SPECTRUM DECISION SUPPORT FRAMEWORK FOR COGNITIVE RADIO NETWORKS

By

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ABSTRACT

The exponential increase of mobile devices and the wide availability of bandwidth-hungry applications have created an eruption in mobile data traffic. Such extraordinary evolution in wireless data usage cause a severe capacity shortage in wireless mobile networks and presents substantial challenges to cellular operators and telecommunication regulatory authorities. Operators consider various technologies to improve their infrastructure, such as upgrading their entire network to LTE, taking advantage of existing available spectrum, or leveraging new spectrum opportunities such as the newly vacated TV band. However, such network designs do not facilitate robustness in spectrum usage. Cognitive Radio Network offers a capable solution for assuaging this problem. In mobile networks, the wireless spectrum bands are also used by the secondary users in the absence of the licensed users. Spectrum decision is to be performed by secondary users while catering for the inconsistent behavior of fluctuating nature of spectrum slots and diverse service requirements of various wireless applications, secondary users have to adopt, aiming at optimizing the transmission performance of SUs. A SU has to sense multiple target spectrum slots in the shortest possible time before deciding to select and occupy the most suitable to its QoS requirements idle slot for its transmission. Spectrum decision process selects the most suited slot from these available slots for opportunistic use by secondary users. A support framework for CRNs has been proposed, which is called Spectrum decision Support Framework (SDSF). SDSF offers an intelligent spectrum decision scheme that first senses the idle slots and then enables SUs to swiftly occupy them effectively. SDSF integrates various spectrum decision techniques and takes into account various spectrum slot characterization parameters. A scientific support framework has been developed for SUs in the CRN which includes spectrum slot viz-a-viz SUs' QoS requirements, simulation evaluation duly validated by practical implementation. In this thesis, the proposed SDSF not only enables SUs to occupy the discretely time and frequency slotted channels in the entire wireless spectrum encompassing the spectrum bands of IEEE802.22, GSM, CDMA, LTE, IEEE802.11, Bluetooth, UWB and 5G, but also guarantees QoS requirements of SUs as per wireless service applications and ensures no interference with PUs. Initially the SDSF comprise of three wireless spectrum slot parameters; spectrum slot idle time, measured with the history of PUs' access, spectrum slot possession by the PUs and the spectrum slot QoS. This scheme was validated by the achieved throughput of SUs at the end of its transmission. The achieved throughput leads to the logical architectural design of 5G services providing flexibility required to support efficiently a heterogeneous set of wireless services including Internet of Things traffic. The proposed SDFS guaranteed QoS requirements for these applications in terms of end-to-end latency, SUs' mobility and no interference with PUs as well as with other SUs of CRN. An empirical SDSF for CRNs consisting of a signal generator, USRP2 and a network analyzer based on the sensing data achieved by a central SU from other (slave) SUs in the CRN has also been proposed. The results obtained validates that the proposed SDSF satisfies complementary receiver operating characteristics at various signal to noise ratio, end-to-end latency and the network congestion. The simulation results indicate the validity of the proposed schemes for spectrum decision for cognitive radio networks.

This thesis is dedicated to

My father, Mr. Ahmed Saeed Akhtar, who died during my PhD

for his love, support and encouragement.

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All praises to Almighty Allah, who gave me the strength and knowledge to accomplish the objectives of this thesis.

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List of Publications

The research for this Phd has yielded few publications out of which following two have been published:

- Fusion Based Spectrum Decision Framework for Cognitive Radio Users Published in World of Wireless, Mobile and Multimedia Networks (WoWMoM), 2015 IEEE 16th International Symposium held at Boston University from 14-17 June 2015 [1].
- Fuzzification Supported Spectrum Decision Framework for Cognitive Radio Networks Published in Transactions in Emerging Telecommunications Technologies (ETT) with an impact factor 1.535 [2].
- Work described in chapter 6 of this thesis titled *Spectrum Decision Framework to Support Cognitive Radio Based IoT in 5G and Beyond* has been accepted as a chapter in the book*Cognitive Radio in 4G/5G Wireless Communication Systems* [3] (in production).

List of Symbols

s	The targeted spectrum slot
N	Number of SUs
L	Total number of licensed slots
k	Total number of available spectrum slots
m	Successful use of spectrum slots by the SU
λ_s	PU arrival rate
T_v	random variable following exponential distribution, defining the idle times of PUs
T_o	random variable following exponential distribution, defining the busy times of PUs
α	mean of T_v
β	mean of T_o
ξ_o	MF of spectrum slot occupied by PU and not available for SU
ξ_{pa}	MF of spectrum slot when arrival of PU is expected
ξ_v	MF of spectrum slot when it is sensed vacant
ζ_v	MF of spectrum slot when it is vacant and available for use
ζ_{pua}	MF of spectrum slot when it was sensed vacant but PU arrived unexpectedly
ζ_o	MF of spectrum slot when it is sensed vacant
ρ_a	MF of acceptable spectrum slot QoS
ρ_r	MF of rejected spectrum slot QoS
τ_{na}	Spectrum (decision) is not available for SU
τ_v	Spectrum (decision) is vacant for SU to occupy
i	real world crisp input values for MFs $\xi(i)$, $\zeta(i)$, $\rho(i)$ and fuzified output
$\mathrm{R_k}$	Recompense function for k^{th} spectrum slot

χ_0	Spectrum slot response
η_s	Sensing duration
Γ_s	Spectrum slot time duration
$r_k(n)$	nth sample of the base band equivalent received signal vector for kth spectrum slot
$\Re\{r_k(n)\}$	Real part of r_k
$\Im\{r_k(n)\}$	Imaginary part of r_k
θ_k	two hypothesis PU signal absent/ present $\in\{0,1\}$
$\mathcal{CN}\{0, \sigma_h^2\}$	Complex Guassian process with zero mean and variance σ_h^2

Abbreviations

AWGN	Additive white guassian noise
AI	Artificial Intellegence
A6	Anything, anytime, anywhere, anyone, along any path
BLE	Bluetooth low energy
BS	Base station
BTS	Base transceiver station
BW	Bandwidth
B5G	Beyond fifth generation
CBSP	Continuous back end spectrum sensing process
CCC	Common control channel
CDMA	Code-division multiple access
CI	Computational Intelligence
CDF	Cumulative distribution function
CSCWG	Circularly symmetric complex white Gaussian
CSMA	Carrier sense multiple access
CR	Cognitive Radio
CRN	Cognitive Radio Network
CRU	Cognitive Radio User
CSD	Cyclostationary based detection
CSS	Cooperative Spectrum Sensing
CSMA	Carier based spectrum multiple access
CFR	Code of Federal Regulations

DCON	Device controller
DSA	Dynamic spectrum access
ED	Energy detection
FCC	Federal Communications Commission
FDMA	Frequency division multiple access
FIE	Fuzzy inference engine
FD	Full duplex
GB	Giga byte
GHz	Giga hertz
GSM	Global system for mobile
HD	Half duplex / High density
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IoT-U	Internet of Things User
I/Q	In-phase (component) / Quadrature (component)
ISM	Industry, Science and Medical Radio band
ITU-R	International telecommunication union’s radio communication sector
KHz	Kilo Hertz
LAA	License Assisted Access
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
LTE-U	Long Term Evolution Ultra
LPWAN	Low- Power Wide Area Network
MCBA	Markov Chain based Greedy Access

MCRA	Markov chain based random access
MF	Membership function
MIMO	Multiple input multiple output
MISO	Multiple input single output
MHz	Mega hertz
MVR	Majority vote rule
NB	Narrow band
NI	National instrument
OFDM	Orthogonal frequency division multiplexing
PC	Personal Computer
PSD	Power spectral density
PU	Primary user
QoE	Quality of experience
QoS	Quality of service
QPSK	Quadrature phase shift keying
RASC	Random channel assignment with single channel
RFID	Radio frequency identification
ROC	Receiver operating characteristics
SDR	Software define radio
SDSF	Spectrum decision support framework
SG	Smart grid
SNR	Signal to noise ratio
SU	Secondary user
TDMA	Time division multiple access

UE	User equipment
URLLC	Ultra-reliable low latency communication
UWB	Ultra-wideband
WCDMA	Wide-band code division multiple access
WiFi	Wider Fidelity
WiMAX	Worldwide interoperability for microwave access
WLAN	Wireless local area networks
WWRF	Wireless world research forum
1G,2G,3G,4G & 5G	1st generation, 2nd generation, 3rd generation, 4th generation and 5th generation
3GPP	3rd generation partnership project
6TiSCH	IP (IPv6 settings) integrated with Time synchronized channel hopping

Chapter 1

INTRODUCTION

During the last two decades, wireless communication systems and technologies have been a subject of extensive research and development, due to their enhanced and essential integration in day to day workings in real world. As a result, the mobile communication has evolved significantly from early simple voice systems and heavy devices to present highly sophisticated integrated communication platforms that provide numerous services, which are used by billions of people around the world. These services, coupled with a rapidly increasing cache of bandwidth(BW) hungry wireless applications, have triggered demands for higher data rates and low latency with sure connectivity. Only in 2016, more than 400 millions mobile handsets and routers and connections have been added [4]. It is obvious to anticipate that the global mobile networks will increase many folds by 2021. Consequently, the mobile data traffic is expected to grow more than 500fold in this decade ending in 2020. On the other hand, as wireless systems evolve, the wireless RF spectrum band has become overcrowded and as the regulatory authorities like Frequency Allocation Board (FAB) in Pakistan, Federal Communication Commission (FCC) in the USA and UK Office of Communications (OFCOM) in UK allocate the RF spectrum band at Fixed Spectrum Assignment policy. As a result, the ever increasing expansion of wireless technologies is hampered with RF spectrum scarcity. On the contrary, due to typical usage of cellular devices by the licensed users (of the RF Spectrum) known as Primary Users (PUs), the major junk of the licensed spectrum is well underutilized [5]. Cognitive Radio (CR) has emerged as an enabling technology to address the spectrum scarcity issue in wireless technology, which provides the capability to share the wireless spectrum with PUs in an opportunistic manner [6]. Today's frequency spectrum for wireless applications is increasingly scarce. Federal Communications Commission (FCC) partitions the RF spectrum into ranges based on the wireless applications requirements depending upon the capabilities of the device. The FCC carried out this sectioning of the RF spectrum across the range as an output of public hearings [7]. Over time, spectrum allocation is now also possible thorough systems such as lotteries and spectrum auctions [8]. Presently, the all-presence of any equipment that uses the RF spectrum bands to include radio, GSM, television and base stations, mobile devices, internet while on mobile through GSM data and router services, UWB devices etc, demands more flexibility of the spectrum allocation process [9]. In the future, the ever expanding wireless footprint implies that devices will need to adapt their transmission and reception capabilities to the RF spectrum in which they carryout their transmission. This process is termed as Dynamic Spectrum Access (DSA) [10]. Optimizing wireless communications to achieve low end-to-end latency, high data rates(throughput), lower probabilities of false alarm and misdetection and robustness requires a complete exemplar shift in the design of wireless technologies and systems. This paradigm change in the mobile telecommunication systems has to be reflected in mobile communication technology fields like air interface structure, signal processing for mobile handsets and routers, BTSs and MSCs and their infrastructure, the infrastructure and mobile architectural considerations, control designing at user end, communication session management and cross layer designing in the networking.

Moreover, some spectrum assignments are applied to all times during a day, yet many are only used consistently for short durations of time. Frequency spectrum slots which may be used at any given time by a specific user, but which are used only periodically, significantly contribute to wasted spectrum assignment. This issue is extensible to the combat's requirement for radios which are required to operate regardless of their geographic location, the time of day, and the local spectrum policy. With radios able to operate in unused spectrum during times of limited actual usage, the spectrum could be used much more efficiently [11]. This research presents a framework which enables radio devices to successfully access the unused spectrum while operating within the legal bounds.

1.1 Cognitive Radio

Cognitive radio (CR), is envisioned to solve the problem of spectrum scarcity for emerging wireless applications as the existing spectrum is underutilized [12]. A CR is a radio that can be programmed and re-configured dynamically to use the most suited RF wireless spectrum slot in its vicinity to avoid user interference and congestion. Such a radio automatically detects available RF spectrum slots in wireless spectrum, configures its communication parameters to enable itself for simultaneous and synchronized radio transmissions and receptions in a given spectrum slot at one location. This process is dynamic spectrum management. That is, CR implements Observe-Orient-Decide-Act (*OODA*) loop as a source to enable Software Defined Radio (SDR) operations by making informed, adaptive decisions on communication in the entire RF spectrum range. The use of the OODA loop for CR has been proposed by Mitola et.al [13] and it offered the signature of initial solution to the problem of RF spectrum scarcity [14]. First, the CR carries out SS the RF spectrum, i.e., the **observation**. Next, the SDR component of CR creates a radio environment map (REM) from which to use available spectrum slots, i.e., the **orientation**. Later, the SUs in the CRN makes a **decision** to occupy the vacant spectrum slots and make the radio transmitting and receiving on the RF spectrum slot(s) sensed vacant by the PUs. Finally, the radio reconfigures its radio conditions for enabling its users to communicate ensuring their QoS requirements, i.e., the **action** [15]. OODA Loop maps directly to DSA techniques as is shown in Figure. 1.1.

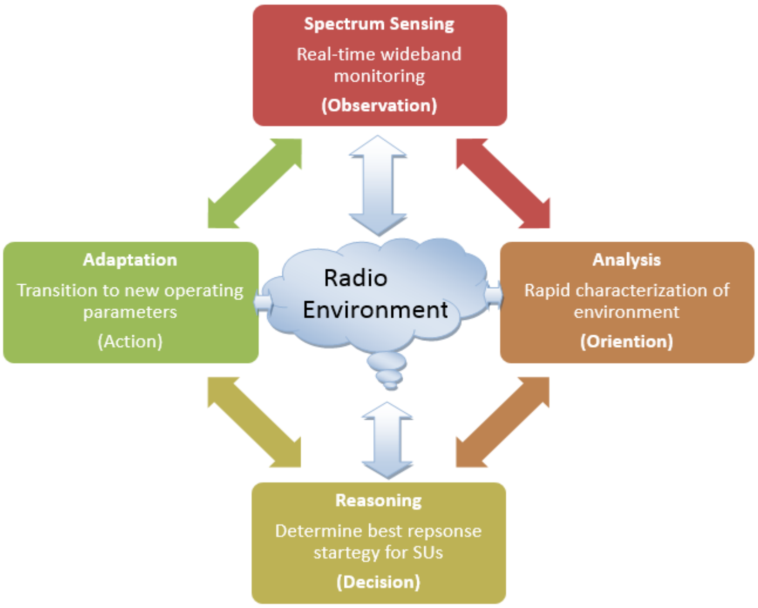

Figure 1.1: OODA Cycle in Cognitive Radio.

CR is an effective technology which is used to implement DSA as a solution to frequency spectrum congestion coupled with fixed spectrum assignment policy. In short, the CR is a DSA enabling smart technology. In CR networks (CRNs), the spectrum slots formally assigned to the licensed/primary users (PUs), are allowed to be opportunistically utilized by unlicensed/secondary users (SUs) whenever not in use by PUs [16]. SUs find out vacant spectrum slots through various signal processing, game theory and artificial intelligence (AI) techniques prior to any transmission attempts. This process is called spectrum sensing (SS) [17] and can be performed using software defined radio (SDR) [18]. It is desireable that the time of spectrum sensing (SS) is reduced as much as possible while satisfying required performance criteria [19]. It is also important in CRN to coordinate multiple SUs to share the spectrum slot, known as spectrum sharing. A fundamental challenge of spectrum sharing is to ensure the quality-of-service (QoS) of PUs while maximizing the achievable throughput of SUs [20]. For CRN, multiple spectrum slots are sensed which are available at a given time slot, due to PU's priority rights on licensed spectrum slot and satisfying SU's QoS requirements. SU is required to decide which spectrum slot be selected to start its communication in the particular time slot. Moreover, it is required that SU does not interfere with PU and maintains its own transmissions' QoS requirements. This selection mechanism (is known as spectrum decision in CRN [21]) has not been explored much (an open research area) [18], [22], [23] and [24]. Related work carried out so far needs deliberation and is the focus of research presented here.

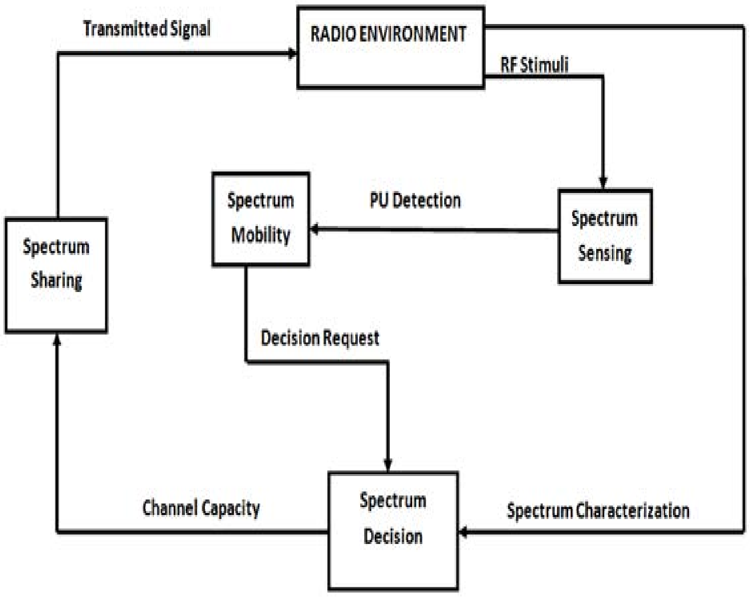

Figure 1.2: Spectrum Management Framework in Cognitive Radio.

Preserving the desired QoS of the PUs along with the user mobility requires the spectrum mobility for the SUs in the network [25]. Due to its mobility, an SU may change its place (cell) in a cellular network during its transmission, therefore may enter a new region in which its spectrum slot is already being used by a PU [26]. The primary traffic in any given region is time-varying and stochastic in nature [27]. In either case, to eliminate any collision of SU with the primary transmission during its channel access and to avoid the termination of SU's communication session, the SU must be able to vacate its transmission channel upon the appearance of a PU and to re-establish another communication link [28]. Since the interruptions by the PU increase the transmission delay of the SU's connection and degrade its QoS, therefore, the interrupted communications are promptly and swiftly switched to another suitable RF spectrum slot and resumed their transmission afterwards [29]. This process makes CRN a network which is connected all the time and the network remain active for transmission for its users. In order to address these challenges and attain the aim of connectivity, each SU in the CRN has to make a decision of occupying or switching to the best available spectrum slot without disrupting its own communication and impairing PU's activity. These capabilities can be comprehended by the process of realizing efficient spectrum utilization through spectrum management function that addresses SS, decision, sharing and mobility [30].

The perfect SS mechanisms are the prior information for which SUs shall work. Spectrum decision is a crucial and important process in CRNs, which enables the SU to select the best channel to transmit data from the targeted spectrum slot(s). In order to distribute the traffic loads of the SUs in CRN evenly to these spectrum slots, an effective spectrum decision scheme should take into account the traffic statistics of the PUs which has been done through Poisson Distribution in this research work. The spectrum decision capability relies on effective SS and reliable data on PU characteristics [22]. Thus, it is significant that the non active time of the spectrum slot be known and the status of the spectrum slot be unoccupied (termed here as spectrum slot activity time and possession respectively). Spectrum parameters (including spectrum slot interference level, error rates, path loss, communication overhead, end to end latency and ergodic capacity) estimate the transmission response of the spectrum slot for SUs are referred here as spectrum slot QoS requirements, which is considered here as third key parameter (along with spectrum slot activity time and possession) in the proposed framework.

In the following sections, related work on spectrum decision techniques and the cognition methods to decision making framework are reported. Based on the conclusions drawn on the related work, the motivation and contributions of the proposed spectrum decision framework has been reported. After that, the outline of the thesis is appended.

1.2 Related Work

To date, significant research work on spectrum decision techniques has been carried out. In [17], a measuring parameter to determine the expected normalized capacity of CRN is proposed while taking the spectrum switching delay into account. However, the scheme is not effective for non-uniform switching delay. In [31], a coordinated access to the spectrum opportunities by multiple SUs does not consider the channel access contention (by multiple SUs). A traffic load balancing decision mechanism based on an analytical structure to design system parameters by maximizing the network throughput appears in the works of [26] and [32]. The scheme has analogous goals to spectrum management in the way that it carries out resource allocation on user's service requirements. In [33], a global optimization scheme based on graph theory for spectrum assignment to a user does not hold validity when the CRN topology varies (as per the node mobility). In [34], the degradation reduction in communication caused by latancy as the computation process is complex since CRN is required to modify the spectrum assignment. In [35], an analytic hierarchy process to choose a channel from available channels is used to work the decision making process as a major component of spectrum decision function of SUs. In [36], a fuzzy logic-based spectrum handoff scheme makes handoff decision in a decentralized fashion. The process includes mobile speed and the strength of signal at the receiver of SU to signify the channel occupancy by PU.

Most of the existing research works aim at SS and spectrum sharing in CRNs, with emphasis on resource allocation of spectrum and power among SUs depending upon interference controls. In [37], a rule-based spectrum management is proposed, where SUs access the spectrum independently according to both local observations and pre-determined rules. However, the time varying nature of channel characteristics have not been considered. The power allocation for SUs targeting the same spectrum slot is another important issue in spectrum sharing. In [38], a power allocation scheme has been suggested to accomplish sufficiently large sample and the outage capacity of the fading channel under varying environment of power constraints. In [39], a wide ranging behaviour of the game theory covers the licensed spectrum sharing of SUs by providing a stochastic decision making algorithm. In [26], a channel selection scheme by analyzing the secondary performance in terms of average sojourn time (for the stay and spectrum handoff). However, the proposed technique lacks simplicity and is complex. In [40], a technique that characterize the probability of utilization of spectrum opportunity under various network topology is not effective for the packet size over 500. In [41], a study on genetic algorithm based on crossover and mutation operators for channel allocation in CR is oriented towards theoretical qualitative analysis and lacks its validity in experimental setup.

1.3 Motivation

CR is a promising technology for realizing the fifth generation (5G) networks as it offers a cutting edge technique to deal with random and varying wireless communication traffic demands in cellular technologies. CR systems overcome the scarcity of frequency spectrum and allows entrant service providers (SPs) to co-exist with licensed mobile SPs. To achieve this, CR users (CRUs) or SUs need to smartly occupy the vacant spectrum slots. Therefore, the decision to occupy a spectrum slot is of foremost importance. The existing spectrum decision schemes are mostly inaccurate, time consuming and are not robust against non uniform switching delays, time varying channel characteristics and unexpected PU's arrival in the spectrum slot. The mobility aspect of SUs in CRN, of these schemes is not well explained. These schemes are mostly computationally complex. Moreover, the existing work is devoid of heterogeneity and the interoperability requirements existent in CRNs. The existing research considered the effects of PU activity and SS results, signal processing characteristics in the wireless scenario and the network parameters like throughput, higher data rates, low latency and receiver operating characteristics (ROC). These considerations do not work for systems other than narrowband (NB) communication technologies. As most current and future wireless communication systems are converging to wide band systems for achieving higher throughput, data rates and low values of probabilities of false alarm and miss detection, i.e, the receiver operating characteristics (ROC). For realization of CR and $5G$ technologies, the standardization of Channel model is an important key in deciding the access of spectrum slots by the SUs in CRN. Stochastically exploiting the statistics of wireless communication channels allow the SUs to access the suitable channel as per characterization of PU activities and SS results. The channel statistics include, variations of the channel gain, delay dispersion and other effects. The choice of channel model is very critical for guaranteeing QoS requirements of SUs in CRN. This all lay the ground to develop spectrum decision framework for SUs in a CRN. A massive increase in the worldwide wireless services subscription, such as broadband wider fidelity (WiFi) services, mobile communications, IEEE802.22 and navigation systems, is under way.

1.4 Contributions

The main contributions of the dissertation are as follows:

- Spectrum Decision Support Framework (SDSF) for CRN is proposed. To address the heterogeneity issue, the SDSF is characterized by PU activity modeling and the spectrum sensing (SS) results. The performance of CRN largely depends upon PU activity and SS results. Therefore, in the proposed SDSF, most suited PU activity model for the entire spectrum band of wireless systems has been adopted alongwith the SS results.

- An AND rule based spectrum decision framework based on three important channel parameters has been proposed. This gives a robust and interference free spectrum decision for SU to carryout their transmission while maintaining its QoS requirements.

