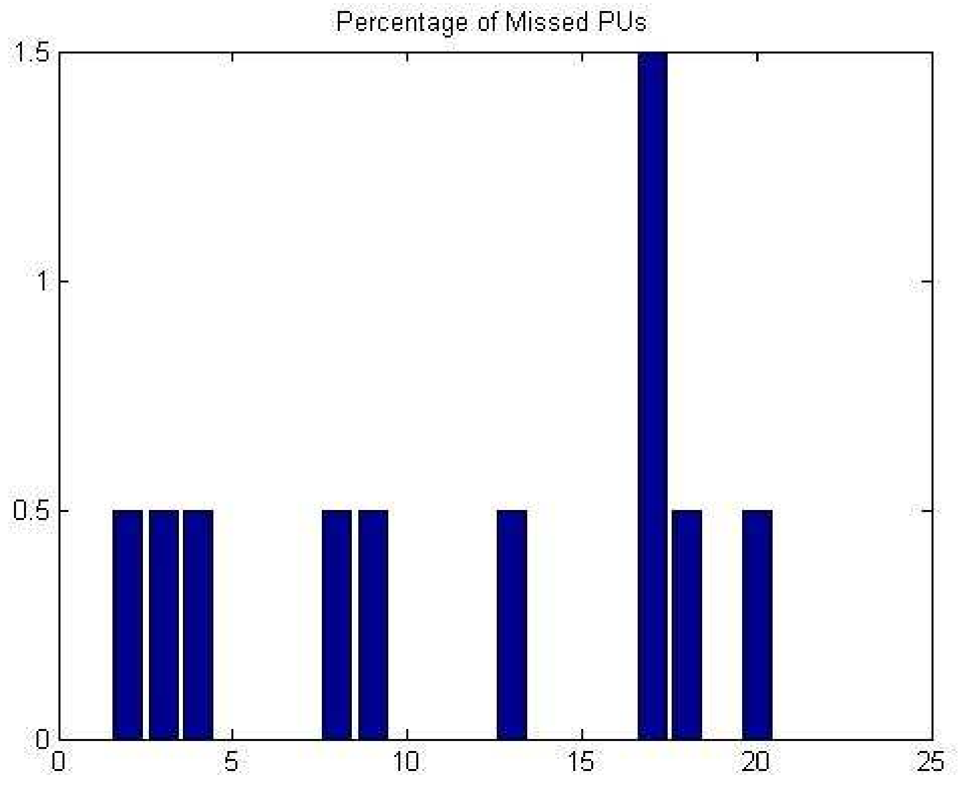


Fig.31. Percentage of missed PUs in our proposed methodology

4.3.4 Test of Frequency Change of PU: In order to assess the effectiveness of our technique in the event that a PU shifts frequency, we created a function that would analyze the results after a PU shifts its frequency. The results proved that there was no change in the grouping after this frequency shift. The function analyzed the results in four repetitions. In each repetition, the frequency of the first PU was changed.

4.3.5 Test of Mobility Tolerance: Mobility of the PUs or SUs directly affects the grouping. This is because the distance between the respective nodes is changing. However, it was observed that the grouping was reasonably tolerant to motion, as long as the moving entity did not encounter fading. This implied that the correlation distance was reasonably large at these frequencies. To test this, a MATLAB function was written that performed five repetitions of our algorithm after modifying the position of one of the SUs in increments of 1 km. Out of the five repetitions, the grouping was maintained in two-three repetitions (2-3 km). In a more complex scenario, in which multiple entities are moving, some form of machine learning algorithm may have to be applied to predict grouping and increase the correlation distance. This, however, is beyond the scope of this work.

4.4 Summary of Results: CSS techniques can address numerous problems associated with CR networks. We have developed a technique for grouping and tasking of CSS nodes on the basis of the sensed environment. The achieved results have shown that our technique ensures near-optimal information gain while obtaining a quantum leap in agility with an accuracy that is close to the peer-based CSS.

Chapter – 5

5. Conclusion and Future Work

In this dissertation, we have proposed a novel technique for CSS that is based on grouping of secondary CSS nodes. Novelty is achieved through the incorporation of correlation metrics to establish the grouping. In the past, grouping had been recommended, however no tested criteria for establishment of groups was ever suggested. By basing our grouping on the sensed spectra of each SU, we have been able to ensure that the members within a group are highly correlated. This high degree of correlation allows us to resort to sensing of non-overlapping bands within the groups. As a result of this, the workload on each sensing node within a group is reduced. The reduction of workload implies consumption of lesser processing power as well as lesser time. Depending on the network design requirements, this advantage can be exploited to enhance agility (as has been done by us) or to increase the sensed bandwidth. Our grouping technique further ensures that the correlation between groups is minimum, thus allowing us to gain maximum advantage from cooperation diversity to achieve near-optimal information gain.

We have compared our results with peer-based cooperation, in which all sensing nodes act as peers and then fuse their results in a centralized fashion.

We were able to achieve a quantum jump in terms of agility without incurring any cost in terms of accuracy. We were also able to achieve a high degree of information gain through cooperation between highly diverse groups.

CSS will form an essential part of the deployment of any future CR network. Grouping of CSS nodes is the next logical step due to its inherent advantages. While our work establishes these advantages comprehensively, there is still a dire need to continue research in this area.

This work is a humble endeavor to extend the revolutionary vision of Dr. Joseph Mitola. Dr. Mitola incorporated the concepts of machine learning and knowledge representation with the software radio platform. The result was the CR concept. Future work in this area could utilize the machine learning capabilities of CR to achieve a high degree of adaptability in the proposed grouping. Such an adaptive grouping would allow CSS nodes to modify the grouping on the basis of estimation of motion of individual entities including PUs and SUs.

Further optimization of this algorithm can be considered in terms of the technique used for grouping. There are numerous algorithms in this regard. In our proposed strategy, we used hierarchical clustering due to its suitability to our data set. This type of clustering has certain limitations in terms of complexity. Lower complexity algorithms may be analyzed in future work.

Another area of possible future research is the development of protocols to support this methodology. Protocols designed to support our proposed grouping-based CSS technique would be based upon the Medium Access Control (MAC) layer as well as the physical layer. Suitable cross-layer designs would have to be developed.

Research is an ongoing process and this work is by no means concluded, rather it is hoped that it will serve as a foundation for future endeavors in this important field.

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