- A fuzzy logic based spectrum decision framework is developed which maintains QoS requirements for spectrum slots selection for SUs. The underlying decision framework incorporates both the statistics of PUs spectrum slot occupancy and the QoS requirements of wireless application of SUs. By using this framework, the SU competitors can achieve an efficient sharing of the available spectrum slots. The output, as a result of defuzzification of the fuzzy inference process is the final spectrum decision which enables the SU to carryout its transmission without interfering with PU while maintaining its QoS requirements. Fuzzy logic has the ability to deal with not exact and accurate to precision data and to validate (parametric) the set benchmark concurrently to offer a robust spectrum decision [31]. As a result, the CRN works in a systematic manner in which SUs configure as per spectrum characteristics to comply their QoS requirements. Although fuzzy rule based scheme for choice of SS techniques has been proposed in [32] and in other decision making algorithms, but (to the best of author's knowledge) no learning technique has been applied in spectrum decision making strategies for CRN [33]. Matlab simulation results are recorded to show the performance and validity of the proposed framework.

- An empirical centralized spectrum decision mechanism has been proposed where PU has been emulated through USRP2. The real traces of PU activity model have been used and the SS results based on PU statistics in using its licensed spectrum slots have been used to determine the CRN performance based on proposed SDSF.

- Latest research on wireless technology and its trends are converging to IoT and CRNs. The things-oriented, Internet-oriented, and semantic-oriented versions of IoT are not likely to be significant and existent if IoT objects are not equipped with cognitive radio capability [42]. This research also focuses on achieving robust spectrum usage in an environment with ever-increasing number of transmitters. As operators seek to leverage new spectrum opportunities in the TV band, the Federal Communication Commission strives to coordinate spectrum usage by deploying spectrum databases. However, misuse of TV spectrum can disrupt existing users and violate basic assumptions and guarantees fundamental to the operation of such systems. Actively maintaining spectrum databases is challenging because transmitters can be dynamic and widely distributed. To address this challenge, we propose and implement a real-time commoditized spectrum monitoring system using smart phones and low-cost sensors. We show the feasibility of low-cost spectrum monitoring as well as implement and evaluate techniques to identify and localize transmitters. The emperical platform used with rigorous experiments and identification from multiple sources of error in the data in this research, like equipment noise, progressive framework, user mobility convergence to seamless communication, and interferences in radio. To address these issues, the proposed SDSF caters for equipment noise mitigation, fidelity prediction, and I/Q interference removal and achieve a robust spectrum scarcity solution through the proposed SDSF.

1.5 Thesis Outline

The remaining part of the thesis follows the sequence as given here. Chapter 2 describes the characterization of SDSF through PU activity modeling and spectrum sensing. Chapter 3 presents a novel fusion based spectrum decision framework for cognitive radio users. It presents a logical solution to the spectrum access problem for SUs to carryout their transmission and validates the proposed framework through radio operating characteristics. Chapter 4 describes an empirical spectrum decision framework to access the wireless spectrum by SUs in the CRN while maintaining QoS requirements of SUs and ensuring no harmful interference with PUs. Chapter 5 proposes a fuzzy logic supported spectrum decision framework. CRN based Internet of Things (IoT) in $5G/B5G$ Networks has been described in Chapter 6. Chapter 7 concludes the thesis and gives possible future work in Spectrum Decision in CRN.

Chapter 2

Characterization of Primary User Activity and Spectrum Sensing Results

RF Spectrum decision in CRN is characterized by PU activity modeling and spectrum sensing (identifying temporarily vacant RF spectrum slots) results. All wireless applications have dedicated RF spectrum bands i.e., fixed RF spectrum assignment policy. Due to the fixed RF spectrum assignment poloicy, PUs are also known as licensed users. In CRN systems, the aim is, SUs have to carryout their transmission while ensuring that PUs are not affected and harmfully interfered. To achieve this aim, PU activities in the licensed bands are modeled to formulate SS techniques. This chapter gives an account of characteristics of PU activity modeling and SS results for the proposed SDSF.

2.1 Importance of PU Activity on CRN performance

Since there is no guarantee that a spectrum slot will be available for SUs to complete its transmission, it becomes imperative to consider the PU appearance and its effects in the proposed SDSF, so that SU senses the spectrum slot either vacant or otherwise accurately and this factor could lead to the correct spectrum decision for SUs in CRN. The pattern of the PU activity can be determined by modeling it with its historical usage of the targeted spectrum slots to enable SUs in CRN to know the future occupancy of the particular spectrum slot. This expected behaviour pattern of spectrum slots in the RF spectrum band is achieved through PU activity modeling. A brief analytical description of PU activity models is given in Table. 2.1 [43]

Effects of PU activity modeling on CRN performance for DSA in both, under-laying and overlaying modes is generally viewed under following three possible cases in CRN operation:-

- Case I: Improved BW Utilization: In this case, the CRN can improve the BW utilization. The overall spectrum slot occupancy is derived as repeated ON/OFF systems derived by the logical functions of the single ON/OFF system of each PU in the network. Hence, by combining the PU activities in all spectrum slots, SUs can optimally utilize the entire BW.
- Case II: SS Errors and interference avoidance: In this case, if PU occupies a spectrum slot for longer than statistically calculated time periods, the spectrum slot is accessed by the SU(s) for significantly shorter time duration. Therefore, if SU continues SS process on that specific spectrum slot, either the transmission of SU will cause harmful interference to PU or will suffer from SS errors. By using real spectrum occupancy measurement method, SUs can have improved SS and both SS and switching times and energy can be saved. Similarly, the interference to PUs can be avoided by keeping very less energy in the sidelobes of the SUs' transmitted signal.
- Case III: Measurement of Spectrum Slot Idle Time: In this case, CRNs offer a solution to the problem of scarcity of spectrum thereby improving RF spectrum utilization by opportunistic access. SUs in a CRN utilize the spectrum slot which is, otherwise allocated to PUs and at that particular (SUs' transmission duration) PUs are not operating ,i.e., when the spectrum slot is idle. It is,therefore, the operation of the CRN is affected by the idle time of a licensed spectrum slot.

2.1.1 Review of PU activity Models Used in CRN Research

By keeping above into consideration, various PU activity models based on stochastic characteristics of real time and best effort wireless applications have been proposed in the literature and PU activity modeling holds the key importance in spectrum decision in CRN. This section provides an insight of most of the PU activity models for CRN, which have relevance to the spectrum decision process and analyze them for selection of suitable models for the proposed SDSF. PUs operate in all spectrum bands depending upon the underlying technology and this spectrum ranges from KHz to GHz, e.g., GSM networks operate in MHz, while TV bands operate on 40-80 MHz. Table 2.2 gives an account of all the wireless applications and the wide ranging operating frequency spectrum bands for which the proposed SDSF will hold good for CRN. A single PU activity model can not capture the PUs' activities of entire range of wireless frequency spectrum band, as these activities vary from one wireless service to other wireless service. In the modern wireless technology age, almost all the wireless standards have been designed which include IEEE 802.11 systems, short ranged narrowband networks such as Bluetooth and Zigbee, $5G/B5G$, LTE-A, IoT etc. For each wireless system, there are statistical variations in PU activities and the model of one service can not be used as a model for the other application. Therefore, there is a need to have an access to the real traces of applications. To proceed in this direction, the proposed framework has considered PU activity by recognizing it and it was observed that the PU activity of all wireless applications more and less converge to poison distribution. Therefore, the proposed SDSF has used PU activities as Poisson distribution within the particular spectrum slot denoted as K(t) with λ_s as the intensity of the process or in other words, the arrival rate. Let T_k be the arrival time of PU at k^{th} arrival, for $k = 1, 2, 3, \ldots$. The inter arrival time Y_k is given as follows:

$$Y_k = T_{k+1} - T_k \tag{2.1}$$

where Y_k is independent and identically exponentially distributed and T_k follows Erlang distribution. When PU is absent, the activity time of the targeted spectrum slot is idle.

Table 2.1: Analytical description of Significant Activity Models

PU activity model types and their significance		
PU Activity	Advantage	Disadvantage
Models based on measured data	The data measured in real time is used	High computational complexity
Models based on statistical analysis	Future PU activity is determined	May cause interference to PU
poisson distribution process	Simple and less complicated to model and is mostly used	limitations in very small variations of PU traces

Similarly, when PU is present or has arrived unexpectedly, the activity time of spectrum slot signifies for SU, not to occupy. Most of the research in CRNs is dependent upon statistical modeling for PU activities as the real traces of PU (mobile operators' users) activity were proprietary and not available as an open data set. A new privacy preserving framework for PUs obfuscation strategy design has been included in the proposed framework, which jointly considers PUs operational privacy in the temporal domain, the obfuscation cost of PUs, the uncertainty of SUs demands, and SUs traffic demand satisfaction. Under such a framework, when PUs add dummy signals to obfuscate the adversary, they also need to consider the trade-off between preserving PUs temporal privacy and satisfying SUs traffic requirements, and thus cannot arbitrarily generate dummy signals for privacy preserving purposes.The accuracy of PU activity modeling can be increased by using real traces of PU in the modeling. In the proposed framework, the real traces have been used in the experimental test bed and a way forward for CRNs towards real environment has been proposed in chapter 4. This is in addition to considering various stochastic based models used in other two techniques for SDSF.

After modeling the PU activity in the proposed SDSF, in addition to the system models defined in each technique mentioned in the respective chapters, following standards have also been used in the proposed SDSF for CRN for SUs' transmission:-

- A WiFi through a router device which supports to freely access internet network connection.
- Increase in the BW, per unit area.
- 100 times more connected devices to project the situation as is mentioned in [4].
- Up to 10 Gbps connection rates to mobile devices in the coverage area of primary servers/BTSs and secondary servers/BTSs.
- A maximum perceived internet, GSM and other mobile services network availability.
- A perceived 100 % network coverage of both voice and data.
- Maximum of 1ms end-to-end round trip delay (latency). This parameter is described through an experimented setup in chapter 4.

The wireless applications, their frequency spectrum bands and BWs being used in the proposed SDSF is given in Table. 2.2.

2.2 Spectrum Sensing

To find available spectrum holes and avoid unacceptable interference to PUs, spectrum sensing (SS) is a pre requisite knowledge for making a spectrum decision by SUs in CRN. The preliminary stage for enabling CR to make a decision for occupying the RF spectrum slot, is to sense the radio environment and find out which slots of the spectrum are available. This is achieved through SS. However, spectrum sensing poses the most fundamental challenge in CRs [44] and requires a carefully designed SS technique to be used which offers near to accurate SS results. Furthermore, there should be a method developed to mitigate SS errors, in case SU occupies a spectrum slot where PU is still present.

Table 2.2: Wireless Systems Used in proposed SDSF

Wireless Applications	Frequency Spectrum Bands	Bandwidth
IEEE802.11g to n/WiFi	2.4GHz	10 KHz
IEEE802.16/LAN/2	5GHz	100 KHz
IEEE802.22	54MHz-862 Mhz	5 to 20 MHz
GSM	890 MHz-915 MHz (uplink) 935 MHz-960 MHz (downlink)	200 KHz
CDMA	800 MHz & 1.9 GHz	125 Mhz
LTE	1710 MHz-1770 MHz (uplink) 2110 MHz-2170 MHz (downlink)	20 MHz
UWB	3.1 GHz- 10.6 GHz	500 MHz
5G	0.5 GHz to 39 GHz	20 MHz for 6 GHz and 100 MHz for 30 GHz and above center frequency*
ZigBee	868 Mhz 915 Mhz 2.4 Ghz	as used in Europe as is in use in USA as is in most Worldwide

* upto 10% of the center frequency but not wider than 2 GHz.

This section describes the need for SS by SUs in CRN. SUs are required to simultaneously detect PU and spectrum slot QoS requirements over fading channels. The SS mechanism is formulated for Rician and Rayleigh fading and 3GPP channels models suitable for all types of wireless applications. The same wireless channel models have been further used in the proposed SDSF.

2.2.1 SS Results

In CRN, PUs have anticipatory priority to access the licensed spectrum band. To avoid harmful interference from SUs to active PU receivers, SS is carried out here to find out the spectrum occupancy status of the channel being accessed by SUs and IoT devices in CRN. The task of SS is to sense and be aware of the statistical and communication parameters related to the wireless radio spectrum band characterization and also real time determination of signal occupying the wireless frequency spectrum slot. These parameters include, types of modulation techniques used, signal waveform and the quality of the spectrum slot. SS results have been ensured to be accurate. For this, the selection of techniques used in the proposed SDSF has been made on the basis of three key parameters used in SDSF and the results obtained in SS before the transmission of SUs have been compared with the results obtained after transmission in chapters 3 to 6. It was found that the QoS requirements of SUs' transmission was maintained, thereby verifying the SS results being accurate and SDSF as robust. Let all devices transmit their packets based on the sensing results. The detailed account of SS techniques used for the proposed SDSF is given in the subsequent subsections.

2.2.2 Energy Detection

Energy Detection(ED) is the most common SS technique used. ED white Guassian noise PSD is measured very accurately. This fact yielded a higher probability of PU's detection anytime during the sensing duration. The explicit consideration of uncertain knowledge of the signal, it has been demonstrated that detection of these signals by an radiometer which measures upto UWB was possible. The worst possible results bound are provided as a function of input signal to noise ratio (SNR). SNR is a blind technique where no prior knowledge of signals of PU is required. The output of ED is compared with the experimentally set threshold values. ED is the most used SS technique as it offers low computational complexity with optimum SS results. Noise variance, σ^2 has been measured from experimental measurements on the switched off PU (emulated by USRP2, the detailed description is given in chapter 4). The limitation of ED SS technique of it being not suitable for spread spectrum signals, has been over come by using OFDM modulation technique and Rician channel model for the system and network models used in SDSF.

2.2.3 Cyclostationary based detection (CSD)

The cyclostationary approach offers a time varying analysis for a signal to be present or absent in a particular spectrum slot. It is non-coherent, because there is no requirement of frequency synchronization. Hence, for PU's emitting signals whose frequency related information is not known, CSD offers a suitable SS technique. As most of the signals (not the noises) in communication, periodicities are involved because of coupling of stationary message signals with periodic sinusoidal carriers or with periodic keying such as in OFDM and other modulation techniques due to sampling, multiplexing and / or repeating codes, therefore, redundant PU's signals are generally modeled as cyclostationary signals. Moreover expected to be To put things into perspective, for a wireless service requiring 1 ms delay as latency, the inter connectivity must occur within 1km of the SU in the cell; to achieve this latency, other non-network techniques, ROC in particular have also be used. To attain this latency and with PU activity modeled and predictable, the SU is required to determine frequency slots where PUs are not active. To attain this, SU in CRN has to identify the un used spectrum slots. Thus the next step is SS. In this section, the techniques used in SS have been discussed and how their errors have been mitigated is also discussed. The results of SS characterize the spectrum decision in CRN.

2.2.4 Cooperative SS

Cooperative spectrum sensing (CSS) is an effective way to counter the hidden terminal problem due to deep fading and shadowing in spatial diversity of SUs. Although CSS detectors can overcome the hidden terminal problem, they require some a *priori knowledge*, such as the statistical characteristics of RF spectrum slots from PU to SUs, SNPR at SUs and noise power [45]. However, the a *priori knowledge* is often unavailable at SUs in practice. To resolve this issue, a CSS detector requiring no a *priori knowledge* has been proposed [46]. In addition, most CSS detectors assume that SUs have an identical background (noise) power, making them vulnerable to malicious interferences (which give rise to non-identical background power).

2.2.5 Need for SS

The SS is one of the most challenging tasks in the future cognitive LTE system as it requires high accuracy and low complexity for DSA. While using the fading channel, it has been observed that the coding techniques suffer from higher latency as the structure is a matrix: bits are read in line-by-line, and read out column-by-column. The communication link is not established until the matrix has been filled up before it can read out the bits. Latency, is thus considerably larger than the separation of bits that can be achieved.

2.2.6 SS Performance measurements

The SS performance metric is usually measured as a trade-off between selectivity and sensitivity, and can be quantified by the levels of detection and false alarm probability. The higher the detection (or lower the miss detection) probability, the minimum would be the interference to PUs by SUs in the CRN. Almost all aforementioned related works demonstrate the capability of radio SS through real world experiments. Since the data set for SS of real traces is limited and generally obtained only through experimental testbed, therefore, there may be a convergence to some bias. Up till now, there is no theory basis for radio based activity recognition, which can mathematically model and analyze the relationship between human activities and corresponding radio transmission features or system parameters. Information theoretic analysis may gain fundamental insights to guide the optimal design of radio based recognition system. The performance of CRN in sensing duration η_s is determined by a reward known as throughput (denoted by R_k) of the CRN. Figure. 2.1 explains the implementation of OODA model in a CRN described in section 1.2. This shows that the interference effects the degradation in QoS requirements of SUs in CRN and the SU's adapting to the current radio environment. At sensing dration A, the CRN system observes the environment. During the sensing period B, a notional expected performance while the

RF spectrum slot was changing has been shown, the CRN has reoriented itself. During the sensing duration marked as C, the SUs in CRN have to decide as per radio conditions which spectrum slot is to be occupied for their transmission. SUs in CRN are now transmitting in the new spectrum slot using its spectrum decision and regains their QoS requirements with three different possible throughput values.

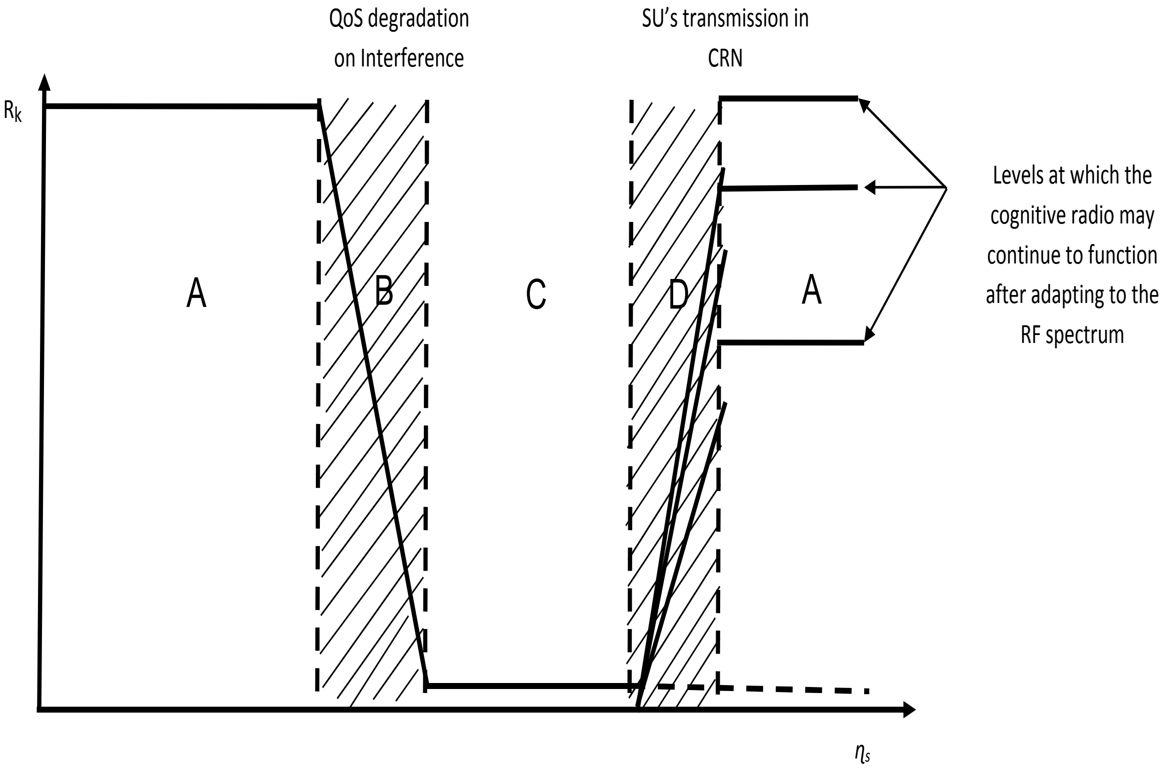

Figure 2.1: Expected CRN based system operation.

In half-duplex (HD) CRNs, the secondary users (SUs) can either only sense the spectrum or transmit at a given time. This HD operation limits the SU throughput because the SUs cannot transmit during the spectrum sensing. However, with the advances in self-interference suppression (SIS), full-duplex (FD) CRNs allow for simultaneous spectrum sensing and transmission on a given channel. This FD operation increases the throughput and reduces collisions as compared to HD-CRNs. To have real time PU activity, a CRN sensor node is used as a receiver as a plateform consisting of a smartphone (as data processor) connected to a USRP2 connected with ubunto installed PC (spectrum sensor). The hardware PC collects raw I/Q samples which are translated into data E1s. Real time spectrum sensor to sense the spectrum usage. This experimental setup emulating real PU traces in the RF spectrum has been further extended to frame a spectrum decision supported framework in chapter 4 of this thesis. To eliminate the interference to the PUs introduced by the SUs in case PUs arrive unexpectedly in their licensed bands, the interference received by the PUs can not exceed a given threshold, measured through statistical behaviour of CRN which is based on channel conditions, physical distance of SU-PU and the CRN configurations. The threshold varies based on the scale of the SUs group in CRN.

Federal Communications Commission (FCC) in part 15 of Code of Federal Regulations (CFR) 47 [47]. The SDSF helps CRUs to use ISM bands to transfer data downloads upto 3.6 Mbits/s for M2M applications and HD video surveillance, thus offering an enabling technology for realization of Internet of Things (IoT) in the fifth generation network ($5G$). This contribution is described in detail in chapter 6 of this dissertation.

2.2.7 Summary

If the CRN can not satisfy SU's QoS requirements, no incoming SU be decided to access the specific spectrum slot in the proposed system model. Since the available BW in the proposed system model varies over time, the CRN would not be able to guarantee QoS requirements as per the wireless applications SUs adopt. The decision framework is characterized by jointly considering PU activity and spectrum sensing results of the spectrum slot. Over the last two decades, with the increased demand, the radio-frequency spectrum - a resource that once seemed unlimited-has become crowded and, now, no longer is able to accommodate all users' needs. As a result, there has been a growing research on using spectrum efficiently.

This chapter provided a basic premise for the proposed SDSF in the form of description of PU activity modeling and SS.

Chapter 3

Fusion Based Spectrum Decision Framework For Cognitive Radio Users

In accessing a frequency spectrum slot by SUs in a CRN, they need to decide basing on statistical information of PUs' arrival and departure to and from that particular slot. With SS data available and PU activity patterns modeled, SUs to occupy the best suited spectrum slot out of available slots for its transmission through a decision process known as spectrum decision. In this chapter, a SDSF based on a fusion rule applied on three parameters of channel including the channel capacity of the licensed channels. The proposed decision technique enables the SUs to decide the best spectrum band to occupy for smooth communication without having an impairment in its communication and without disrupting the PU. The results of this work have been published in proceedings of 16th IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM 2015) [1].

3.1 Introduction

Spectrum decision is a step taken by the SUs in CRN after SS. The SS data gives SUs information about the vacant spectrum bands and SUs access the spectrum bands as per their applications guaranteeing the QoS requirements. To ensure no interference to PU, the spectrum decision process must be robust and error free from the possibility of interfering with the transmission of PU as well as continuing transmission when PU arrives. Therefore, the proposed SDSF offers a robust and definite decision to occupy the vacant channel with the assurance that SU would not interfere with PU, would complete its transmission and will be able to swiftly switch to another vacant channel on PU's unexpected arrival.

3.2 Contribution

Our spectrum decision scheme is based on fusing each separate decision of three key parameters with AND rule, thereby, giving a hybrid spectrum decision scheme. The decision technique developed will first find the channel idle time determined with stochastic analysis, channel occupancy status at that particular time and channel performance based on its capacity.

3.3 Chapter Layout

Section 4 gives an account of the proposed methodology for SDSF. Results and discussion is given in section 5 and the chapter is concluded in section 6.

3.4 Spectrum Decision Framework

The detailed explanation of the proposed spectrum decision scheme is described in subsequent sections. In the proposed framework, three channel parameters, channel idle time, channel performance and channel occupancy status have been incorporated and an AND rule has been applied to these parameters to give the slot availability. This decision module is shown in Fig. 5.1. If the slot has been identified as available, then the SU will occupy the channel and start its communication. Simultaneously, SU will keep sensing the channel and if PU arrives, then SU will vacate the channel and the process of decision framework will restart for that particular SU. The complete algorithm is shown via flow chart in Fig. 3.2.

The CRN is considered to function in five licensed spectrum bands, the carrier frequency of these bands ranges between 1 MHz to 5 MHz. The Poisson distribution is used to model the PU activities, i.e., its arrival and departure, and the secondary connections [40]. PU's activity is shown in Fig. 3.3. Three parameters are defined below.

Arrival and departure times are probabilistically calculated via Poisson distribution given as

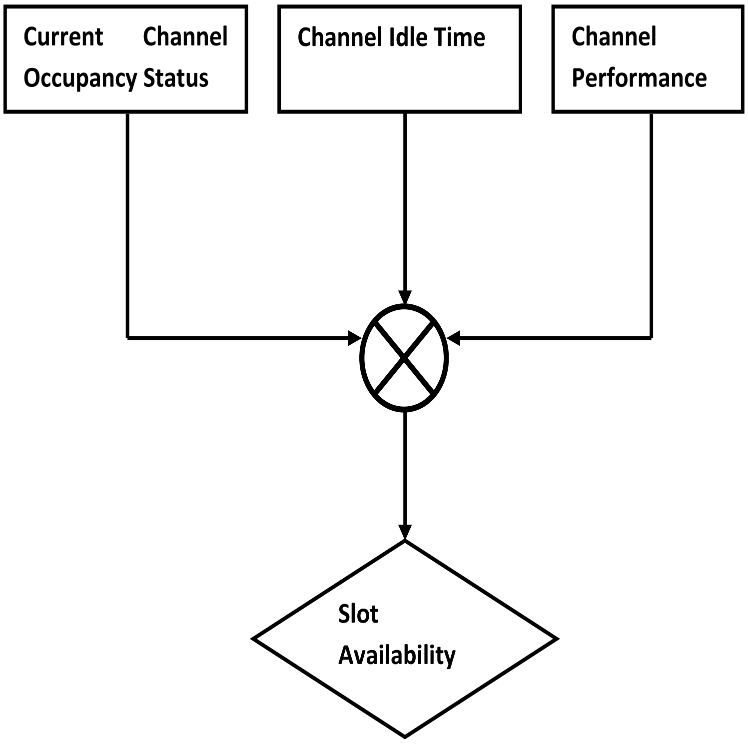

Figure 3.1: Decision module; giving fusion of three key parameters via AND rule.

follows;

$$f(k;\lambda) = P(T = k) = \frac{\lambda^k e^{-\lambda}}{k!}, \tag{3.1}$$

where T is a discrete random variable and $k = 0, 1, 2, 3, ..., n$. Let the channel idle time be represented by τ which is a vector representing idle time for all the channels. Let the channel number be represented as *i*, where $i = 1, 2, 3, ..., n$. Here, we define a selection map ξ, which is assigned a value $'1'$ for those channels whose idle time is greater than a set threshold γ. Mathematically, we define it as follows:

$$\xi(i) = \begin{cases} 1; & \tau(i) > \gamma \\ 0; & otherwise \end{cases} \tag{3.2}$$

Channel performance is monitored based on the respective channel capacity. Let the channel capacity be represented by κ given in Eq. 6.20 where $\mathbf{H}$ denotes a fading channel gain which is a complex Gaussian random variable and δ denotes signal-to-noise ratio. Here, we define

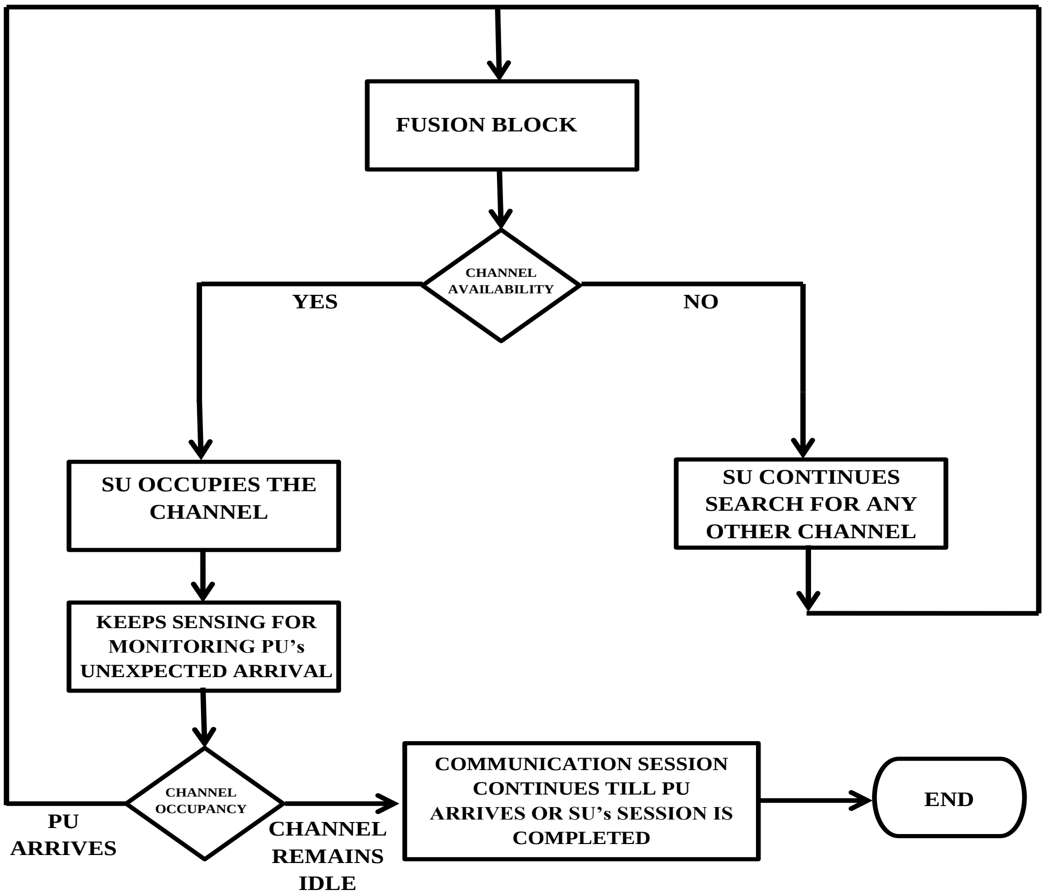

Figure 3.2: Flow chart of the proposed spectrum decision scheme.

a selection map ζ, which is assigned a value $'1'$ for those channels whose performance is greater than a set threshold ϵ. Mathematically, we define it as follows:

$$\kappa = log_2\left(1+\delta\left|\mathbf{H}\right|^2\right) \tag{3.3}$$

$$\zeta(i) = \begin{cases} 1; & \kappa(i) > \epsilon \\ 0; & otherwise \end{cases} \tag{3.4}$$

The targeted channels are continuously sensed to get channel occupancy status. SU is continuously sensing the channel(s) and estimating the power spectral density (PSD) using the periodogram for any particular signal $y[k]$ carrying energy transmitted by PUs as follows;

$$P_K(e^{j\omega}) = \frac{1}{K}\left|\sum_{k=0}^{K-1} y[k]e^{-jk\omega}\right|^2 \tag{3.5}$$

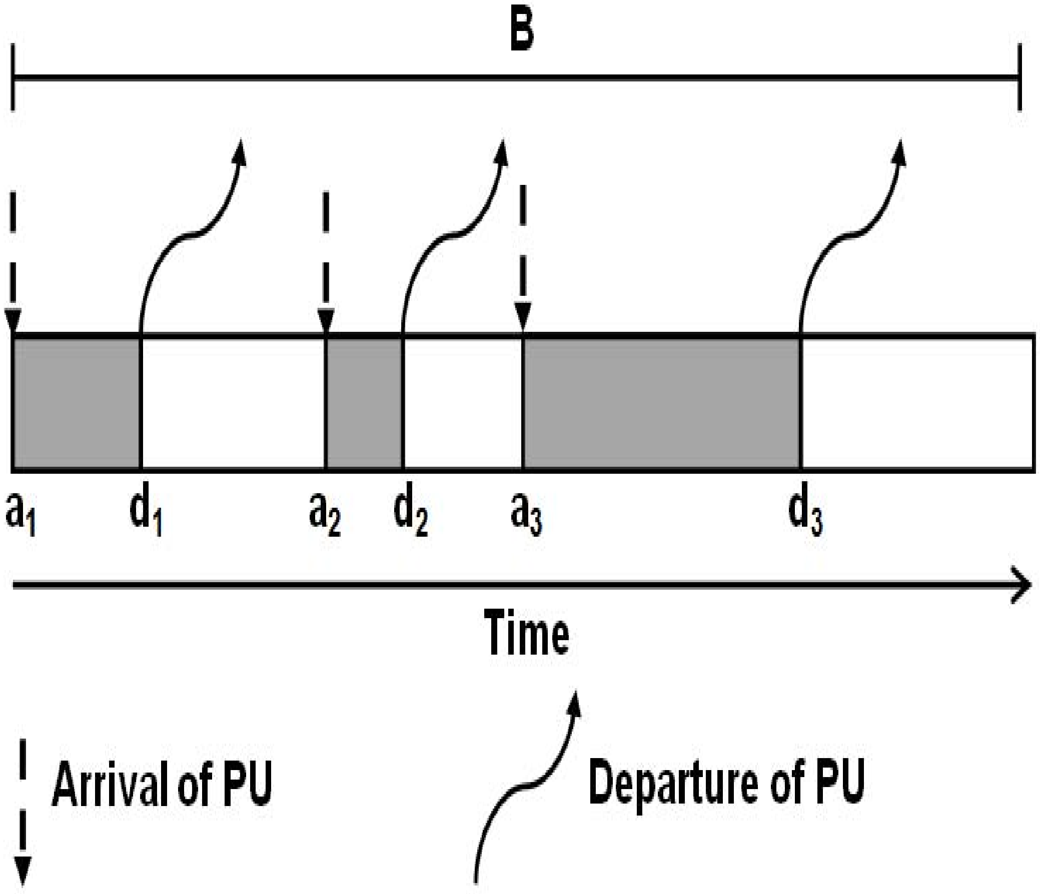

Figure 3.3: PU's activity in a particular spectrum band B showing vacant(white space) and occupied (grey) spaces. Arrival and departure times of the PU are represented as a_i and d_i respectively. Channel idle time is found using $a_i - d_{i-1}$

.

$$P_K(e^{j\omega}) = \frac{1}{K} \sum_{k=0}^{K-1} y[k]e^{-jk\omega} \sum_{s=0}^{K-1} y[s]e^{js\omega}, \tag{3.6}$$

where the power is found to be less than a set threshold, the SU considers it vacant. Let ρ denotes the channel occupancy status, which is assigned a value $'1'$ for vacant channels and $'0'$ for the occupied ones. The above three results are fused using AND rule to decide for spectrum to be occupied by SU of a CRN. Mathematical model of the proposed technique is given as under;

$$\left(\xi_i \otimes \zeta_i \otimes \rho_i\right)(t) \xrightarrow{x} x(\left(\xi_i \otimes \zeta_i \otimes \rho_i\right)(t)) \Rightarrow c_i(t), \tag{3.7}$$

where ξ, ζ and ρ denote the channel idle time, channel performance and channel occupancy status respectively. Similarly, $c_i(t)$ denotes the selected channel for SU to occupy, based on

AND rule of the three parameters mentioned above. Therefore, the rule that connects $c_i(t)$ with the parameters (ξ_i, ζ_i, ρ_i) is given by the decision making algorithms. Let x represents the rule known as spectrum decision rule. This rule allows SU to decide to occupy a specific spectrum hole which has been declared the best available channel by our decision module. Moreover, $x(\xi_i, \zeta_i, \rho_i)$ indicates a decision making outcome, which leads to the decided channel $c_i(t)$ for communication by SU. The possible outcome of the decision block will be either to occupy a particular channel whose channel idle time, channel performance and channel occupancy status are found greater than the set respective threshold. If the PU has arrived unexpectedly in this particular channel, when our decision scheme has declared the channel vacant, the SU will vacate the channel and decision module will restart its functionality. Spectrum sensing component through channel occupancy status would have identified other vacant channel for SU, at that time. Accordingly, the SU will occupy any suitable channel and there will be no interference with PU as well as QoS of SU's communication will not be degraded.

3.5 Results and Discussions

The network model used comprised of five PUs, five corresponding channels and one CRU. The PSD of all five PUs calculated using Eq. 3.5 and Eq. 3.6 and is shown in Fig. 6.4. The SU will make decision of channel status; either to be vacant or occupied by spectrum sensing. SU continuously senses the channel status and keeps the record of latest sensing results. It can be seen in Fig. 6.5 that the PSD of user 4 is very low which signifies that the PU has vacated the channel. For above mentioned five targeted channels, we have run the simulation for our decision module for 24 iterations to evaluate the proposed decision framework.

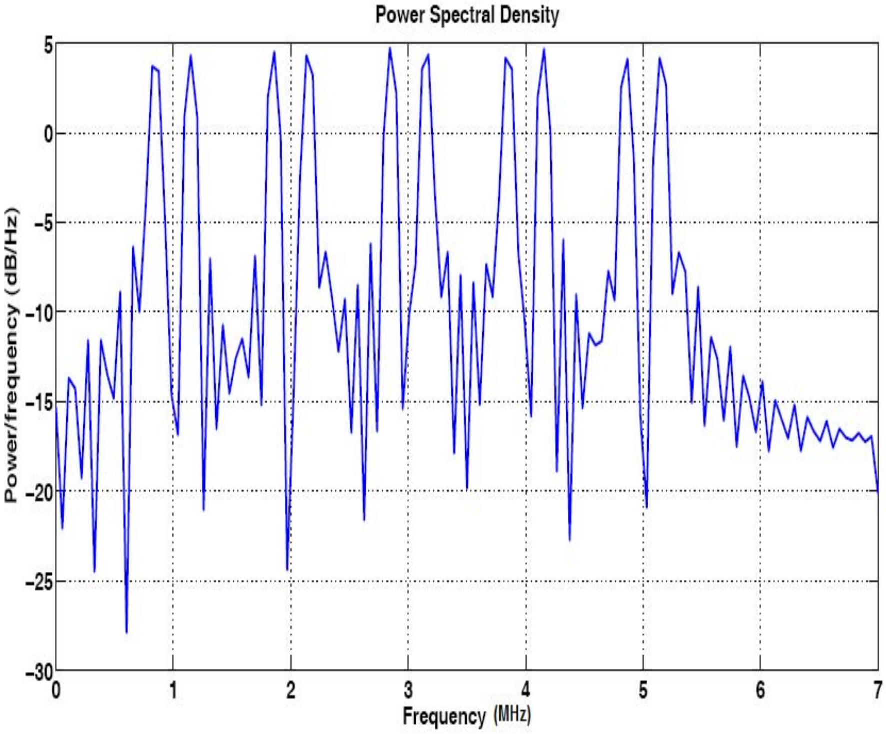

Figure 3.4: Power spectral density of the data transmitted by all five PUs.

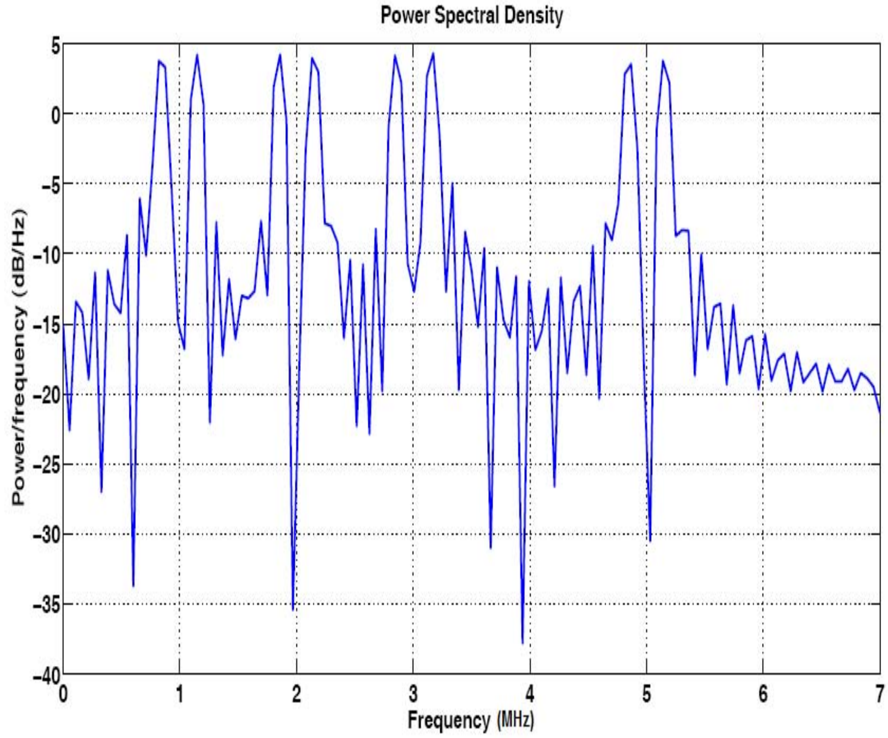

Figure 3.5: Power spectral density after the departure of fourth PU.

The parameters, detection probability P_d, False alarm probability P_{f_a} and missed detection probability P_{md} as key measurement metrics that have been used in our previously published work [48] to analyze the performance of spectrum sensing technique, are also used here to verify the correctness of decision purposed in this paper. With the increase in P_{f_a}, P_{md} should decrease. It signifies that SU in CRN in the channel, sensed idle, occupied as an outcome of our decision module, is not causing interference to PU and also maintaining QoS in its own transmission. Fig. 3.6, Fig.3.7 and Fig.3.8 show that the purposed decision framework scheme has yielded almost the same results for higher as well as lower values of SNR, as were found when the channel was sensed idle.

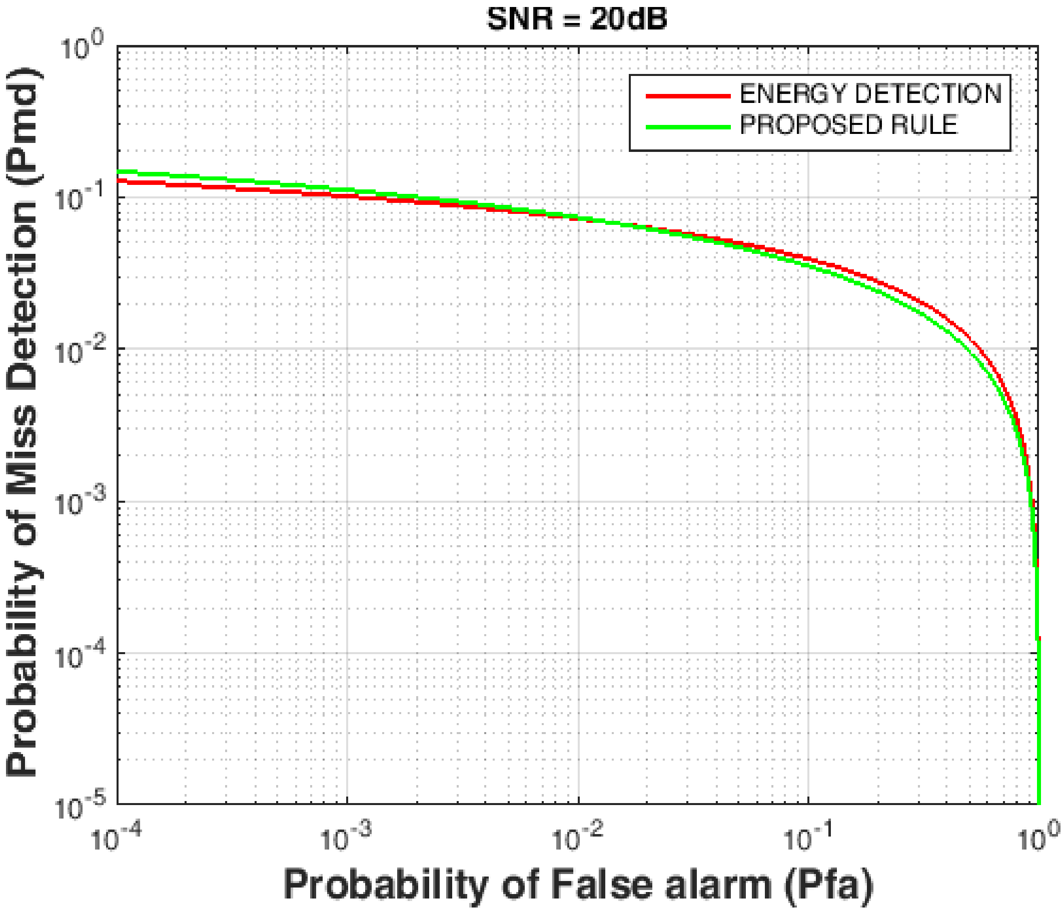

Figure 3.6: ROC Curve when SNR=20 dB obtained using our proposed decision framework and conventional spectrum sensing technique

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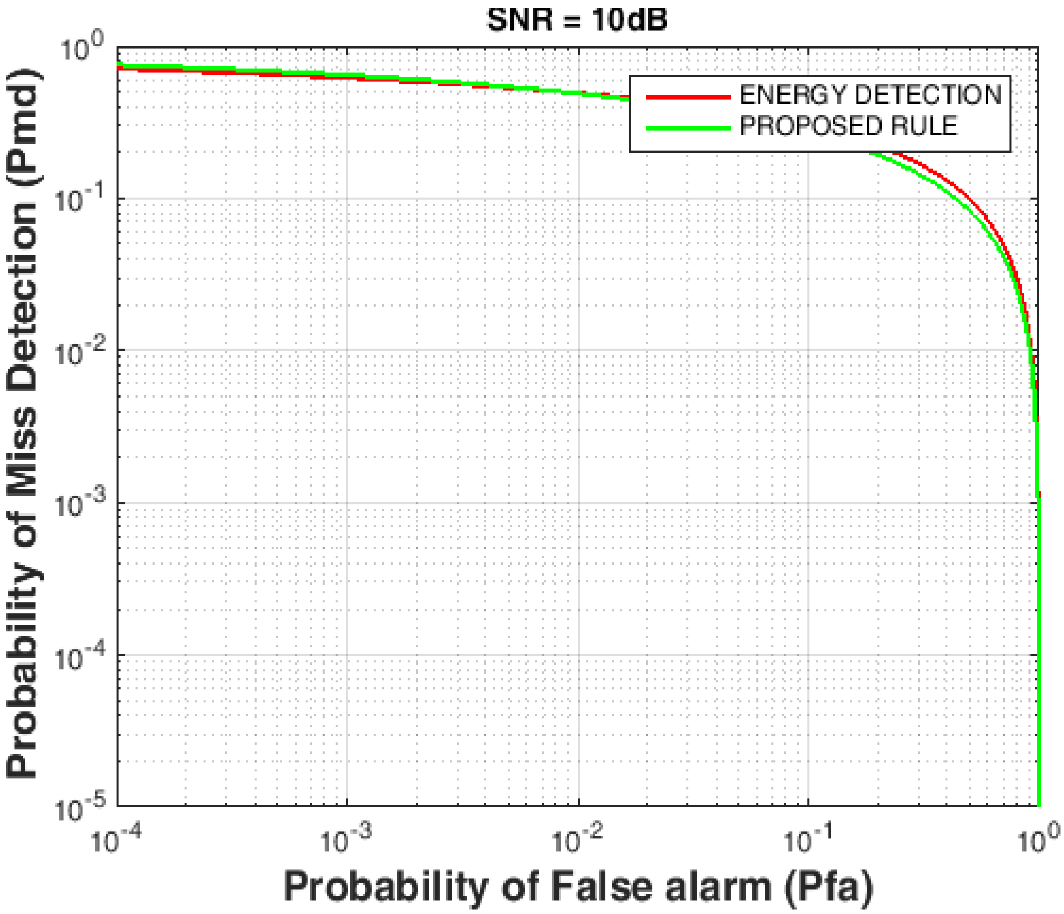

Figure 3.7: ROC Curve when SNR=10 dB obtained using our proposed decision framework and conventional spectrum sensing technique

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3.6 Summary

In this chapter, a fusion rule based SDSF has been proposed which enables SUs in CRN to complete their transmission without causing any harmful interference to PUs and also maintaining their QoS requirements as per their wireless application adopted. The proposed framework applies AND rule to the most important parameters namely, channel ideal time, channel occupation status and the channel capacity. These three parameters integrated together give a lead for SU to occupy the targeted spectrum slot. Thus, the most suitable available channel is determined by the AND value of channel ideal time, channel occupancy status and channel capacity. Further investigations can be made on optimizing these three parameters with lower values than 1 as in AND rule, i.e., using fuzzy logic.

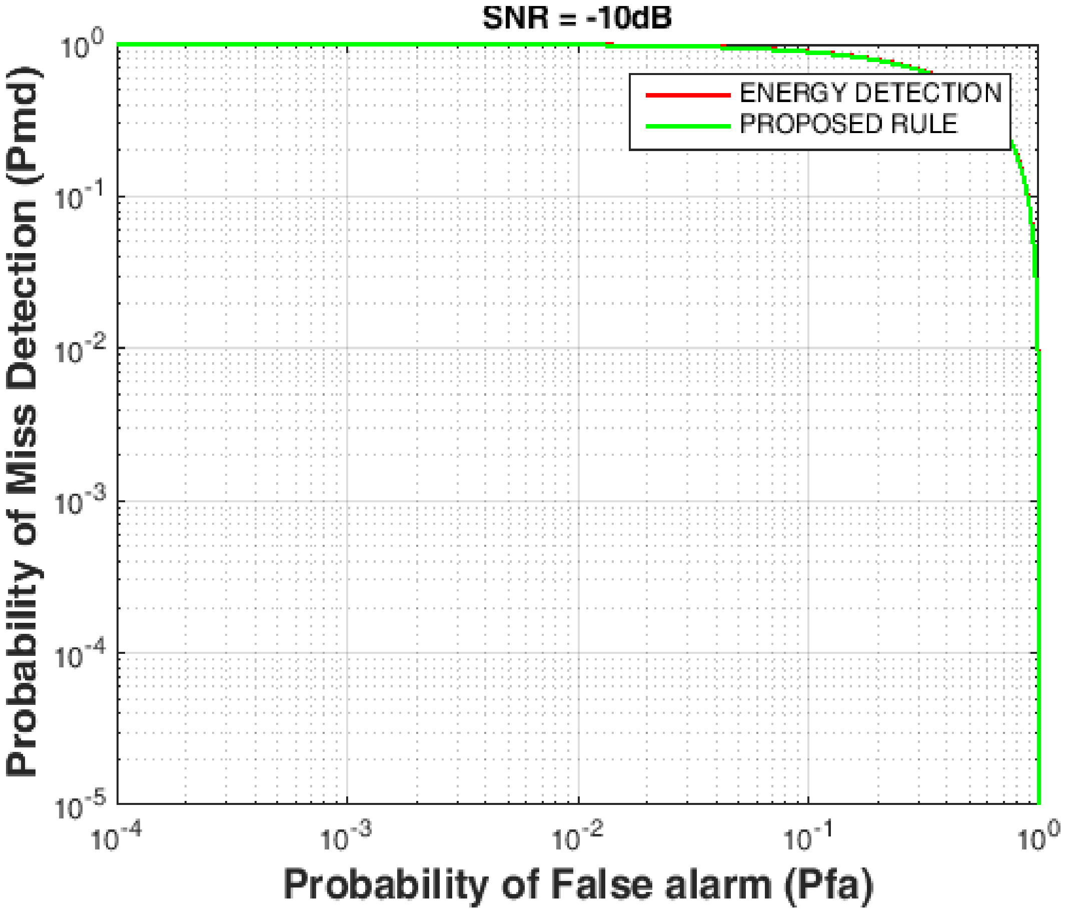

Figure 3.8: ROC Curve when SNR=-10 dB obtained using our proposed decision framework and conventional spectrum sensing technique

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Chapter 4

Empirical Centralized Spectrum Decision Strategy For Cognitive Radio Networks

This chapter deals with quantifying and evaluating the effects of primary user activities in multiple lisenced spectrum slots available to SUs in the CRN under cooperative SS leading to SUs taking the decision to occupy the slots. The spectrum decision framework presented in previous chapter was based on logical AND combination of three key parameters, here, closed-form expressions are formulated for ROC where interference models of SU's transmitters and receivers are considered. Along with sensing the spectrum for the availability of idle channels, SUs in the CRN have to take quick decision which channel is to be opportunistically occupied on appearance of PU in the existing channel. The channel should be free and must conform to SU's QoS requirements. A novel centralized spectrum decision strategy for SDSF has been proposed in this chapter.

4.1 Introduction

The rapid growth in wireless services and the existing fixed RF spectrum policy have converged to the spectrum scarcity problem. Moreover, due to typical usage of wireless technology, the allocated RF spectrum bands are underutilized. As per FCC ,the temporal and geographical variations in the utilization of the assigned spectrum range from 15% to 85% [12]. Moreover, there have been measurement campaigns conducted in various regions [49] showed that operators and their users have very limited RF spectrum usage across wide frequency ranges. Amongst many explored challenges in the realization of CR systems, the Spectrum decision by SUs in CRN in exploitation of known patterns and exploration of new and changing RF spectrum dynamics needs to be worked out. For this, a systematic testbed is required which can sense MHz and GHz of spectrum in its location [50]. Moreover, it should sense narrow, wide and ultra bandwidths, yet providing a finer details (efficiency in propagation, immunity to noise and impairments and the size of antenna required) at each frequency of wireless spectrum. Presently, CR has been adopted in various wireless communication standards [51]. Spectrum sensing and decision are two essential functions in the operations of CRs, where they operate in HD and/or FD modes. As mentioned in previous chapters, a significant research has been carried out in SS and spectrum decision. Most of the work assumed ideal hardware structures and PU activity modeling based on stochastic analysis. However, practical CR devices are expected to suffer from hardware imperfections and the real traces of PU activity can not be obtained due to copy right issues.

4.2 Motivation

While the SU is already carrying out its transmission in CRN, if a PU starts its communication, the SU detects the potentially vacant bands through SS, decides onto which channel to switch and then finally adapts its transceiver so that the active communication is continued over the new channel. SUs cooperate among themselves in CRN thereby improving the SS performance by combining local decisions measured over independent sensing channels. This cooperation decreases the probability of wrongly detecting the channel free or occupied by PU. Not only is the spectrum decision of SU in CRNs an unexplored area of research, the techniques available in the literature also suffer from incompleteness and lack of simplicity in computational complexity. Most of the spectrum decision methods take the decision as a sequence in time and the results are given for the communication session of SU that follows the session in which decision is made. In such scenarios, the latency causes degradation in communication. Given a realistic CRN, problems of SS errors, simultaneous access of channels by multiple SUs and SUs causing interference with PU(s) and amongst each other, can not be avoided. In underlying scenarios, a fundamental challenge of spectrum sharing is to ensure the QoS of PUs while maximizing the achievable throughput of SUs. In this chapter a novel spectrum decision strategy has been proposed. The strategy suggests centralized spectrum decision scheme basing on cooperative sensing data provided by individual SUs. The total error rate is minimized as the central SU senses the idleness of the channel through energy detection applied on the received signals samples from individual SUs. Thus the decision taken to occupy the channel by an SU is accurate and robust. The experimental testbed using USRP2 and signal generator was used to check the scheme in real time. At the end, the computational complexity of the proposed technique is also analyzed.

4.3 Chapter Structure

The chapter is organized as follows: Section 1 gives a brief introduction of the topic and related work. Section 2 provides an overview of the spectrum decision strategy. The proposed decision scheme is presented in section 3. Experimental testbed is presented in section 4. Results and discussion are delved in section 5 and the paper is concluded in section 6.

4.4 Centralized Spectrum Decision Strategy: Overview

A multi PUs and SUs OFDM-based CRN with $\aleph$ SUs where $\aleph = 1, 2, ..., N$, attempting to access the spectrum slots of κ PUs. The entire frequency spectrum band is into ϖ OFDM slots in the CRN which is deployed to efficiently utilize the spectrum band. The SUs are devices that configure their transmission parameters after intelligently learning from the wireless radio environment to perform in CRN. The proposed work presented in this based is based on a spectrum decision framework. A detailed overview of which is described in this section.

A centralized spectrum decision framework for CRN has been proposed here, where the

CRN consists of PUs and SUs. There is one central SU which is in fact a ”serve to provide” element i.e. the base station (BS) that coordinates the spectrum decision mechanism. The cognitive users are identified as slave SUs. Each slave SU senses a particular spectrum band, being used by PU and forwards this sensing data to the central SU as shown in Fig. 4.1. The central SU manages the spectrum decision through energy detection technique and propagates back the result to the slave SUs. Centralized spectrum decision strategy is proposed here, as only the central SU will be equipped with cognitive capabilities that demands hardware complexity. The slave SUs will rather have a simple conventional hardware design. Moreover, with individual spectrum sensing based decisions, the probability of collision among SUs increases as all of them would compete for the same spectrum band at the same time. Thus, the proposed centralized spectrum decision mechanism avoids these collisions which further reduces latency in communication.

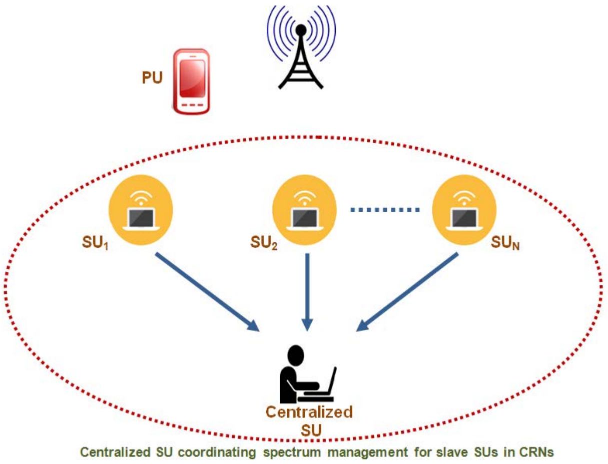

Figure 4.1: Cooperative spectrum decision scheme for cognitive radio networks.

4.4.1 System Model

A multi channel CRN with N SUs and one PU (at a time of SUs’ attempts to access the particular slot) in an overlay manner is considered. Let $a(t)$ be the PU signal generated at frequency f_s with OFDM modulation technique. Similarly, let $r(t)$ be the AWGN noise. Let $y(t)$ be the received signal by SUs which is defined as follows:

$$y(t) = \{y_1(t), y_1(t-1), ..., y_1(t-T+1)\}\,, \tag{4.1}$$

where T is the total number of samples received by SU. Basing on these received signals, the slave SU will sense the spectrum for presence of PU and/or any other SU of the CRN. In the proposed scheme of our CRN system the centralized SU which gathers the sensing data from N independent SUs, assigns the channel as per their requirements to perform their transmission. The spectrum sensing mechanism considers the hardware capabilities of the radio environment. To assist the spectrum sensing technique, Common Channel Control (CCC) in our CRN performs the operations of transmitter-receiver compatibility, channel access approaches for SUs and cooperation amongst SUs in the network. For the N number of SUs in CRN in the cooperative configuration, the spectrum sensing approach will finally lead to the sensing of the complete network, thus applying centralized spectrum decision technique. The spectrum sensing approach is given by;

$$y(t) = \begin{cases} r(t) & \text{when } \ H_0 \\ a(t) + r(t) & \text{when } \ H_1 \end{cases} \tag{4.2}$$

where H_0 is the null hypothesis describing the absence of PU and H_1 is the alternative hypothesis indicating the presence of PU. The slave SUs carry out sensing and inform central SU regarding the updated data of channels. The central SU applies energy detection technique over sensing data received from each slave SU to check the channel occupancy status. The individual decisions are then fused using majority vote rule to get a single spectrum decision.

4.4.2 Energy Detection

Energy detection, which is the mostly used spectrum sensing technique because of its simplicity, easy implementation, low complexity and accuracy in sensing the vacant slot, is used here as the spectrum sensing scheme. The basic approach behind energy detection is the estimation of the power of the received signal $y(t)$. To evaluate the power of the received signal, the output of a band-pass filter with bandwidth 200 kHz is squared and integrated over an interval of time. At the end, the integrated value is measured up to an experimentally set threshold to find out whether the PU is occupying the channel or not. The test statistic $X(y)$ received signal is given as follows:

$$X(y) = \frac{1}{T}\sum_{t=1}^{T} \|y(t)\|^2 \tag{4.3}$$

In a CRN, the PU always has the higher priority for accessing the spectrum. Therefore, the probability of miss detection of a PU must be reduced to minimum value. The probability of false alarms and detection of the j^{th} SU for the case of CRN noise can be approximated from the probability density function of the test statistic $X(y)$ as given below:

$$P_{f,j}(\tau_s) = Q\left(\left(\frac{\lambda}{\sigma_s^2} - 1\right)\sqrt{\tau_s f_s}\right) \tag{4.4}$$

$$P_{d,j}(\tau_s) = Q\left(\left(\frac{\lambda}{\sigma_s^2}\rho - 1\right)\sqrt{\frac{\tau_s f_s}{2\rho + 1}}\right), \tag{4.5}$$

where $Q(.)$ is the complementary cumulative distribution function of the Gaussian variable and f_s is the sampling frequency mentioned in Hertz.

4.4.3 PU Activity Model

A real time PU activity in the GSM band at frequency 900 MHz and bandwidth 200 kHz has been considered. The PU activity in a channel is undeterministic and can be represented as average duration of its occupying the channel i.e., ON and not occupying the channel, i.e., OFF on the assumption that the PU activity is modeled as exponentially distributed inter-arrivals with φ_{ON} and φ_{OFF}. The PU activity ρ is given as:

$$\rho = \frac{\varphi_{\mathrm{ON}}}{\varphi_{\mathrm{ON}} + \varphi_{\mathrm{OFF}}} \tag{4.6}$$

4.4.4 Spectrum Decision Parameters

There are number of challenges to be addressed to make best use of the concept of CR deployed in a network which is characterized as an efficient spectrum utilization. Therefore, there emerges a requirement to suggest a novel spectrum access technique which addresses both the spectrum sensing errors and computational complexity. To address this issue, following parameters are defined here which affect the proposed decision strategy.

4.4.4.1 Interference Analysis

The interference among mobile, heterogeneous and independently operated SUs over shared spectrum is required to be analyzed. A model for SU's coexistence is used here to ensure no interference in the wireless applications. The possible assignment of spectrum can either be on an exclusive basis, or on a shared basis. This assignment determines the multiple access schemes and the interference resistance that the network has to provide. In application where spectrum can be used for a certain service like cordless telephones in Europe and Japan, but is not assigned to a specific (licensed) user/operator. Users can set up qualified equipment without a license, i.e., a CRN. In such usage of RF spectrum bands, the networks are designed in such a way that it avoids interfering with other users in the same region. Since in the proposed methodology, the only interference can come from equipment source of (either) SU and (or) of PU, coordination between different devices is simple. The transmit power (identical for both SUs and PUs in CRN) is the key component here. Since, the co-existence of SUs with PUs in CRN makes a non-linear system and its components cause spurious signals, which is a source of interference amongst spectrum slots. When a non-linear device is used simultaneously by number of carriers, intermodulation products are generated, which result in distortion in the signals. Analytically, the coexistence is a non linear function of following four factors:

- The number of SUs in the cell of cellular area. We have assumed N number of SUs in the CRN. These SUs move according to general mobility model whose steady-state frequency distribution has a PDF.
- The traffic pattern of each SU. In other words, a new phenomenon SU activity is introduced here. SU activity is just like the PU activity and its response is to coordinate its access to the vacant spectrum slots.
- The mobility pattern of each SU. The proposed architecture enables SUs to carryout their transmission while maintaining their QoS requirements.
- The coexistence interference range of each SU, which depends on any arbitrary geographical location of a SU in the network at a specific time. Then we can model a reference distance as a coexistence interference range. The value of this distance would primarily depend on the SU's transmission power, its sensitivity and the channel model which SU will adopt for its wireless transmission.

4.4.4.2 Complementary Radio Operating Characteristics

The process resulting in either a collision with PU or under utilization of the bandwidth, requires an inquiry to find out whether it was because of false alarm or the missed detection. False alarm is due to wrong detection of PU at a given time by the channel allocation algorithm. As a result, no SU utilized the channel hence, the concept of CR is compromised. On the contrary, the missed detection is the failure of PU activity detection and causing harmful collision between PU and SU. To address these two eventualities, some intelligent scheme is to be deployed to find the factors affected in wrong decision. The proposed spectrum decision strategy makes the CRN free from false alarm and miss detection errors.

4.4.4.3 Latency

The link delay between sender and receiver known as latency is a network measure in digital radio technology. In CRN, the SU has to transfer data fastly and accurately while maintaining its its QoS requirements. The proposed spectrum decision scheme offers reduced latency in the CRN with the help of device controller (DCON) which is responsible for physical layer connectivity to the network. DCON includes the user equipment (UE) radio access (RA) application.

4.4.4.4 Robustness

The network's capability to perform its transmission functions in an efficient and uninterrupted manner is composed of two aspects, reliability and resilience. CRNs are expected to be more resilient in the relevant wireless applications, as they are deployed in harsh radio environments and have to quickly reconfigure their operational parameters compatible to new spectrum band while maintaining their QoS requirements.

4.4.4.5 Congestion

The densities of SUs in a cell of cellular network is usually higher than the number of nodes in the standard network, therefore there will be congestion in CRN. For an efficient spectrum decision strategy, the congestion of SUs must be addressed.

These four factors ensure that the interference to the PU(s) remains below an interference temperature limit which does not effect the PU's communication.

4.5 Proposed Centralized Spectrum Decision Scheme

Each SU senses the spectrum for detection of PU's signal as per spectrum sensing approach given in Eq 4.2. This data is sent to the centralized SU which has requisite hardware to keep the sensing data updated. An ideal RF front end has been emulated in the experimental testbed described in section 4.2. This SS provides better sensing accuracy. The SS accuracy here countermeasures the joint effect of IQ imbalance and self interference. The central SU basing on their data carries out spectrum decision process through energy detection technique. Centralized SU also has the information of the wireless application requirements of each slave SU in the CRN. Accordingly, the centralized SU will allocate suitable channel to the desirous SU ensuring no collision/interference with PU or other SU already occupying the channel. The accuracy of energy detection output for the spectrum sensing data depends on noise level variations with respect to the signal levels. The centralized SU will apply majority vote rule (MVR) on the individual spectrum decision results to obtain a single decision which is accurate and reduces the probability of interference. This complete process is explained graphically in Fig. 4.2. The centralized SU could also identify the spectrum occupant as PU or SU depending on the received signal. PU will transmit signals with OFDM and SU's signals are propagated by QPSK modulation scheme. In case the received signal is identified as SU's, centralized SU will look for co-existence basing on the parameters of transmission. If the channel occupant is a PU, the centralized SU will not allow any transmission in that particular channel by the SU.

For the MAJORITY rule, the false alarm and detection probabilities are respectively expressed as 4.4 and 4.5.

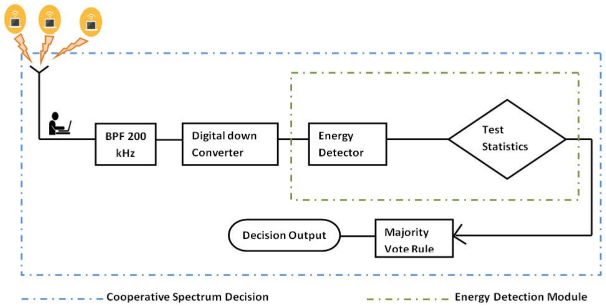

Figure 4.2: Centralized spectrum decision mechanism showing output through majority vote rule.

4.6 Experimental Testbed

The algorithm was tested by setting an experimental testbed consisting of USRP2 and signal generator. USRP2 manufactured by National Instruments (NI), are generally used as hardware platforms in the field of CRNs and SDR . When USRP2 is connected to a host-PC via Gigabit ethernet cable, it acts as a SDR with host-based digital signal processing capabilities. Each USRP2 device provides an independent transmit and receive channel capable of full duplex in hardware configurations. For our experimental setup, SUs were emulated by USRP2 as shown in Fig. 4.3 and PU was emulated using signal generator of Agilent Technologies (see Fig. 4.4) ranging 9 kHz to 2000 MHz, connected with the host computer system (Core i7, 2.20 GHz processor with 8 GB RAM). The signal of 900 MHz with bandwidth of 200 kHz at SNR ranges from 5 dBm to 20 dBm was generated and the signal was observed over a network analyzer. The transmitted signal was received at USRP2 emulating slave SUs. The host-PC has ubunto installed for observing the transmitted and received signal waveforms and other characteristics. The centralized SU receives the sensing data forwarded by individual SUs and applies proposed spectrum decision strategy.

4.7 Results and Discussion

This section describes the performance of the proposed spectrum decision strategy with reference to probabilities of detection (P_d) and miss detection (P_{md}) versus probabilities of false

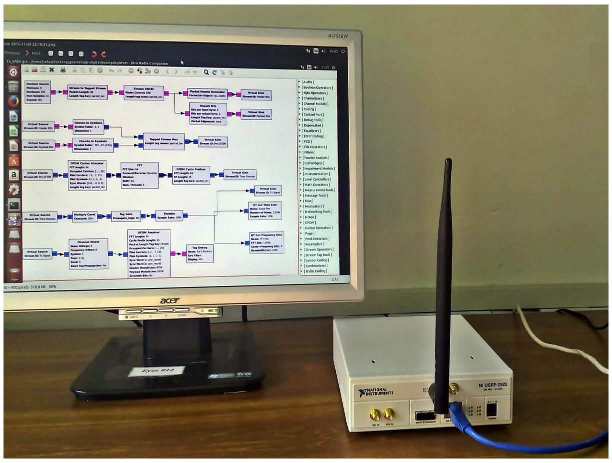

Figure 4.3: Experimental setup showing a NI USRP2 emulating a slave SU connected to a host-PC. The SU receives the signal to apply spectrum sensing test statistic.

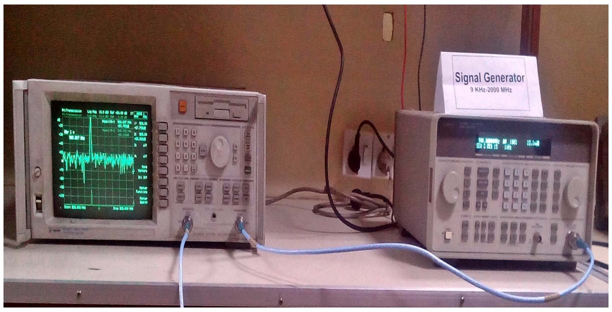

Figure 4.4: Experimental setup showing the signal generator connected to a network analyzer emulated as a PU.

alarm (P_{fa}) for presence or absence of PU signal in the spectrum band. A centralized SU acts as a centralized node which receives information about the locally sensed spectrum by each SU. The N SUs in the network carefully receive the signal transmitted by PU as shown in Fig. 4.6. If the received signal has OFDM modulation technique, it is identified as PU. In this case there can be two possibilities; one, that the SU finds PU present or wrongly senses it vacant. Centralized SU then evaluates the presence of PU and analyzes for interference as described in section 2.4.1. Secondly, the central SU has wrongly detected the presence of SU. In this case it is expected that no SU would be allowed to occupy the channel. Since, the proposed scheme works in both, overlay and underlay Cognitive Radio scenario, therefore, there will be SU transmission coexisting with PU, ensuring no interference and the frame-

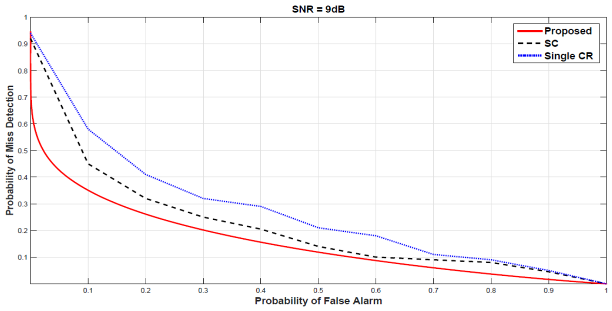

Figure 4.5: Probability of miss detection (P_{md}) vs Probability of false alarm (P_f)

work guarantees QoS of applications of SUs' as well as of PUs'. Similarly, multiple SUs can be allocated the same channel with different QoS and wireless application requirements. The proposed technique has effectively analyzed the occupancy of the spectrum band ensuring low latency, no interference and the robustness. These merits are achieved by centralized SU's capability of assigning alternate channels if a PU has unexpectedly arrived. Since, PU is found absent and centralized SU has allocated the band suiting to QoS and wireless application requirements, therefore, the SU is expected to be enabled to carryout its transmission without any delay. Similarly, the network will not be congested as the proposed strategy allocates the channel(s) to SUs judiciously through centralized SU's capability of intelligently assigning the channel to the SUs. The results are compared with the single CR SS and the selection combining method, known as SC which selects the user with maximum SNR as shown in Fig. 4.5 [49].

We also analyzed the computational complexity of our proposed spectrum decision mechanism which comprises of two major steps; one, is the energy detection method applied on the sensing data received from each slave SU. Second is the application of MVR. The complexity of first step is O(NM^2), where M is the number of received samples. Similarly, for application of MVR the complexity is O(M). Therefore, the total complexity of the proposed strategy is O(NM^2)+O(M).

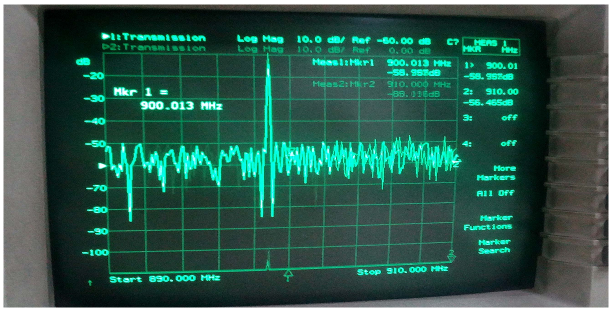

Figure 4.6: PU signal transmitted at 900 MHz frequency with 200 kHz of bandwidth using a signal generator as seen over a network analyzer.

4.8 Summary

This chapter presented a spectrum decision scheme for SUs in the CRN. The proposed SDSF works in the presence of SS errors, simultaneous access by multiple SUs and SUs possible interfernces. SDSF works in a centralized mechanism where a central SU (BS) was configured with more cognitive capabilities and the SUs behaved as slaves within the network. The slave SUs keep on sensing the frequency spectrum and forward their gathered data to central SU. The central SU applies energy detection technique on each stream of data received from slave SUs and then applies majority vote rule to get a single spectrum decision to verify whether the particular frequency band is available or not. Moreover, the central SU has a special receiver design where it could also check whether the occupant is a PU or SU. If an SU is found as occupant, then it enables the coexistence of multiple SUs by deciding the communication parameters to be kept during transmission. Numerical simulations show that decision taken by the centralized SU offers better probability of detection as compared to spectrum sensing techniques available in literature. Since, the centralized SU takes decision while considering the QoS requirements of SU and its wireless applications requirements, the scheme offers an accurate and robust decision for the SUs under real time CRN where an experimental testbed has been used. Further techniques for proposing a SDSF is presented in the next chapter. This centralized spectrum decision framework would be useful in making a continuous backend spectrum sensing process (CBSP) as well, which can be applied in Internet of Thing implementation, the account of which is given in Chapter 6 of this dissertation,

Chapter 5

Fuzzification Supported Spectrum Decision Framework For Cognitive Radio Networks

5.1 Introduction

In this chapter, a fuzzy rule based decision framework is proposed. This framework is an extension of the SDSF presented in Chapter 3. The term fuzzy logic has been used in two varying concepts. In a convergence concept, fuzzy logic refers to a logical mechanism that generalizes classical two-valued logic for reasoning uncertainty and in a broader definition, fuzzy logic refers to all of the theories and technologies that employ fuzzy sets, which are classes with unsharp boundaries. This chapter deals with fuzzy rule based SDSF on the activity time, possession and QoS of the spectrum slot. Values greater than experimentally set threshold values of these parameters are fed as input to the fuzzy inference engine which has a set of predefined rules. The output, as a result of defuzzification of the fuzzy inference process is the final spectrum decision which enables the SU to carryout its transmission without interfering with PU while maintaining its QoS requirements. Fuzzy logic has the ability to deal with imprecise data and to evaluate (parametric) criteria simultaneously to provide a robust spectrum decision . As a result, the CRN works in a systematic manner in which SUs configure as per spectrum characteristics to comply their QoS requirements. Although fuzzy rule based system for the selection of SS techniques has been proposed in and in other decision making algorithms, but (to the best of author's knowledge) no learning technique has been applied in spectrum decision making strategies for CRN .

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Table 5.1: List of symbols

Symbols	**Descriptions**
s	The targeted spectrum slot
N	Number of SUs
L	Total number of licensed slots
k	Total number of available spectrum slots
m	Successful use of spectrum slots by the SU
λ_s	PU arrival rate
T_v	random variable following exponential distribution, defining the idle times of PUs
T_o	random variable following exponential distribution, defining the busy times of PUs
α	mean of T_v
β	mean of T_o
ξ_o	MF of spectrum slot occupied by PU and not available for SU
ξ_{pa}	MF of spectrum slot when arrival of PU is expected
ξ_v	MF of spectrum slot when it is sensed vacant
ζ_v	MF of spectrum slot when it is vacant and available for use
ζ_{pua}	MF of spectrum slot when it was sensed vacant but PU arrived unexpectedly
ζ_o	MF of spectrum slot when it is sensed vacant
ρ_a	MF of acceptable spectrum slot QoS
ρ_r	MF of rejected spectrum slot QoS
τ_{na}	Spectrum (decision) is not available for SU
τ_v	Spectrum (decision) is vacant for SU to occupy
i	represents the real world crisp input values for MFs $\xi(i)$, $\zeta(i)$, $\rho(i)$ and fuzified output of three inputs mentioned in sub section 5.1
$\mathrm{R_k}$	Recompense function for k^{th} spectrum slot
χ_0	Spectrum slot response
η_s	Sensing duration
Γ_s	Spectrum slot time duration

gies [2].

5.2 Motivation

A *fuzzy set* is a set with continued and indistinct boundary which establishes the approach of membership from 0 and 1 binary distribution in canonical set theory into a distribution that allows partial membership. The representation of membership in fuzzy sets thus becomes a metter of degree, which has a value between 0 and 1 unlike logic science where the output is either 0 or 1 only. In mathematical terms, a *fuzzy set* is characterized by a mapping from its universe of oration into the interval, [0,1]. This mapping is the *membership function* of the set [52].

5.3 Spectrum Decision Support Framework Overview

The SU configures its transmission parameters after learning from the radio environment to perform in CRN [53]. For efficient use of the spectrum, the spectrum decision framework is essential. Symbols used in this chapter have been described in the list of symbols given in the beginning of this thesis are listed here as well in Table. 5.1 for easy referring:

5.3.1 System Model

Consider a time slotted CRN with a single SU which intends to exploit vacant spectrum slot of given band (IEEE802.22, GSM, CDMA, LTE, Wi-Fi, Bluetooth, UWB [54], and 5G [55]) which can be configured using software. The spectrum bandwidth and channel models for above mentioned wireless standards in the given spectrum band are given in [22], [54], [55]. It is assumed that the channel state remains stationary during PU's transmission for a particular time slot. The channel models are characterized by Rician fading channel [53] as:

$$P_{r,\phi}(r,\phi) = \frac{r}{2\pi\sigma^2}e^{-\frac{r^2+A^2-2Acos\phi}{2\sigma^2}}, \tag{5.1}$$

where $A^2/2$ is the dominant component of the signal, r is the probability density of the signal, ϕ is the phase variable and σ^2 is the local mean scattered power at the envelope detector for the received signal. Let the SU carry out SS using any of SS techniques (including enabling algorithms and cooperative sensing [56]). Each licensed slot is considered to evolve independently with a varying usage pattern of PU over time, but is identical in terms of bandwidth, channel fading characteristics and other spectrum slot parameters [57]. Let the PU arrival rate for each spectrum slot be denoted as $\lambda_s \in$ [0,1], where s is the number of available targeted spectrum slot. Let *L* be the number of licensed spectrum slots. Large *L* increases chances of sensing large k, where k ($\leq$ *L*) is the total number of available spectrum slots.

Since the SS duration for SUs is quite small [58] the decision taken by SU through the proposed framework to occupy a particular slot has to be swift and accurate. Also, the PU activity time of spectrum slots at adjacent locations in the cell area has to be accurately known to ensure seamless transmission in SU's mobility. SU should vacate the slot in less than 2 seconds when the PU appears in this slot. The initial velocity of each SU and the acceleration of all 10 SUs in the proposed model have been considered as 25 m/s and ± 2

m/s^2 respectively. The velocity of SU in CRN changes every 10 seconds and its direction changes randomly every time. Thus a SU in the CRN requires QoS of its communication maintained while it is mobile.

5.3.2 Spectrum Selection Process

A scheme for spectrum decision by a SU in CRN is developed based on the system model described above. Any SU in CRN occupying the spectrum slot in the absence of PU is considered a PU for waiting SUs in CRN. As a result, the task of coordination for sharing spectrum slot by multiple SUs in CRN is not required in the proposed decision framework.

Figure 5.1 shows the layout scenario of SU to take decision to occupy the targeted spectrum slot and the time slot when the spectrum slot is sensed vacant. Assume that this layout of CRN is an area of 500m x 500m of a cell. The unexpected arrival of PU to the spectrum slot is also shown in Figure 5.1. The SU decides to occupy the spectrum slot in the occurrence of a sequence of events performed iteratively as; (1) SU appears in the network, (2) SU searches for the vacant spectrum slot through SS, (3) SU decides to occupy the vacant spectrum slot, (4) SU occupies the vacant spectrum slot ensuring the maintenance of its QoS requirements, (5) on appearance of PU in the occupied spectrum slot, SU terminates its transmission and vacates the spectrum slot immediately, (6) steps (3) to (5) are repeated until a suitable spectrum slot is found vacant.

By managing these events effectively, a scheme leading to spectrum decision framework by the SU in CRN is evolved by considering the targeted spectrum slot conditions. The framework manager determines whether the SU should transmit or not under these spectrum slot conditions. The spectrum decision allows SU to occupy a specific spectrum slot in the network. The decision is taken after two sequential tasks; SS and QoS monitoring of the spectrum slot. This implies, that before occupying the spectrum slot by SU in the specific time slot, it has to be vacant at the time SU intends to communicate, it has to be sensed idle by CRN SS mechanism. SS would reflect activity time, which is the temporal activity of the spectrum slot, to characterize its access by the SUs in CRN. The primary value of the activity time is the probabilities of T_o and T_v [59], given as under:

$$P_{T_o} = \frac{\alpha}{\alpha + \beta}, \tag{5.2}$$

$$P_{T_v} = \frac{\beta}{\alpha + \beta}, \tag{5.3}$$

To maintain the QoS of SU's transmission and maximum capacity of CRN, the SU selects the spectrum slot for which the spectrum slot QoS is optimized as follows:

$$Maximize : \sum_{s} \frac{\rho_a}{\lambda_s} \tau_s, \tag{5.4}$$

$$subject\ to : \sum_{s} \tau_s = N, \tag{5.5}$$

where τ_s is the spectrum decision parameter within the range [0,1], obtained after fuzzifying the proposed decision parameters.

5.3.3 PU Activity Model

The PU activity is modeled within the particular spectrum slot as a Poisson process denoted as K(t) with λ_s as the intensity of the process or in other words, arrival rate. Let T_k be the arrival time of PU at k^{th} arrival, for $k = 1, 2, 3, \ldots$. The inter arrival time Y_k is given as follows:

$$Y_k = T_{k+1} - T_k \tag{5.6}$$

where Y_k is independent and identically exponentially distributed and T_k follows Erlang distribution. When PU is absent, the activity time of the targeted spectrum slot is idle.

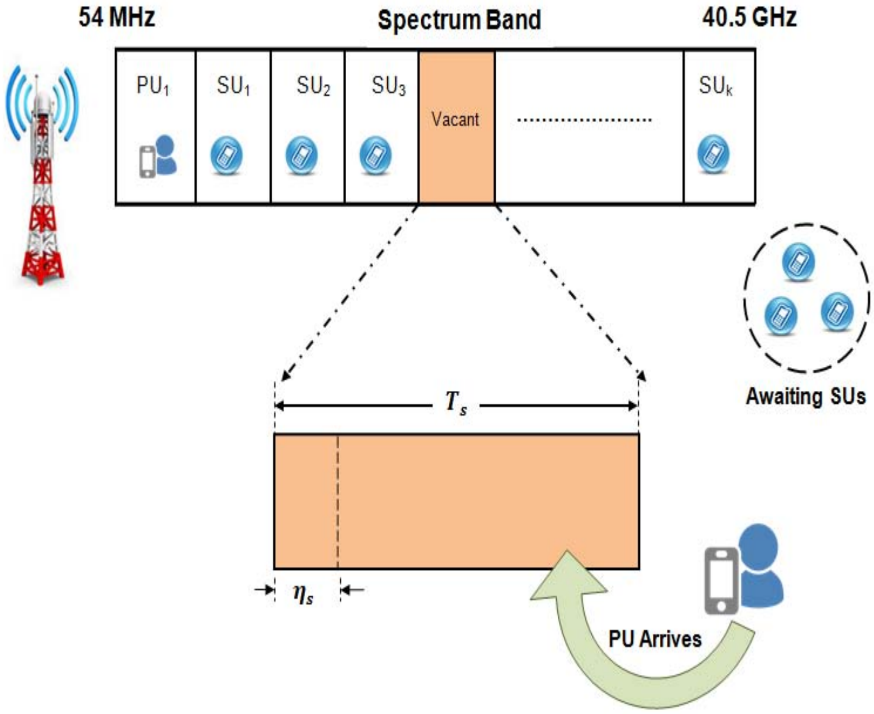


Figure 5.1: PU activity model and SU occupancy in the given spectrum

Similarly, when PU is present or has arrived unexpectedly, the activity time of spectrum slot signifies for SU, not to occupy. The primary value for PU's occupancy in the wireless spectrum is 16.83% to 43.28% [60].

5.4 Proposed Spectrum Decision Framework

CR technology is characterized by PU and SUs, coordination amongst SUs to use the licensed bands when PUs are not using spectrum slots in given spectrum band. A fuzzy inference-based decision making strategy is used for spectrum decision framework. The fuzzy decision-making scheme appears in [61] for SS technique (not for spectrum decision framework). The use of fuzzy logic for the availability of spectrum is suitable as it offers conciliation focusing output as decision with varying requirements. It offers quick processing at the output, a decision for SU whether to occupy or reject the spectrum slot. The membership functions (MFs) for the parameters used as input to fuzzy inference engine (FIE) are defined.

The three input parameters are used for the spectrum decision. These parameters are stated as follows:

- *Input 1:* The time duration (activity time) in which PU is likely present in the targeted spectrum slot. This will also give the detection of PU in the targeted spectrum slot.
- *Input 2:* The possession.
- *Input 3:* The spectrum slot QoS of the spectrum slot.

These parameters are fuzzified from measureable values (greater than the set threshold for each paramter) to fuzzy linguistic variables by using input MFs. These MFs values are then processed into a rulebase by FIE using a set of 18 predefined IF-THEN rules. The output after defuzzification process is interpreted as the decision for SU whether to occupy the spectrum slot or not. To represent the various preference structures of a decision framework, various MFs like pure linear, piecewise linear, tangent, triangular, convex, concave, quasi-concave, trapezoidal, exponential, dynamics, V-shaped, U-shaped, S-shaped, and reverse S-shaped, etc. have been employed in existing works [62]. In the proposed framework, triangular and S- shaped MFs have been used due to the reason that triangular MFs give values from 0 to 1 along a slope with linear increase/decrease and there is no noise in triangular MFs. Moreover, triangular functions are good at the initial values [63]. Similarly, the S-shaped is a type of polynomial MFs which provides many values of MF against one input as well as one value of MF at many values of input [62]. Further, the shapes of the MFs are tuned as such to optimize the proposed fuzzy logic based spectrum decision framework.

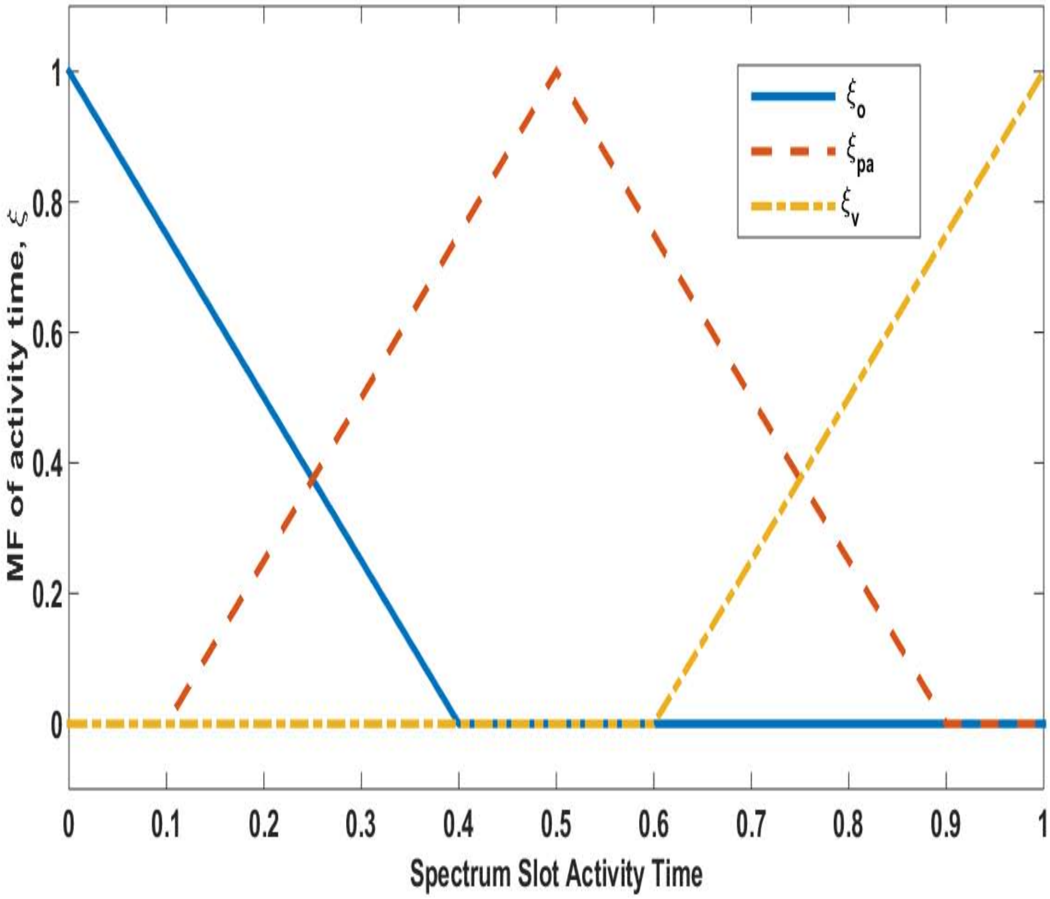


Figure 5.2: Three MFs for activity time of spectrum slot.

5.4.1 FIE

Let the MFs for the activity time of the spectrum slot occupied by PU, partially available and vacant be defined as ξ_o, ξ_{pa} and ξ_v respectively and are given as:

$$\xi_o(i) = -2.5|i| + 1 \tag{5.7}$$

$$\xi_{pa}(i) = \begin{cases} 0 : & 0 \leq i \leq 1 \\ 2.5[0.4 - |i - 0.5|]; & 1 \leq i \leq 0.9 \\ 0; & 0.9 < i \leq 1 \end{cases} \tag{5.8}$$

$$\xi_v(i) = \begin{cases} 0; & 0 \leq i \leq 0.6 \\ 2.5|i| - 1.5; & 0.6 < i \leq 1 \end{cases} \tag{5.9}$$

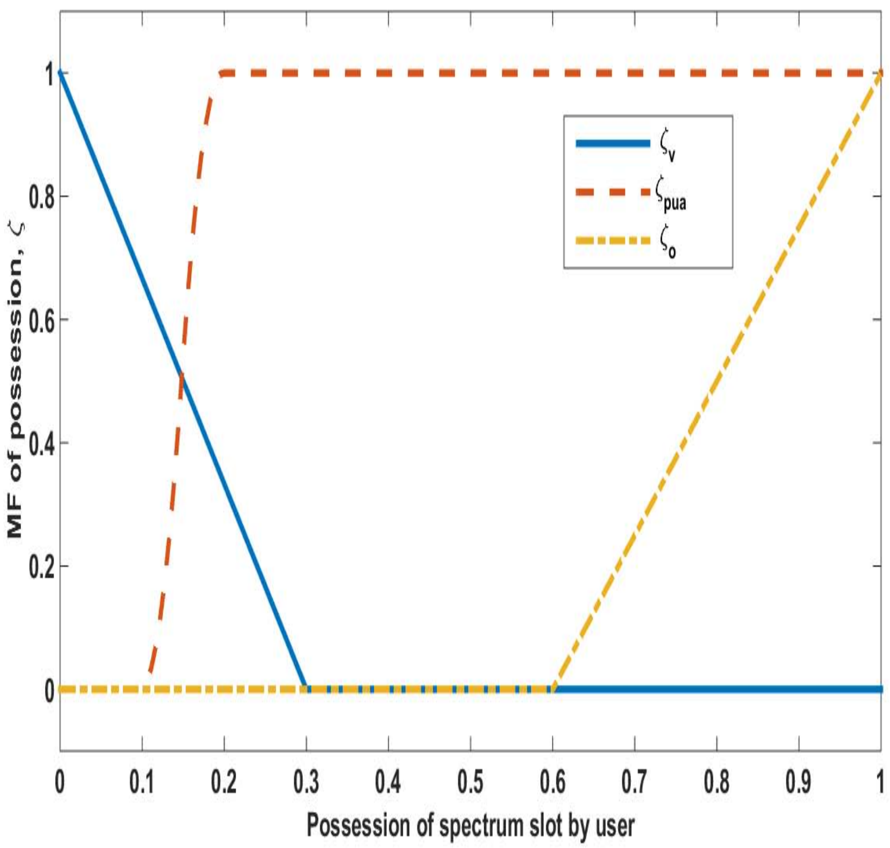


Figure 5.3: Three MFs for possession of spectrum slot.

The activity time and MFs inputs are given in Table. 5.2 and shown in Figure 5.2.

Let the MFs for the possession of spectrum slot by PU i.e, either vacant or PU arrives unexpectedly or occupied be defined as $\zeta_v(i)$, $\zeta_{pua}(i)$ and $\zeta_o(i)$ respectively and are given as:

$$\zeta_v(i) = -3.33|i| + 1 \tag{5.10}$$

$$\zeta_{pua}(i,[0.1,0.3]) = \begin{cases} 0; & i \leq 0.1 \\ \frac{(i-0.1)^2}{0.04}; & 0.1 \leq i \leq 0.2 \\ 1 - 2\frac{(i-0.1)^2}{0.04}; & 0.2 \leq i \leq 0.3 \\ 1; & i \geq 0.3 \end{cases} \tag{5.11}$$

$$\zeta_o(i) = 2.5|i| - 1.5 \tag{5.12}$$

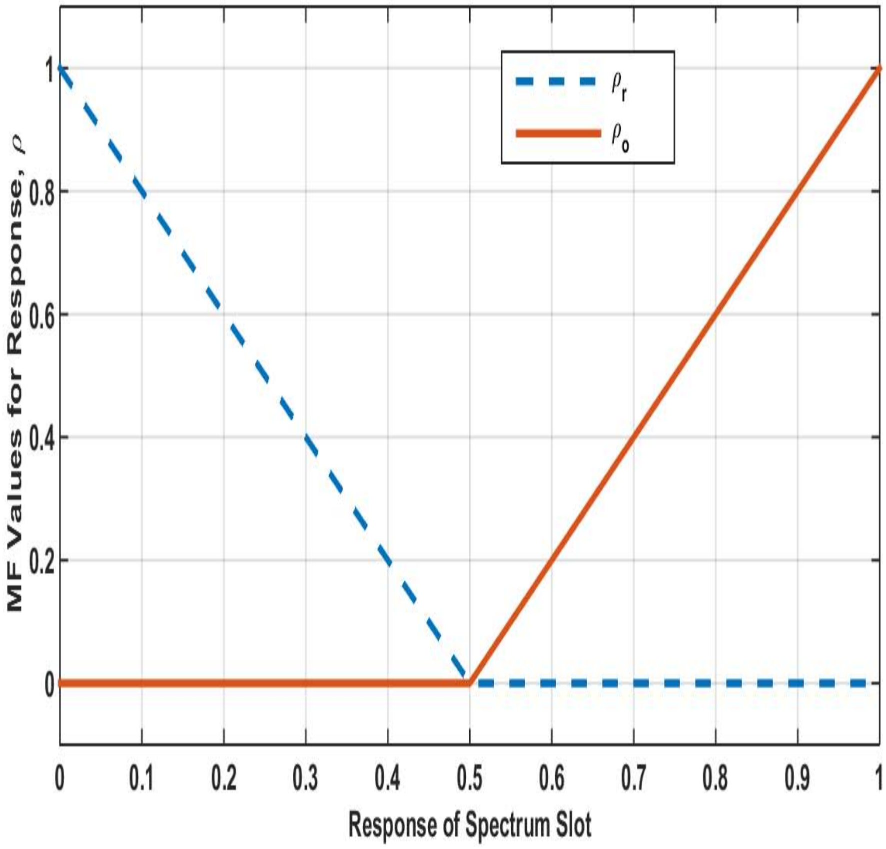


Figure 5.4: Two MFs for spectrum slot QoS.

The MFs of possession and the corresponding fuzzified inputs are given in Table. 5.2 and shown in Figure 5.3.

Let the MFs for the spectrum slot spectrum slot QoS for accepting and rejecting the spectrum slot by SU are defined as accept, ρ_a and reject, ρ_r respectively and are given as:

$$\rho_a(i) = 2|i| - 1 \tag{5.13}$$

$$\rho_r(i) = -2|i| + 1 \tag{5.14}$$

The input values of this parameter and the corresponding fuzzified inputs are given in Table. 5.2 and the MFs are shown in Figure 5.4.

Let the defuzzified output of the MFs be represented by τ and the output MFs as decisions 'not available' for the SU and SU to 'occupy' are defined as τ_{na} and τ_v respectively and are

Table 5.2: Parameters of spectrum slot

Parameter	**Range of i**	**MF Inputs**	**MF Values**
Activity time	$0 \leq i \leq 0.4$	Slot is occupied	$0 \leq \xi_o \leq 1$
	$0.1 \leq i \leq 0.9$	PU arrives in the slot	$0 \leq \xi_{pa} \leq 1$
	$0.6 \leq i \leq 1$	Slot is vacant	$0 \leq \xi_v \leq 1$
Possession	$0 \leq i \leq 0.3$	Slot is vacant	$0 \leq \zeta_v \leq 1$
	$0.1 \leq i \leq 0.3$	Arrival of PU in the slot	$0 \leq \zeta_{pua} \leq 1$
	$0.3 \leq i \leq 1$	Slot is occupied	$0 \leq \zeta_o \leq 1$
Spectrum slot QoS	$0 \leq i \leq 0.5$	Not available	$0 \leq \rho_a \leq 1$
	$0.5 \leq i \leq 1$	Occupy	$0 \leq \rho_r \leq 1$

Table 5.3: Spectrum decision

Output	**Range of i**	**MF Outputs**	**MF values**
Spectrum decision	$0 \leq i \leq 0.5$	Spectrum slot is not available	$0 \leq \tau_{na} \leq 1$
	$0.5 \leq i \leq 1$	Spectrum slot is vacant and SU to occupy	$0 \leq \tau_v \leq 1$

given as:

$$\tau_{na}(i) = -2|i| - 1 \tag{5.15}$$

$$\tau_v(i) = 2|i| - 1 \tag{5.16}$$

The output values of this parameter and the corresponding fuzzified outputs are given in Table. 5.3 and the MFs are shown in Figure 5.5

The defuzzified output, decision represented as $\tau_s(i)$ for SU about s is given as

$$\tau_s(i) = \min_{\{c,d,e\}} [\xi_c(i), \zeta_d(i), \rho_e(i)] \tag{5.17}$$

where, $\xi_c(i) \in \{\xi_o(i),\ \xi_{pa}(i),\ \xi_v(i)\}$, $\zeta_d(i) \in \{\zeta_v(i),\ \zeta_{pua}(i),\ \zeta_v(i)\}$ and $\rho_e(i) \in \{\rho_a(i),\ \rho_r(i)\}$.

Accordingly, the rules mentioned in Table. 5.4 lead to the decision for SU to occupy the best spectrum slot.

Table 5.4: Rulebase for spectrum decision framework

Rule	**Inputs**	**Output**
1	IF (activity time is occupied) & (possession is vacant) & (spectrum slot QoS is reject)	THEN spectrum slot is not available
2	IF (activity time is occupied) & (possession is vacant) & (spectrum slot QoS is accept)	THEN spectrum slot is not available
3	IF (activity time is occupied) & (possession is PU arrives) & (spectrum slot QoS is reject)	THEN spectrum slot is not available
4	IF (activity time is occupied) & (possession is PU arrives) & (spectrum slot QoS is accept)	THEN spectrum slot is not available
5	IF (activity time is occupied) & (possession is occupied) & (spectrum slot QoS is reject)	THEN spectrum slot is not available
6	IF (activity time is occupied) & (possession is occupied)& (spectrum slot QoS is accept)	THEN spectrum slot is not available
7	IF (activity time is partially available) & (possession is vacant) & (spectrum slot QoS is reject)	THEN spectrum slot is not available
8	IF (activity time is partially available) & (possession is vacant) & (spectrum slot QoS is accept)	THEN SU to occupy the spectrum slot
9	IF (activity time is partially available) & (possession is PU arrives) & (spectrum slot QoS is reject)	THEN spectrum slot is not available
10	IF (activity time is partially available) & (possession is PU arrives) & (spectrum slot QoS is accept)	THEN spectrum slot is not available
11	IF (activity time is partially available) & (possession is occupied) & (spectrum slot QoS is reject)	THEN spectrum slot is not available
12	IF (activity time is partially available) & (possession is occupied) & (spectrum slot QoS is accept)	THEN spectrum slot is not available
13	IF (activity time is vacant) & (possession is vacant) & (spectrum slot QoS is reject)	THEN spectrum slot is not available
14	IF (activity time is vacant) & (possession is vacant) & (spectrum slot QoS is accept)	THEN SU to occupy the spectrum slot
15	IF (activity time is vacant) & (possession is PU arrives) & (spectrum slot QoS is reject)	THEN spectrum slot is not available
16	IF (activity time is vacant) & (possession is PU arrives) & (spectrum slot QoS is accept)	THEN spectrum slot is not available
17	IF (activity time is vacant) & (possession is occupied) & (spectrum slot QoS is reject)	THEN spectrum slot is not available
18	IF (activity time is vacant) & (possession is occupied) & (spectrum slot QoS is accept)	THEN spectrum slot is not available

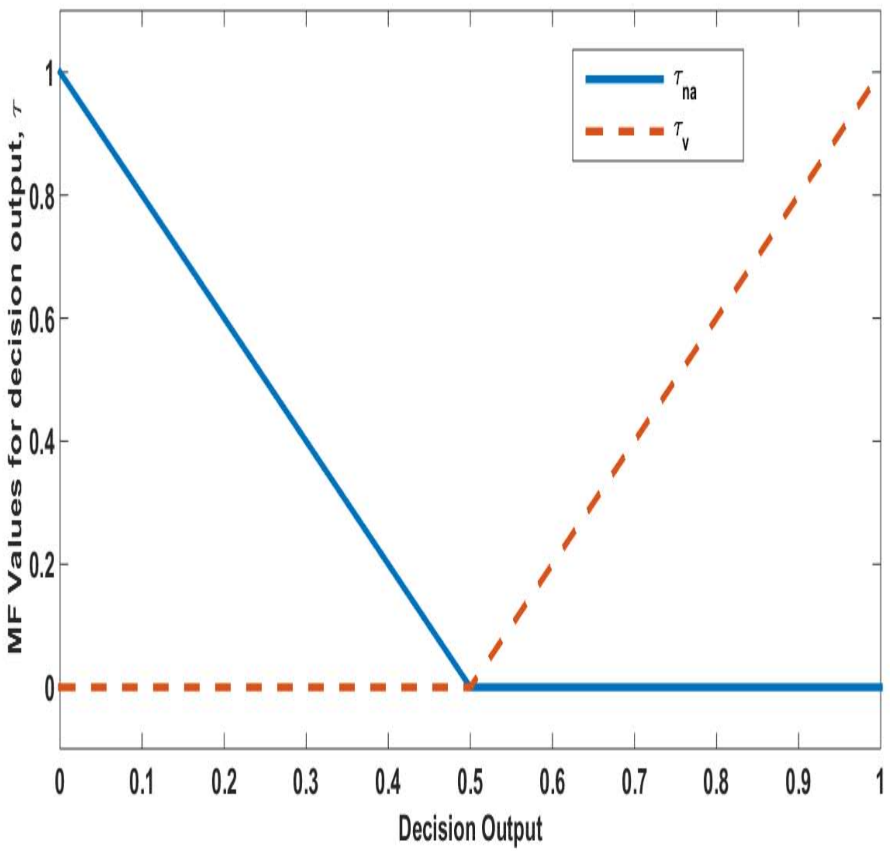


Figure 5.5: Two MFs for decision output of spectrum slot.

5.4.2 Performance Evaluation

The proposed technique for SDSF has been evaluated for its performance through two parameters. First, through the throughput achieved here and its comparison with the existing techniques given in the literature, and secondly, with receiver operating characteristics. Both the parameters are given in the following subsections.

5.4.2.1 Recompense Function for Validation

Whenever SU carries out its transmission while using a spectrum slot after sensing it idle, a certain amount of SU throughput as a recompense of efforts of spectrum management is obtained. Obviously, if the slot is sensed occupied by the PU then SU will not get any recompense. The SU throughput over a given slot depends on number of factors, like, the transmission duration, the spectrum slot QoS etc. For simplicity, here it is assumed that the spectrum slot QoS of all the idle spectrum slots is same and is denoted by χ_0, when the spectrum slot can be used during the complete time slot. Therefore, the recompense function on a given spectrum slot k is given as follows:

$$\mathrm{R_k} = \begin{cases} \frac{\Gamma_\mathrm{s}-\eta_\mathrm{s}}{\Gamma_\mathrm{s}}.\chi_0.\tau_s(i) & if \text{ decision } = \text{ occupy} \\ 0 & if \text{ decision } = \text{ not available,} \end{cases} \tag{5.18}$$

where Γ_s is spectrum slot time duration and η_s is the sensing duration. We configured the CR network with 10 licensed channels and the traffic over these channels was generated randomly with Gaussian distribution. The spectrum slot time duration was set to 1 second and sensing time was set as 0.1 second. We configured the response of the spectrum slot $\chi_0 = 1$ Mbps.

5.4.2.2 Analysis for False Alarm and Miss Detection.

In finding the spectrum slot idle through activity time of PU, there can occur two types of errors; false alarm and miss detection. False alarm is due to sensing an idle spectrum slot as occupied and miss detection is due to assuming an occupied slot as idle. The performance of proposed decision framework is also assessed by means of Receiver Operating Characteristics (ROC), which is represented as a curve between probability of miss detection and probability of false alarm. These two are the inter-related parameters in the proposed decision process. To have accurate data of PU(s) activity time and occupancy status, there should be low values of both the probabilities, which cannot be achieved as both are inter related to each other. Therefore, an optimal set of range must be obtained. Transmission at different values of SNR give different ROC curves for the PU's activity time and its occupancy in the spectrum slot. The lower the probability of miss detection (or higher the probability of detection) for a given probability of false alarm, the more reliable and accurate the detection would be, which is desirable for taking the decision by the SU(s) to occupy that particular spectrum slot in CRN. Energy Detection (ED) in SS offers a fast and reliable detection method for SUs in CRN. The detection performance of ED depends on effects of multipath fading [64]. Accordingly, the proposed decision framework has been validated by ROC curves compared with those of SS through ED method at various SNR values. There are closed form expressions for the ROC of ED in Additive White Gaussian Noise (AWGN) and Rayleigh fading channels, where PU's signal was detected through its transmission power [65].

5.5 Results and Discussion

The fuzzified supported spectrum decision framework with activity time, possession and spectrum slot QoS of spectrum slot as the MFs is used in the simulation. Out of given spectrum band (IEEE802.22, GSM, CDMA, LTE, Wi-Fi, Bluetooth, UWB and 5G), 10 spectrum slots with Guassian distribution of GSM band are considered for simulation purpose only. Some parameter values include η_s=1 second, Γ_s=0.1 second and $\chi_0 = 1$ Mbps. 100 iterations have been performed to evaluate the proposed spectrum decision framework. The rician fading channel in 3 GPP channel model as given by Equation (5.1) is used. Core i7 processor with 2.2 GHz speed and 8 GB RAM is used for the simulation.

The proposed spectrum decision technique is compared with three channel access frameworks presented in [31]. These frameworks include Markov Chain Based Random Assignment (MCRA) 2nd-choice channels, Markov Chain Based Greedy Assignment (MCGA) 2nd-choice channels and Random Channel Assignment with Single Channel (RASC) sensing.

SU can sense two channels with varying degree of priority using MCRA and MCGA techniques. Single SU makes use of the 1st-choice channels and multiple SUs share the 2ndchoice channels. Furthermore, the expected total SU throughput is maximized by assigning 2nd-choice channels by using MCGA algorithm in a two step process. The first step is the assignment of unique 1st-choice channels to the SUs and subsequent arrangement of the SU in ascending order of probability of assessing the 2nd-choice channels. In case the number of SUs is more than the number of available channels, each SU in the CRN is allocated to the 2nd-choice channels. The impact of spectrum slot conditions is not taken into consideration in this two step technique.

RASC randomly allocates a single channel to be sensed by SU. When average PU occupancy increases, the expected total throughput decreases largely as the higher PU channel occupancy indicates fewer spectrum opportunities exploited by SUs. Moreover, when the PU channel occupancy is very low, this technique can only obtain a small improvement in spectrum opportunities. This is due to the lower probability of SUs accessing the 2nd-choice channels. When the PU channel occupancy is very high, not much improvement in spectrum opportunities can be obtained since the 2nd-choice channels are expected to be busy, although SUs have a higher chance of sensing the 2nd choice channels. In the other range of PU channel occupancy, RASC algorithm can achieve a very stable performance improvement.

The MCGA scheme has shown lowered values of throughput under SS errors scenario. MCRA and MCGA achieve better performance as compared to RASC because a SU explores more slots per time slot. However, the work has not catered for the impact of channel conditions. The varying conditions of a spectrum slot effect the user’s transmission. Hence, the factor of spectrum slot QoS as an input in the proposed framework mitigates these effects of spectrum slot as well.

Figure 5.6 shows the achieved SU throughput with the proposed decision scheme compared with the existing spectrum access techniques [34]. The maximum throughput for

SU is attained with respect to the lowest probability of PU's presence in the spectrum slot. With the increase in probability of PU's arrival, the throughput is decreased. The proposed scheme offers improved throughput against the compared methods. The improvement in SU's throughput is achieved due to the reason that SU can carry out its transmission for longer duration whenever it occupies the spectrum slot under the conditions given in the proposed framework in the single time slot. The higher values of throughput achieved signify that the SU has explored more spectrum slots in a sensing time slot than the existing works while being mobile in the network.Similarly, the achieved throughput allows all SUs in the CRN to pass typical signal handoff data while the SU is in move to carryout seamless inter-cell handoffs in GSM applications. The SU always has the spectrum opportunities to swiftly switch over to another suitable spectrum slot if a PU arrives in the currently occupied spectrum slot. The processing time of the proposed scheme was 0.18 seconds, whereas the allowable switching time in the existing CR based standard (IEEE802.22) is around 2 seconds [24].

The achieved throughput allow all SUs in the CRN to pass typical signal handoff data while the SU is in move thereby validating the proposed spectrum framework for SU's mobility as well.

SS is carried out to find whether the PU is present or otherwise in the targeted spectrum slot. On sensing the slot idle, SU(s)occupy the targeted slot. This decision to occupy the slot, enables SU to carry out its transmission with good values of SNR and to achieve higher throughput. Moreover, the reduced probabilities of miss detection and false alarm for various values of SNR shown in Figure 5.7 affirm that it has accurately detected the activity time and spectrum slot occupancy of PU. These ROC curves show that the proposed framework outperforms ED SS method.

The parameter used here to evaluate the GSM spectrum usage is termed as Decision Struc-

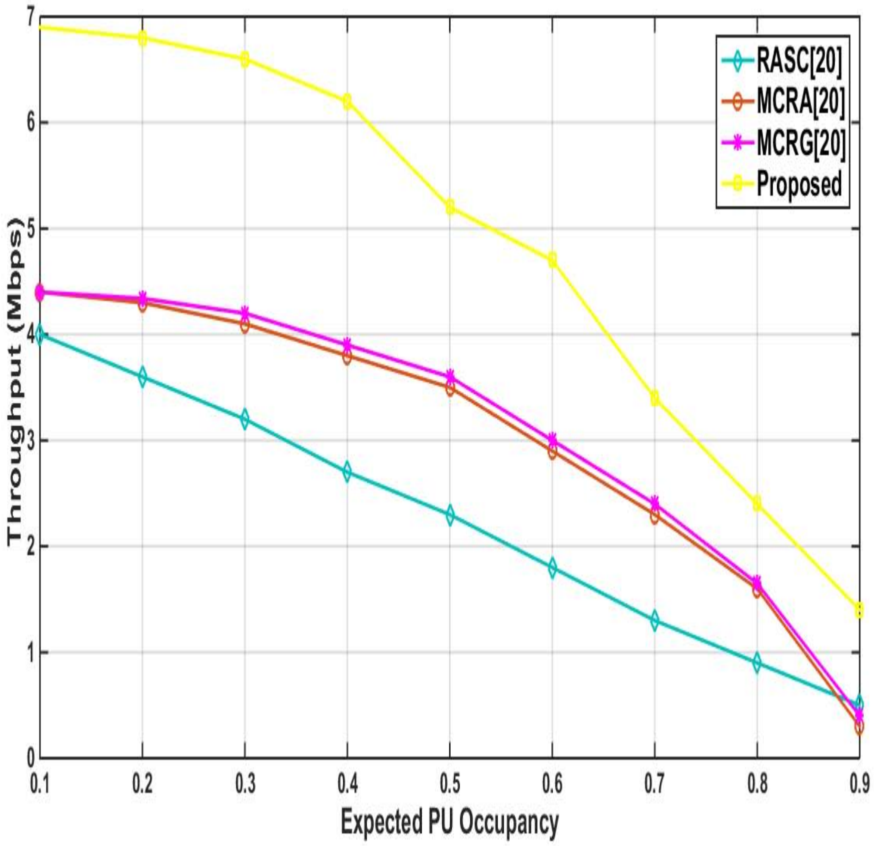


Figure 5.6: SU’s throughput.

tural Function (DSF),

$$DSF = \frac{m}{k} \tag{5.19}$$

where m is the number of optimally used spectrum slots by the SU. The value of DSF ranges between [0,1], where ’1’ reflects that SU has successfully used the spectrum slot.

The graph for DSF over 15 iterations is shown in Figure 5.8. It can be observed that the proposed spectrum decision framework allows SUs to successfully occupy the available spectrum slots without causing any disruption.

Since the proposed decision framework functions on combined effect of three suggested parameters and not on any one of them alone, hence, the spectrum slot occupied by the SU

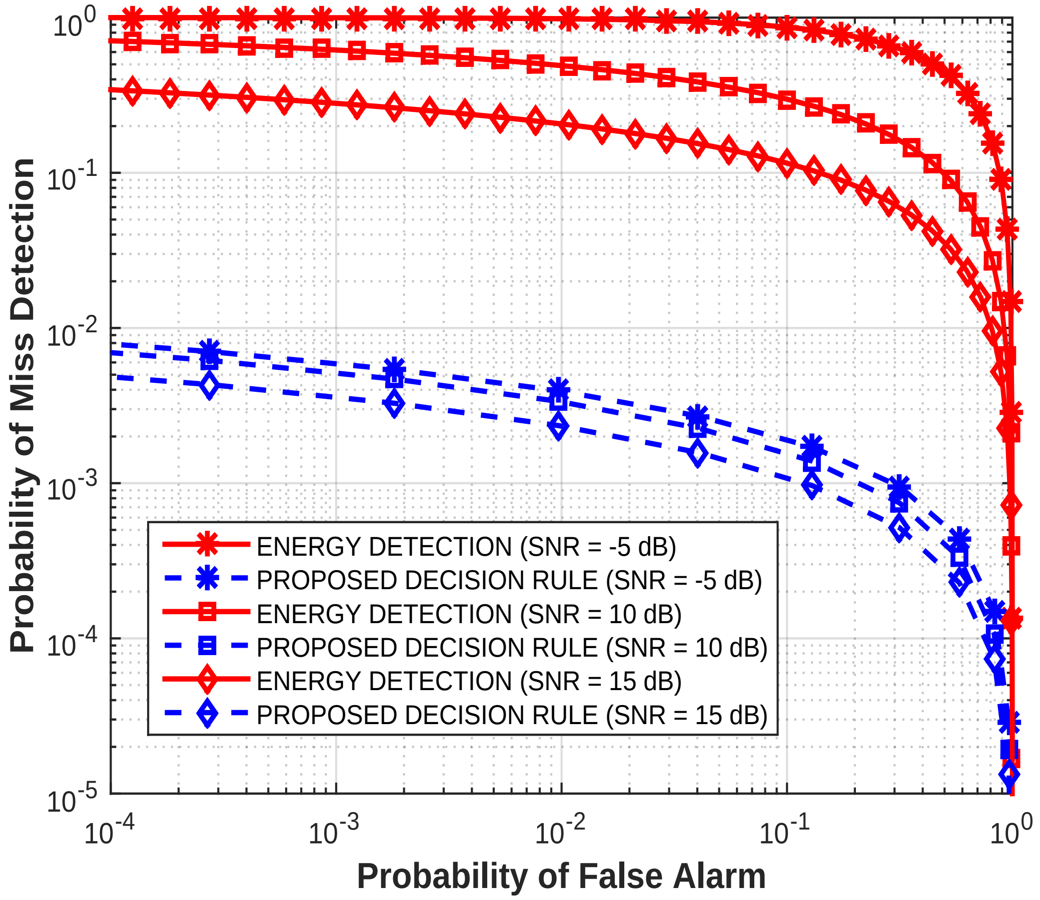


Figure 5.7: ROC Curves for SNR values of 5dbs, 10dbs and 15dbs.

is not solely based on SS results. Therefore, the sensing errors do not cause any degradation in SU's QoS requirements. In addition to SS, the factor of QoS of spectrum slot sensed idle, makes the decision framework affirm. It is fair to suggest that decision of assessing and using the spectrum slot reached through proposed spectrum framework is robust and without any possibility that SU's transmission is suspended due to degradation in its QoS requirements.

5.6 Summary

Fuzzy logic has been used as an application to CRN which is otherwise difficult to model. The developed SDSF first finds the spectrum slot activity time basing on PU's activity in the slot. On finding the spectrum idle and when the spectrum slot is sensed idle, the SU considers to occupy the targeted slot. Further, it is investigated that the spectrum slot QoS ensures that SU carries out its transmission as per its application. The SU only occupies and

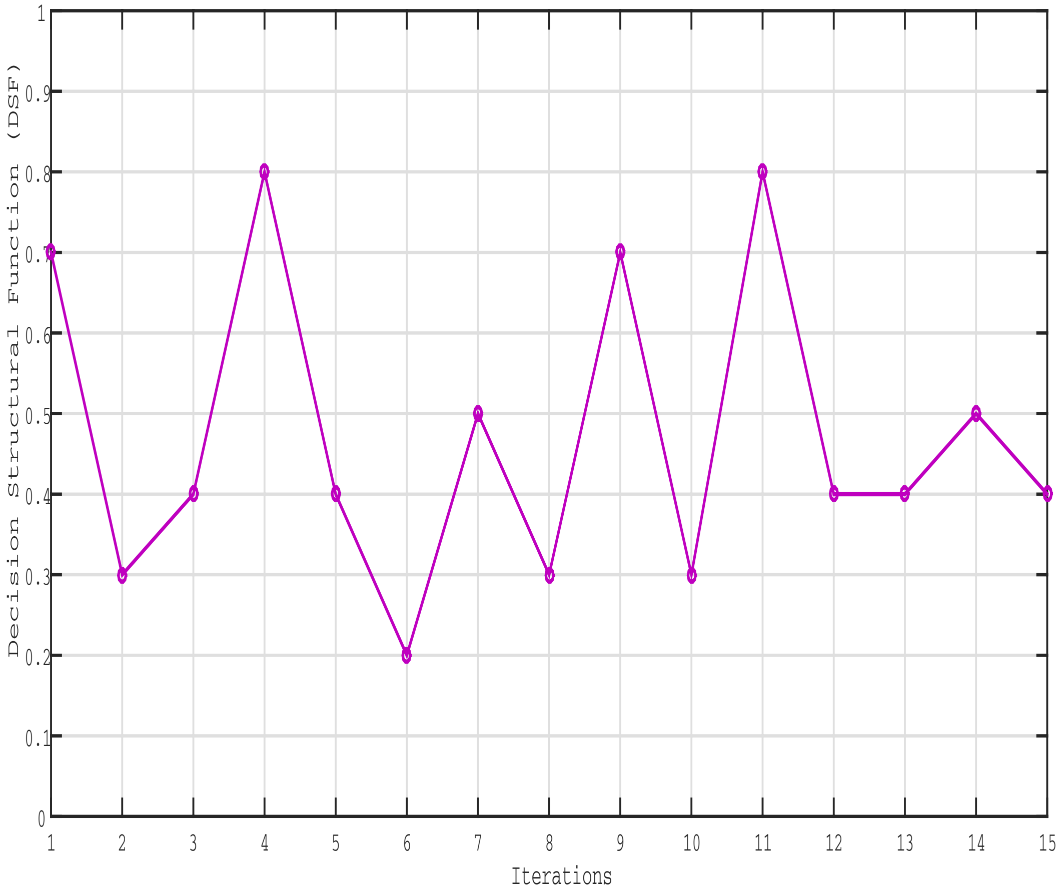


Figure 5.8: DSF for 15 iterations.

starts its transmission on validation of spectrum slot vacant and capable for transmission. This enables SU to transmit for longer duration. The proposed SDSF also works as multi-user spectrum access model as the SUs already occupying the licensed slots referred to as virtual PUs for the SU taking decision to access the spectrum slot. The study of impact of spectrum slot QoS on SU's communication adds to the novelty of work.

Chapter 6

Spectrum Decision Framework For Cognitive Radio Networks Enabling Internet of Things In 5G and Beyond

Internet of things (IoT) is the term used for universally intelligent things which are electronically connected with each through wireless connections and technologies in order to interact with each other through unique IP addressing schemes based on standard communication protocols [66]. IoT connectivity needs high throughput values. The SDSF proposed in chapter 5 offers higher system throughput. The Fuzzy logic scheme proposed in previous chapter has been applied for IoT in 5G network in this chapter. This work described here has been accepted as a chapter in the book*Cognitive Radio in 4G/5G Wireless Communication Systems* [3] (in production).

6.1 Introduction

Numerous aiding wireless communication technologies including ultra-densification, millimetre wave communications, massive MIMO, FD technology, and DSA are being investigated in industrial and academic sectors in order to stimulate the implementation of the fifth generation (5G) of wireless communications [67]. In this regard, time has come to consider how CR principles, which have been the focus of research in wireless communications for last two decades, can be incorporated in 5G wireless communications [68]. As the existing LTE and LTE-A (beyond 4G) systems use throughput as the main reward parameter and target it as a performance indicator, the proposed research offers an application for 5G in general and IoT in 5G/B5G in particular. Emerging cognitive radio communications and networking technologies potentially provide a promising solution to the spectrum under utilization problem in wireless access, improving the interoperability and coexistence among different wireless/mobile communications systems and making the future generation radio devices/systems autonomous and self reconfigurable. With swift shift to smart communication technologies and infrastructure, the Internet of Things (IoT) has emerged as a modern challenge in international Telecommunication industry and wireless applications. SUs access RF spectrum bands in hetrogeneous manners in CRN and IoT supported smart area consists of heterogeneous devices, which are mobile as well as static in nature [69]. The conventional communication networks with various connected devices e.g., routers, BTSs, MSCs, intermediate and end devices like smart phones are designed with wireless application-specific hardware for specific applications. The reconfiguration of radio conditions capability of SUs in CRN provides flexibility to the existing networks to shift to IoT paradigm in the 5th Generation and beyond ($5G/B5G$). As a case study, The internet application of CR based on the IEEE 802.22 standard in the Smart Grid (SG) wide area networks has been investigated in [70] in which the opportunistic access of TV spectrum bands for the power grid makes a case of IoT. In this chapter, a CR based IoT technology for realization of $5G/B5G$ has been proposed. A novel spectrum decision framework has been proposed which enables SUs (IoT devices, here) to smartly execute DSA for all wireless applications. The proposed decision framework is based on the combined effects of radio configuration (spectrum slot and channel transmission formats like data rates, throughput, IP settings and modulation characteristics) and protection from interference in which IoT-Us maintained different QoS requirements including data rate, latency, reliability and robustness by effectively accessing the vacant spectrum slots. The proposed frameowrk has been evaluated using PSD and probabilty of false alarm curves at various values of SNR which signify that the proposed framework can offer a solution in CR based IoT communication in $5G/B5G$ networks in future wireless systems.Long Term Evolution Unlicensed (LTE-U), also known as Licensed Assisted Access (LAA), is a promising enhancement that enables LTE to operate in unlicensed bands, with a clear focus on the 5 GHz band [71]. Existing mobile communications networks have efficaciously connected a gigantic bulk of worldwide populace [72]. Now the focus of cellular technologies and mobile communications is drifting towards ubiquitous connectivity for smart phones and laptops and other telecommunication devices, thereby creating the IoT [73]. Services in 5G/B5G require spectrum tractability to support devices in operating across the wide range of WRFS. Spectrum decision is an important module in CR which enables mobile data traffic users to optimally utilize Radio Frequency(RF) spectrum for wireless applications, which is otherwise under utilized. CR, as was perceived by Motila just under two decades ago, is a wide ranging paradigm in wireless technology which has emerged as a smart solution to RF spectrum scarcity. CR suggests telecommunication devices that are fully conversant with radio environment around, incitement from other users and various internal and external parameters like waveform, bandwidth, frequency and adoption to channel modeling etc [74]. The ability of CR to orient, plan and decicide to use RF spectrum band covering all wireless applications merits its use for Internet of Things (IoT) which aims at establishing communication among physical objects by empowering them with the ability to sense, transmit with respective receivers and process. IoT enables real time world objects to exchange information, connect everything for everyone all the time. The devout method to spectrum management in wireless technologies is very inflexible in the sense that each wireless operator is assigned an exclusive license to operate in a certain frequency band, i.e, fixed spectrum assignment policy. The licensed users use their spectrum for transmission as per their requirement but the usage remains for a very short period of time. The decision of accessing the vacant spectrum slots would enable the SU to be connected Anytime, Anyplace, with Anything and Anyone using Any network and Any service (A6 connections), making an IoT environment.

It is, therefore, the SU is renamed in this work as IoT-User (IoT-U). The premier work in describing the way forward for $5G$, by Beccardi *et al.* [75]. The work mentions that the design of the $5G$ mobile networks will be dictated by five innovative technological directions: (1) millimeter and micro waves (2) end-device centric; (3) massive MIMO; (4) smarter devices; and the last but not the least (5) IoT paradigm.

Spectrum Decision in CR technology is the foremost important feature in its realization for IoT in future wireless communications i.e., 5th Generation and beyond 5th Generation Networks (5G/B5G). Related work carried out in spectrum decision for CR has evolved significantly in the recent 5 years. Now this feature of CR is required to be converged to IoT for implementation of 5G/B5G and is the focus of research presented in this chapter.

A CR user(CRU), alternatively an IoT-U in the CRN should be able to decide to occupy or switch to the best available channel without affecting degradation to its own communication as well as without impairing the PU's activity. This whole procedure is termed as *spectrum decision framework* for IoT-U. The main characteristics of IoT-Us is their capability of continuously carrying out SS at the back end and maintaining a data of suitable spectrum slots for IoT-Us to occupy whenever PU arrives in the spectrum slot they were transmitting. This process is termed here as contonuous back end spectrum sensing process (CBSP) which would enable CRN to ensure A6 connectivity.

6.2 Related Work

Recently, researchers have proposed CRN for implementation of IoT in 5G networks [76]. However, premier work in spectrum decision in CRN, by Akyildiz *et al.* took into account the spectrum switching delay. A new metric was proposed for finding the capacity of a SU, called the expected normalized capacity of a SU in a particular channel. Since the approach assumed a uniform switching delay, therefore may not work for non-uniform switching delays in CRN. Moreover this framework was restricted to best effort and real time applications only and may not be suitable for IoT applications. $5G$ mobile networks are expected to comply some basic requirements for IoT systems, to include, (1) maximum data rate; (2) low end-to-end latency and (3) support of huge IoT nodes network. According to LTE-U, the unlicensed spectrum can be used by mobile devices, which should significantly increase the capability of $5G$ to accommodate a large IoT nodes based infrastructure in CRN. A resource management technique based on CRN is proposed for heterogeneous networks in [7].

It is anticipated that by 2021, there will be monthly global mobile data traffic will be 49 exabytes, annual traffic will exceed half a zettabyte, mobile will represent $20\ \%$ of total IP traffic, the number of mobile-connected devices per capita will reach 1.5, the average global mobile connection speed will surpass 20 Mbps, the total number of smartphones and phablets will be over 50 percent of global devices and connections, smartphones will surpass four-fifths of mobile data traffic ($86\ \%$), $4G$ connections will have the highest share ($53\ \%$) of total mobile connections, $4G$ traffic will be more than three-quarters of the total mobile traffic, more traffic was offloaded from cellular networks (on to Wi-Fi) than remained on cellular networks in 2016, over three-fourths ($78\ \%$) of the worlds mobile data traffic will be video [4]. The evolution to 5G networks in chronological order is given in Table. 6.1.

6.3 An overview of CR-based IoT Systems

The Internet of Things (IoT) envisions thousands of constrained devices with sensing, actuating, processing, and communication capabilities able to observe the world with an unprecedented resolution. According to Cisco, more than 50 billion devices are expected to be connected to the internet by 2020 and 20 $\%$ of which are from the industry sector. These

Table 6.1: Chronological evolution to 5G

Wireless Technology/ Generation	Applications	Standards	Data Rates	Mobility Offered	Time Span
1G (Analog)	1st Generation of the mobile telecommunication technology standardized by the voice service	NMT,AMPS, TACS,ETACS and JTACS	14.4 kbps	Low speed	1995-1997
2G (Digital)	2nd Generation of wireless telephone technology introducing a data service; SMS (short message service)	TDMA,GSM, CDMA, 2.4 GHz narrowband WLAN	144 kbps	Low & medium speed	1997-2000
3G (IMT 2000)	3rd Generation of mobile telecommunications (International Mobile Telecommunications-2000)	TDMA 2000, EV-DO, W-CDMA, 802.11 PAN, Bluetooth	384 kbps	Medium & high speed	2000-2005
B3G	Beyond 3rd Generation	WiBro802.16e, WiMax, 3GPP, LTE	<50 Mbps	High speed	2005-2010
4G	4th Generation of mobile telecommunications	DAB/DVB, cellular GSM, IMT-2000, WLAN,IR, UWB,DSL, LTE-A, IEEE 802.16e	<100 Mbps	Very high speed	2010 onwards
5G/B5G	5th Generation and beyond	4G+WISDOM	Enhanced data rates	Very high speed, scalability and connectivity	2019 onwards

connected things will generate huge volume of data that need to be analyzed to gain insight behind this big IoT data. Moreover, in the industrial environments (industry 4.0) as well in in smart spaces (building, houses, etc.) and connected cars communications often require high reliability, low latency and scalability. Several technologies such as BLE, Zigbee, WirelessHART, 6TiSCH, LPWAN (Lora, Sigfox, etc.) have been proposed to fit these requirements. The forthcoming $5G$ networks is promising not only by increased data rates but also low-latency data communication for latency-critical IoT applications. $5G$ will enable massive IoT devices connected via a myriad of networks and critical machine type communications. While the massive IoT is more concerned about scalability deep coverage and energy efficiency, the latter requires ultra-low latency and extreme reliability (URLLC). Recently, the fog-to-thing continuum is proposed to mitigate the heavy burden on the network due to the centralized processing and storing of the massive IoT data. Fog-enabled IoT architectures ensure closer processing in proximity to the things, which results in small, deterministic latency that enables real time applications and enforced security. The IoT is a novel paradigm which is shaping the evolution of the future Internet. According to the vision underlying the IoT, the next step in increasing the ubiquity of the Internet, after connecting people anytime and everywhere, is to connect inanimate objects. By providing objects with embedded communication capabilities and a common addressing scheme, a highly distributed and ubiquitous network of seamlessly connected heterogeneous devices is formed, which can be fully integrated into the current Internet and mobile networks. Formally, IoT can be defined as, " *A world wide network on electronically interconnected devices uniquely addressable, based on standard communication protocols and allows users to be A*6 *connected*" [77]. Thus allowing for the development of new intelligent services available anytime, anywhere, by anyone and anything. Latest research work and technological systems are converging towards IoT and CRNs. A typical CR-Based IoT system model is shown in Fig.6.1

The SU activity is characterized by suspending its transmission when a PU reappears and resuming operation via contingency planning, i.e., through SS results. The proposed spectrum decision scheme is based on the transmission process for PUs and IoT-U by mitigating the interference and using SS results, adopting the channel configurations ensuring user's QoS requirements are fulfilled thereby making the region a smart city.

6.4 Spectrum Decision Framework

Key communication parameters are extracted from each available spectrum slot and tagged for A6 connection according to their level in order to build a matrix of available spectrum slots [78]. In the proposed framework, transmission process of both, the PUs and IoT-U is

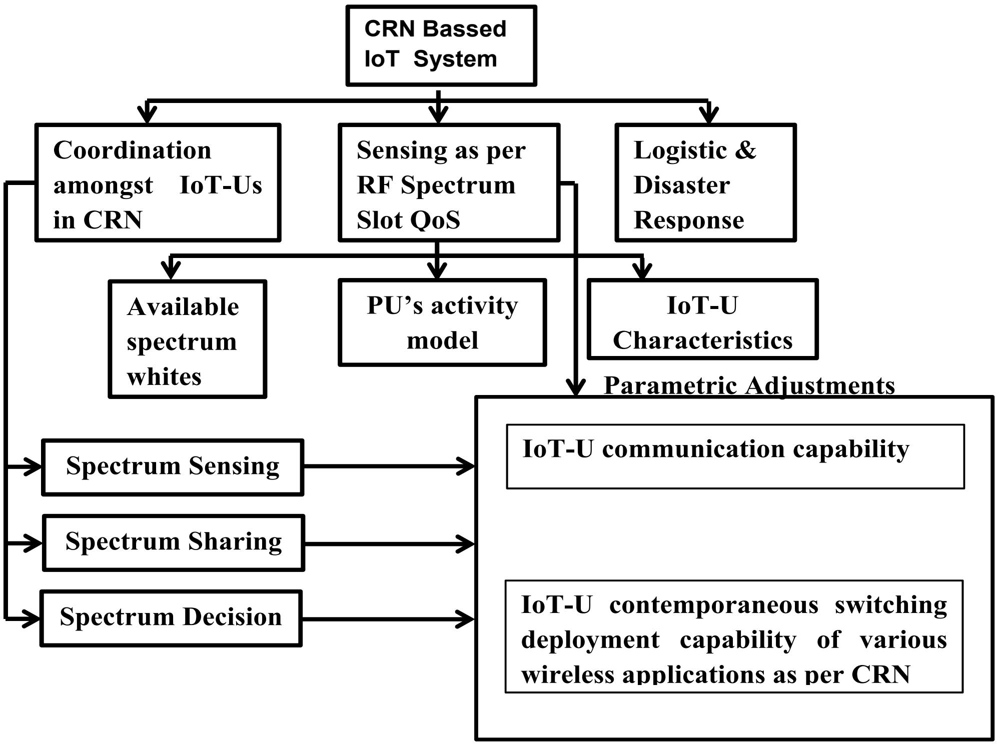
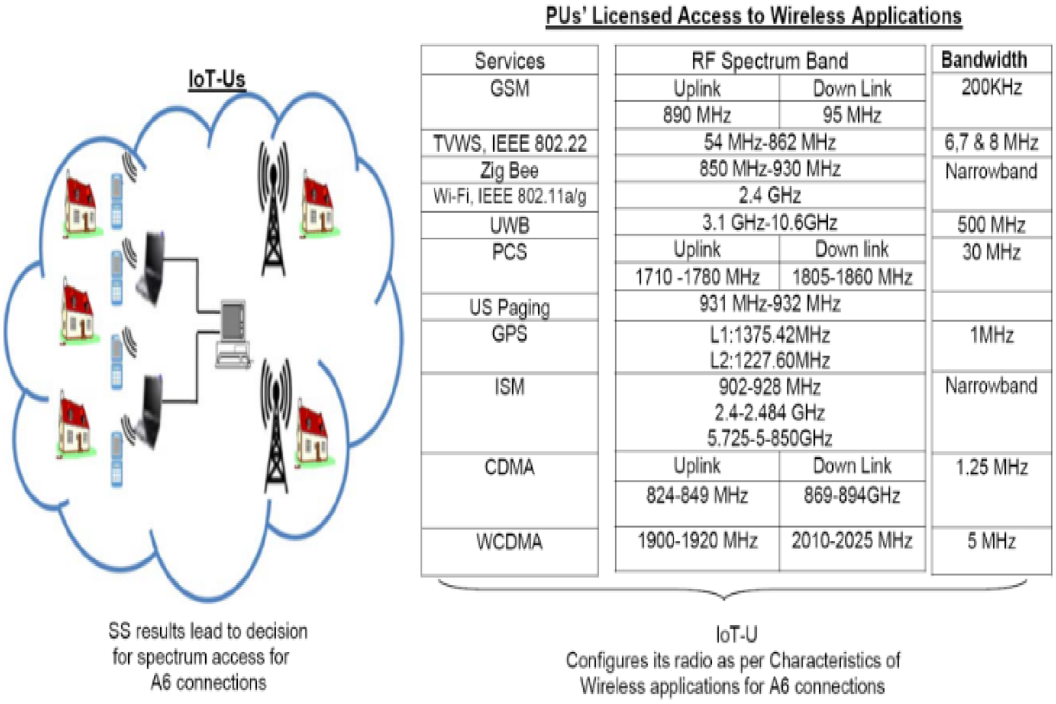


Figure 6.1: CR Based IoT System for A6 connections.



PUs' Licensed Access to Wireless Applications

Services	RF Spectrum Band		Bandwidth
	Uplink	Down Link	
GSM	890 MHz	95 MHz	200KHz
TVWS, IEEE 802.22	54 MHz-862 MHz		6,7 & 8 MHz
Zig Bee	850 MHz-930 MHz		Narrowband
Wi-Fi, IEEE 802.11a/g	2.4 GHz		
UWB	3.1 GHz-10.6GHz		500 MHz
PCS	Uplink	Down link	30 MHz
	1710 -1780 MHz	1805-1860 MHz	
US Paging	931 MHz-932 MHz		
GPS	L1:1375.42MHz L2:1227.60MHz		1MHz
ISM	902-928 MHz 2.4-2.484 GHz 5.725-5-850GHz		Narrowband
CDMA	Uplink	Down Link	1.25 MHz
	824-849 MHz	869-894GHz	
WCDMA	1900-1920 MHz	2010-2025 MHz	5 MHz

Figure 6.2: RF Spectrum Management Framework in CR Based IoT Device for A6 connections.

designed where interference avoidance is ensured as shown in Fig. 6.3.

$$P_{TB} = P\left(i,j\right) = \frac{\lambda_p \left(P_{i-1,j}\right) \varphi\left(i+1.j\right) + \left(j+1\right)\mu_s P(i,j+1) \varphi\left(i.j+1\right)}{i\mu_\mathrm{p} + j\mu_\mathrm{s} + \lambda_p + \lambda_s} \tag{6.1}$$

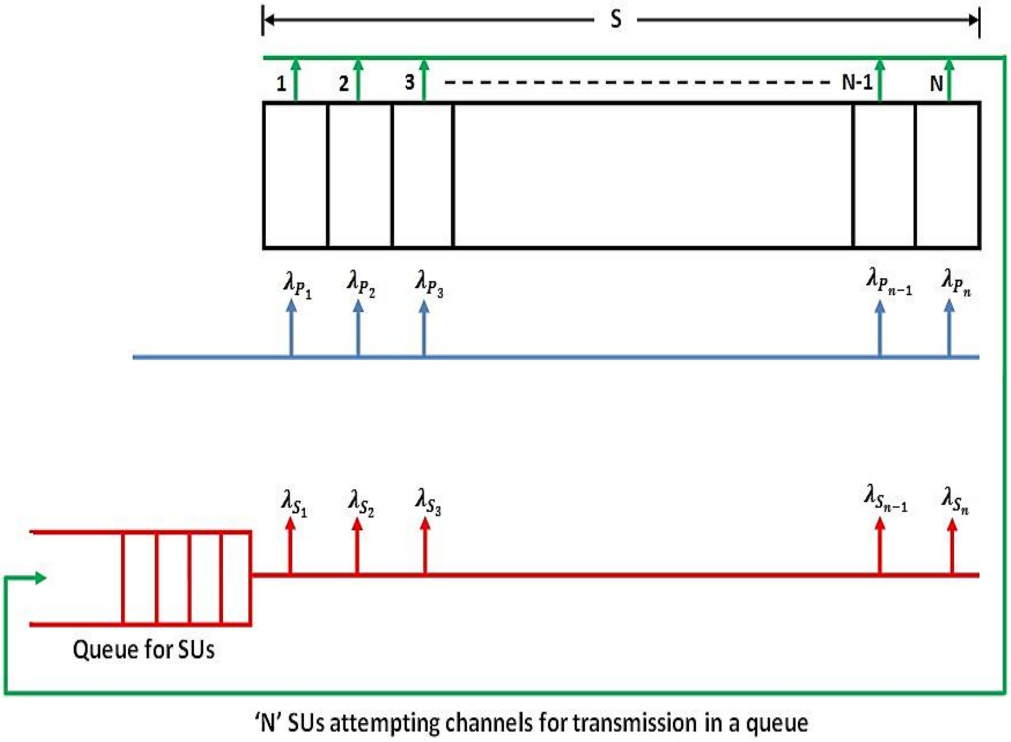


Figure 6.3: Interference avoidance.

where PUs and IoT-Us arrive and depart from each spectrum slot in *s* at the rate λ_p and λ_s respectively. Similarly, the μ_p and μ_s are the mean values of the respective transmission durations of PU and IoT-U in the network. The number of spectrum slots in *s* by PU and SU at some specific time are represented by *i* and *j* respectively, such that *i+j≤N*. *P(i,j)* is the stationary probability of two dimensional Markov state which is P_{TB}. The state space ϖ for PUs and IoT-Us occupying spectrum slots in *S* is given as under;

$$\varpi = \{(i,j) \mid 0 \leq i \leq N; 0 \leq j \leq N\} \tag{6.2}$$

and

$$\varphi\left(i,j\right)=\begin{cases}1, & \left(i,j\right)\,\epsilon\,\varpi\\ 0, & \text{otherwise}\end{cases} \tag{6.3}$$

6.4.1 System Model

A region comprising of 2 BTSs, unlimited number of mobile devices, all buildings in the neighborhood are under the coverage of all the wireless services as shown in Fig. 6.2. A wide range wireless based applications, i.e, GSM, bluetooth, UWB, NB, video conferencing, IP based communication, office automation systems, building security management systems, $5G$ and RFID, connected through IP based communication radios. Third Generation Partnership Project ($3GPP$) channel model has been used owing to its typical characteristics for wireless systems, i.e, it has properties that impact on system performance by reflecting the important properties of propagation channels. Moreover, wireless networks are optimized in the region of system model. Wireless services employ a combined FDMA/TDMA approach for Air Interface. The empirical results given in Chapter 4 has shown that, although hotspots at 2.4 GHz traffic contains many white spaces to be opportunistically accessed, the existing coexistence mechanisms such as Carrier Based Spectrum Multiple Access (CSMA) are inadequate for exploiting these white spaces.

6.4.2 Traffic Model

As mentioned earlier, there are two types of radio frequency spectrum users, PUs and SUs, in the proposed SDSF. PUs are the wireless communication users which use the licensed RF spectrum slots and can not be controlled in the CRN. SUs are CR nodes and have been named here IoT-Us as they are required to have A6 connections. IoT-Us are connected with the energy scheduling which is used to communicate with the BTS. The correct RF spectrum decision in CRN is dependent on PU activity modeling. In IoT supported environment, all users are required to be connected all the time exchanging information with each other as well as with intermediate devices and BTSs. On arrival of PU(s) in their licensed bands, the transmitting IoT-Us have to vacate the spectrum slot and switch to other sensed vacant slot. This means that the process of SS is carried out simultaneously. Therefore, the IoT-U signal is modeled in such a way that it is flexible for switching delays and maintaining low end-to-end latency. The real signal model for IoT-Us, where the receicer is considered to suffer from RF imperfections, such as nonlinear behavior of low noise amplifier (LNA) and the phase noise etc. In this traffic model, *K* RF spectrum slots are down converted to the baseband using both, the narrow and wide bands direct conversion principle, termed here as multi-channel down-conversion.

6.4.2.1 Practical IoT-Us Signal Model

The two hypothesis, namely absence and/or presence of PU signal is denoted with a parameter, $\theta_k \in \{0, 1\}$. The PU signal has r samples and let the n-th sample is *y(n)*, is transmitted over a Racian fading channel as is described in section 5.3.1, with channel gain, *h(n)* and additive white noise, *w(n)*. The received wide band RF signal is passed through various RF front-end satges, i.e., filtering, amplification, analog I/Q demodulation i.e., down-conversion to base band and sampling. The wide band channel after sampling has a bandwidth *W* and contain *L* spectrum slots. Thus the bandwidth of each spectrum slot is given as under:

$$B_{spectrumslot} = B_{sb} + B_{gb} \tag{6.4}$$

where B_{sb} and B_{gb} are the signal band and total guard band bandwidth with the spectrum slot, respectively. Here, the sampling is performed with rate *B* and the rate of the signal is reduced by a factor of,

$$M = \frac{B}{B_{sb}} \geq K \tag{6.5}$$

Where $M \in \mathbb{Z}$.

After the selection filter, the nth sample of the base band equivalent received signal vector for the *k*th spectrum slot is given as

$$r_k(n) = \Re\{r_k(n)\} + j\Im\{r_k(n)\} = \theta_k h_k(n) s_k(n) + b_k(n) \tag{6.6}$$

where h_k, u_k and w_k are zero-mean Circularly Symmetric Complex White Guassian (CSCWG) processes with variances σ_h^2, σ_s^2 and σ_b^2, respectively.

6.4.2.2 PU Activity Model

As 5G will be ultra-dense networks (UDNs) and heavily sliced to meet the tremendous increase in data downloading and subscribers connectivity by end-users [79], the PU activity is to be modeled all the time in CRNs. Real traces of PU activity in wireless communication systems are not available due to copy right issues. At present, the real traces of IEEE 802.11 have been reported in [80]. Therefore, PU activity is modeled here through Poisson distribution, given as follows and stochastically gives the most accurate pattern of PU's arrivals and departures in the RF spectrum slots;

$$f(k;\lambda) = P(T = k) = \frac{\lambda_s^k e^{-\lambda_s}}{k!}, \tag{6.7}$$

where *T* is a discrete random variable and $k = 0, 1, 2, 3, ..., n$.

The SU activity is characterized by suspending its transmission when a PU reappears and resuming operation via contingency planning, i.e., through SS results. The proposed spectrum decision scheme is based on the transmission process for PUs and IoT-U by mitigating the interference and using SS results, adopting the channel configurations ensuring user's QoS requirements are fulfilled thereby making the region a smart city.

6.4.3 Methodology of the proposed framework

For this work, the CRN is considered to function in five licensed spectrum slots, the carrier frequency of these bands ranges between 1 MHz to 39 GHz to support all wireless applications described in the proposed system model in $5G$ network. The Poisson distribution is used to model the PU activity, i.e., its arrival and departure, and for the secondary connections as well [40]. The PUs holds the priority access rights to use the RF spectrum slots and can access any spectrum slot being used by any IoT-Us. The call holding time duration follows the Poisson distribution, as has been mentioned in the system model in section 3.1.

The parameters used to formulate the RF spectrum decision framework are defined below. Let the IoT-U appearance be represented by τ which is a vector representing the spectrum slot usage by all users. Let the spectrum slot number be represented as *i*, where i=1,2,3,..,k,...,n. Here, a selection map ξ is defined, which is assigned a value $'1'$ for those spectrum slots whose SS result is idle, is greater than a set threshold γ. Statistically, it is defined as follows:

$$\xi_k(i) = \begin{cases} 1; & \tau_k(i) > \gamma \\ 0; & otherwise \end{cases} \tag{6.8}$$

In the classical ED, the energy of the received signals is used to determine whether the particular spectrum slot is idle or occupied by a PU. Basing on the IoT-U signal model and PU activity models presented in section 6.4, the ED calculates the test statistics for the targeted spectrum slot, i.e., the kth slot in the RF spectrum range in the proposed system model,

$$T_k = \frac{1}{N_s} \sum_{m=0}^{N_s-1} \Re r_k(n)^2 + \Im r_k(n)^2 \tag{6.9}$$

where N_s is the number of complex samples used for finding whether the kth spectrum slot is occupied by PU or otherwise. This test statistic is compared against the threshold (γ) given in equation 6.9, to yield the result for this parameter in the proposed SDSF, whether the slot is idle or occupied by the PU. Basing on the IoT-Us' signal and PUs' activity model given above and taking into consideration that

$$\sigma^2 = E[\Re\{r_k^2\}] = E[\Im\{r_k^2\}] = \xi_k[\Re\{h_k^2\} + \Im\{h_k^2\}]\frac{\sigma^2}{2} + \frac{\sigma_w^2}{2}, \tag{6.10}$$

and

$$E[\Re\{r_k\}\Im\{r_k\}] = 0, (6.11)$$

for a given spectrum slot gain h_k and spectrum slot occupation ξ_k, the received energy follows chi-square distribution with $2N_s$ (nyquist criteria) and the CDF is given by,

$$F_{T_k}(x\|h_k, \xi_k) = \frac{\gamma(N_s, \frac{N_s x}{2\sigma^2})}{\Gamma(N_s)} \tag{6.12}$$

The test statistics used here is a closed form expression for its CDF given that the spectrum slot is occupied by the PU. The closed form expression for CDF of test statistics for taking the both, either the RF spectrum is occupied by PU and is busy or it is idle, is derived from Theorem, given below:-

Theorem *The CDF of the test statistics for the energy of the signal for a RF front end and the spectrum slot being occupied by the PU is evaluated by*

$$F_{T_k}(x|\xi_k = 1) = 1 - e^{\frac{\sigma_w^2}{\sigma_h^2\sigma_s^2}} \sum_{k=0}^{N_s-1} \frac{1}{k!}[\frac{N_s x}{\sigma_h^2\sigma_s^2}]^k \Gamma[-k+1, \frac{\sigma_w^2}{\sigma_h^2\sigma_s^2}, \frac{N_s x}{\sigma_h^2\sigma_s^2}, 1] \tag{6.13}$$

- Proof As $h_k \sim \mathcal{CN}(0, \sigma_h^2)$, and follows that the variance follows exponential distribution with PDF,

  $$f_{\sigma^2}(x|\xi_k = 1) = \frac{2e^{\frac{\sigma_w^2}{\sigma_s^2\sigma_h^2}}}{\sigma_s^2\sigma_h^2} e^{\frac{-2x}{\sigma_s^2\sigma_h^2}} \tag{6.14}$$

  with $x \in [\frac{\sigma_w^2}{2}, \infty]$. Therefore, the unconditional CDF is given as

  $$F_{T_k}[x|\xi_k = 1] = \frac{1}{\Gamma[N_s]} \frac{2e^{\frac{\sigma_h^2}{\sigma_s^2\sigma_h^2}}}{\sigma_s^2\sigma_h^2} \int_{\frac{-\sigma_h^2}{2}}^{\infty} \gamma(N_s, \frac{N_s x}{2y}) e^{\frac{-2y}{\sigma_h^2\sigma_s^2}} dy \tag{6.15}$$

i.e.,

$$F_{T_k}[x|\xi_k = 1] = -\frac{1}{\Gamma[N_s]}\frac{2e^{\frac{\sigma_h^2}{\sigma_s^2\sigma_h^2}}}{\sigma_s^2\sigma_h^2}\int_{\frac{\sigma_h^2}{2}}^{\infty}\gamma(N_s,\frac{N_s x}{2y})e^{\frac{-2y}{\sigma_h^2\sigma_s^2}}dy+\frac{1}{\Gamma[N_s]}\frac{2e^{\frac{\sigma_h^2}{\sigma_s^2\sigma_h^2}}}{\sigma_s^2\sigma_h^2}\int_{\frac{\sigma_h^2}{2}}^{\infty}\gamma(N_s)e^{\frac{-2y}{\sigma_h^2\sigma_s^2}}dy \tag{6.16}$$

$$F_{T_k}[x|\xi_k = 1] = 1 - \frac{1}{\Gamma[N_s]}\frac{2e^{\frac{\sigma_h^2}{\sigma_s^2\sigma_h^2}}}{\sigma_s^2\sigma_h^2}\int_{\frac{\sigma_w^2}{2}}^{\infty}\Gamma(N_s,\frac{N_s x}{2y})e^{\frac{-2y}{\sigma_h^2\sigma_s^2}}dy \tag{6.17}$$

$$\Gamma(N_s,\frac{N_s x}{2y}) = \sum_{k=0}^{N_s-1}\frac{(N_s-1)!}{k!}(\frac{N_s x}{2y})e^{\frac{-N_s x}{2y}} \tag{6.18}$$

$$F_{T_k}[x|\xi_k = 1] = 1 - \frac{2e^{\frac{\sigma_h^2}{\sigma_s^2\sigma_h^2}}}{\sigma_s^2\sigma_h^2}\sum_{k=0}^{N_s-1}\int_{\frac{\sigma_h^2}{2}}^{\infty}\frac{1}{k!}(\frac{N_s x}{2y})^k \times e^{(}\frac{-N_s x}{2y} - \frac{2y}{\sigma_h^2\sigma_s^2})dy \tag{6.19}$$

where Γ_s is spectrum slot time duration (used in Eq. 5.18 in chapter 5), which follows gamma random variable distribution. The gamma random variable is a useful random variable to model the transmission in spectrum slot in queuing systems (section 4.4.4 0f [81]). Algebraic manipulations in equation 6.19 gives an expression of equation 6.13 to conclude the proof of the theorem.

Spectrum slot QoS requirements is maintained by monitoring the respective spectrum band capacity. Let the spectrum band capacity be represented by κ given in Eq. 6.20 where $\mathbf{H}$ denotes a fading channel gain which is a complex Gaussian random variable and δ denotes signal-to-noise ratio. Here, we define a selection map ζ, which is assigned a value $'1'$ for those RF spectrum slots whose performance is greater than a set threshold ϵ. Statistically, it is defined as follows:

$$\kappa = log_2\left(1 + \delta\left|\mathbf{H}\right|^2\right) \tag{6.20}$$

$$\zeta(i) = \begin{cases} 1; & \kappa(i) > \epsilon \\ 0; & otherwise \end{cases} \tag{6.21}$$

The entire RF spectrum range is continuously sensed to get the real time spectrum slot occupancy status. IoT-U is continuously sensing the spectrum and estimating the power spectral density (PSD) using the periodogram for any particular signal $y[k]$ carrying energy transmitted by PUs in the spectrum slot as follows;

$$P_K(e^{j\omega}) = \frac{1}{K}\left|\sum_{k=0}^{K-1} y[k]e^{-jk\omega}\right|^2 \tag{6.22}$$

$$P_K(e^{j\omega}) = \frac{1}{K}\sum_{k=0}^{K-1} y[k]e^{-jk\omega}\sum_{s=0}^{K-1} y[s]e^{js\omega}, \tag{6.23}$$

where the power is found to be less than a set threshold, the IoT-U considers the spectrum slot vacant for access. Let ρ denotes the spectrum slot occupancy status, which is assigned a value $'1'$ for the vacant slots and $'0'$ for the occupied by the PUs.

As described in section 3.4, these three parameters enable IoT-U to decide to occupy a specific spectrum slot which has been declared the best available spectrum slot by the proposed spectrum decision framework. Moreover, ξ_i, ζ_i, ρ_i indicate the spectrum decision outcome, which leads to the decided channel $c_i(t)$ for the transmission session by IoT-U. The possible outcome of the decision block will be either to occupy a particular spectrum slot whose idle time, QoS requirements parameters and its occupancy status are found greater than the set respective threshold. If the PU has arrived unexpectedly in any particular spectrum slot, when the proposed decision framework has declared the spectrum slot vacant, the IoT-U will vacate the spectrum slot and decision framework will restart its functionality as the IoT-U can not detect the appearance during its transmission but can detect the appearance of PU during sensing duration. It is, therefore, IoT-U carries out SS and its transmission simultaneously. The SS component through spectrum slot occupancy status would have identified other vacant spectrum slots for IoT-U as a contingency plan for the user's transmission. Accordingly, the IoT-U will occupy any suitable spectrum slot and there will be no interference with PU as well as QoS of IoT-U's requirements will not be degraded. Thus, CR's role in enhancing the performance of IoT technology by accessing spectrum opportunistically is of high significance.

6.5 Results and Discussions

An infrastructure-based CRN consisting of two BS and multiple IoT-Us. Each IoT-U is uniformly distributed over the CRN coverage in the geographical region. The CRN is assumed to function in 5 licensed RF spectrum slots consisting of one each of GSM, Narrow Band bluetooth and ZigBee, wideband CDMA and WCDMA and UWB frequency spectrum slots. The PU activity of each wireless application is modeled by randomly selecting over $[0,1]$. The IoT-U activity is determined by its access to the spectrum and is characterized by transmit power keeping to 1 over all spectrum slots and interference avoidance to the PU. The PSD of all five PUs calculated using Eq. 6.22 and Eq. 6.23 and is shown in Fig.6.4. The IoT-U will find out about the slot to be vacant through SS and continuously senses the channel status and keeps the record of latest sensing results. It can be seen in Fig. 6.5 that the PSD of user 4 is very low which signifies that the PU has vacated the slot. The spectral efficiency of 5 spectrum slots in the RF spectrum range occupied by 5 PUs taken into account is shown in Fig.6.6 for SNR=10db.

An optimization problem has been formulated to find minimum number of spectrum slots to be sensed by each IoT-U while satisfying the requirements for the probability of miss detection and false alarms. CROC, i.e, curves between detection probability P_d, False alarm probability P_{f_a} and missed detection probability P_{md} as key measurement metrics that have been used in our previously published works [48] and [82] to

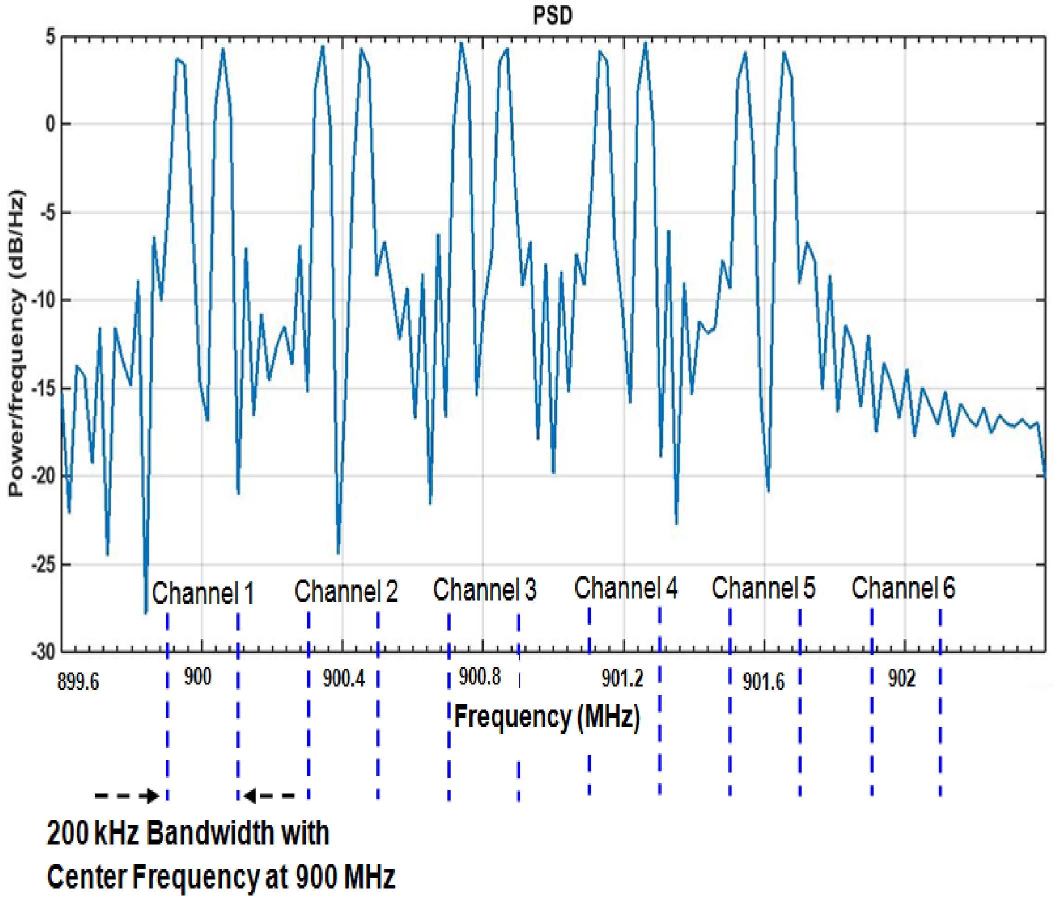


Figure 6.4: Power spectral density of the data transmitted by all five PUs.

analyze the performance of spectrum decision framework under a scenario for frequency ranges (800 MHz to 900 MHz), are also used here to verify the correctness of decision purposed in this paper. With the increase in P_{f_a}, P_{md} should decrease. It signifies that IoT-U in CRN in the spectrum slot, sensed idle, occupied as an outcome of the proposed decision framework, is not causing interference to PU and also the QoS requirements of its own transmission are maintained. The purposed decision framework has yielded the same results for higher as well as lower values of SNR, as were found when the spectrum slot was sensed idle.

For the communication overhead as an outcome of information exchange required by the statistical approach, has been significantly reduced by using existing common control channels(CCC) by IoT-Us. This complexity cost is fully justified given the

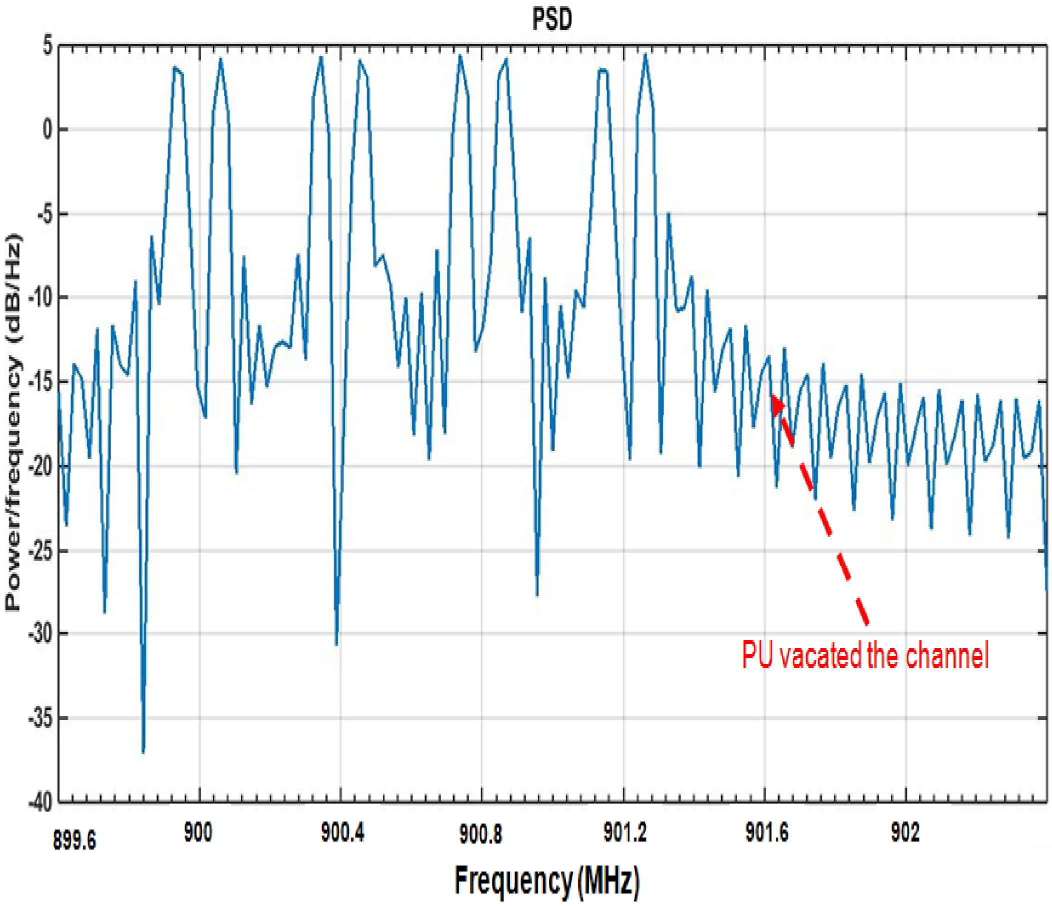


Figure 6.5: Power spectral density after the departure of fourth PU.

significant performance improvement that the proposed framework offers in terms of latency, throughput, energy efficiency, delay, and the reliability for realization of IoT in terms of A6 connections.

6.6 Summary

CR is a promising technology in future wireless systems and Spectrum decision is one of the most important module in CR. The IoT is a vision, which is currently under progress. 5G/B5G is everything, everywhere and always connected and the test solutions provided in this chapter can enable deeper insights as development of the standard evolves. CR offers the enabling platform for IoT under 5G/B5G standards. Spectrum decision in CRN is a vital mechanism in spectrum management that ensures

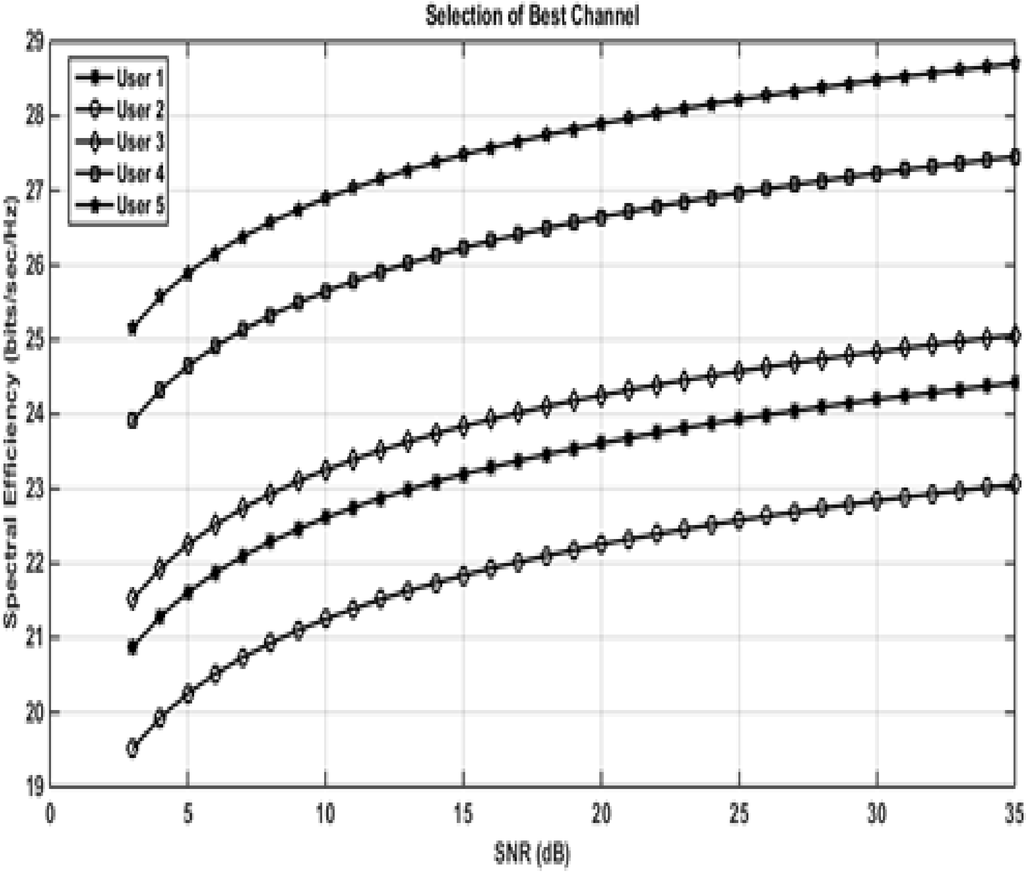


Figure 6.6: Spectral Efficiency of 5 PUs

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the efficient operation of both SU (IoT-U) and PU networks. In this paper a spectrum decision framework has been proposed which weighs the spectrum band on its idle time, occupancy status and performance and ensures A6 Connections.

Chapter 7

Conclusion and Future Work

CR system has been studied to enhance the spectrum utilization efficiency. Where there is a serious dreath of wireless spectrum, there exists under utilization of the spectrum by wireless applications. This chapter sums up the conclusions drawn from each contribution of this research for enhancing the spectrum utilization through the proposed SDSF. While it also presents some future extensions in this field.

7.1 Conclusions

The first chapter of this thesis studied the concept of CR, its realization and implementation, related work in spectrum decision in CR and when CR meets with IoT in 5G wireless networks and how spectrum decision framework affects IoT. An overview of Spectrum Decision Support Framework for cognitive radio networks was presented. Several important research contributions are as follows:

The spectrum decision support framework proposed in this research is a novel scheme by which the realization of CR becomes implementable. This framework allows SUs to coexist with other RF spectrum users. SUs' transmission on vaccant channels while maintaining its QoS requirements. Chapter two suggested a fusion based spectrum decision framework which offered a combined effect of three important parameters; channel vacant time, channel occupancy status and channel capacity. The results obtained validated the work.

PU activity modeling plays an important role in CRN operations. Due to copy right issues, the real traces of PU activity can not be modeled. It is therefore, PU was emulated as USRP2 and the proposed framework was proposed through a testbed consisting of signal generator and GNU Radio features on ubuntu, in chapter 4. The results showed the workability of the proposed scheme.

The research work described in chapter 5 was extended in its applicability and the framework was fuzzification supported. A detailed analysis of membership functions was given viz-a-viz to their effects on defuzzified output as a spectrum decision for the SUs to occupy the most suited spectrum slot for its transmission. Results showed that the overall throughput of CRN was much higher than the existing spectrum selection techniques.

The research was extended for spectrum access consideration as a decision for SUs, in which the QoS requirements for SUs to include the blocking probability, latency and termination probability of SUs in the wireless applications. As PUs turn up unexpectedly on their licensed channels, the QoS of SUs can not be ensured. The proposed scheme here enables SUs to switch to other vacant channels without degrading their QoS requirements. This scheme is envisioned to work well for CR based IoT by utilizing RF spectrum band efficiently in the CRN. An analysis model has been presented in the proposed spectrum decision technique for SUs as IoT devices to satify the A4 regime.

7.2 Future Work

Although the CR area is relatively new, it has grown rapidly in the last two decades. Due to the fact that CRs appeared on wireless environment, it has received considerable attention from regulatory and standardization, academia and industry around the globe. This research covered spectrum decision, one of the important module of CR technology and an effort has been made to converge its effects in realization of IoT in 5G networks as well. The open research challenges in making CR technology an worthy addition in wireless applications for efficient spectrum management, the future looks all CR enabling 5G networks in telecommunication industry. The potential future developments in CRs as an enabling technology for DSA can be listed as under:-

- Research be oriented focusing on the algorithms associated with Artificial and Computational Intelligences to include machine learning, optimization, game theory, genetic algorithm etc to fill up the SDSF.
- Formulate widespread usage of approaches involving game theories as a statistical tool to suggest frequency spectrum handoffs and access issues to enable CRNs independent on the vacant frequency band slots.
- The requirement for accurate PU characterization and activity modeling need the realistic on-line databases. The real traces can not be obtained due to the copy right issues, therefore, a broad devices base testbeds to emulate wireless networks be created to validate these spectrum decision algorithms. To start the task, an effort made here has been reported in chapter 4 of this dissertation.
- The system performance of cellular CRNs be analyzed and the transmission performance of SUs in CRNs based on relay logic be improved.
- Investigate the quantized Multi-User-MISO downlink scenario to see whether improper signaling and higher rank transmit covariance matrices should improve the performance in the presence of additional multi-user interferences.

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