BOTSWANA INTERNATIONAL UNIVERSITY OF SCIENCE & TECHNOLOGY

# SPECTRUM HANDOFF IN COGNITIVE RADIO BASED SMART GRID NETWORK

by

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The undersigned certifies that he has read and hereby recommends for acceptance by the College of Engineering a dissertation titled: Spectrum Handoff In Cognitive Radio Based Smart Grid Network, in fulfilment of the requirements for the degree of Master of Engineering in Telecommunication Engineering of the BIUST.

| | |
|---|---|
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# Dedication

This work is dedicated to the Almighty God for helping me through this program in spite of all odds, and to my wife and children for their unrelenting support and cooperation.

# Abstract

The Smart Grid (SG) as an intelligent power network, depends on a reliable and efficient communication network to provide two-way communication, which is a prime feature of the smart grid. Many researchers have proposed cognitive radio (CR) as a viable wireless communication technology that can be adapted for smart grid communication in order to improve spectrum utilisation and address communication challenges being faced by conventional wireless communication technologies. A major issue to address in the use of cognitive radio is spectrum handoff. This is because cognitive radio uses the spectrum of a licensed user as its main operating channel and must handoff to another spectrum hole when the licensed user returns. Multiple spectrum handoff degrades the cognitive radio user communication and spectrum handoff schemes are employed to mitigate this negative effect. In this work, a spectrum handoff scheme is proposed for cognitive radio communication in the smart grid neighbourhood area network. The proposed handoff scheme using backup channel scenario is modelled as an overflow system with mixed renewal and Poisson inputs from the perspective of a teletraffic loss system. The performance of the proposed scheme is evaluated in terms of blocking probability, link failure probability and link maintenance probability and compared to that of an existing scheme. Simulation results obtained showed that it is possible to improve the performance of cognitive radio operating in a classical situation by up to 22.8%, 83.2% and 45.2% respectively, for the above performance metrics, depending on selected network parameters. A comparison between the proposed and existing scheme showed that the proposed scheme outperformed

the existing scheme with respect to the above spectrum handoff performance parameters

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# 1

# Introduction

## 1.1 Background

The current electricity grid was designed as a centralized system with a one-way flow of energy from utilities to the consumer. This system lacks adequate interaction between utility providers and the consumers, responds slowly to rapidly changing loading and lack of proper control. This results in blackouts and inability to respond to the ever-increasing energy demands of the 21st century [1]. The smart grid which is the next generation power grid, is designed to address the limitations of the current grid [2]. It introduces a two-way dialogue were electricity and information can be exchanged between utilities and its customers to make the grid intelligent. It is a developing network of communications, control, automation, computing and management tools working together to achieve a more efficient, reliable, secure and greener electricity grid.

The smart grid connects customer appliances via smart meters and other intermediate devices/infrastructure to the utility control centre. A reliable communication system is a key groundwork of the smart grid and is pivotal for collection, distribution and analysis of metering and monitoring infrastructure information for effective control and optimization of the power system [3].

Several wireless communication technologies have been identified and deployed for two-way communication in different strata of the smart grid in order to provide connectivity among grid components in transmission, distribution and consumption in near real time.

These wireless communication technologies utilize the radio frequency spectrum for communication. However, with the proliferation of wireless devices and increase in demand for radio spectrum, the report of the study conducted by the Spectrum Policy Task Force of the Federal Communications Commission (FCC)[4], has revealed a scarcity of radio spectrum due to under-utilization of most of the spectrum allotted to licensed users based on the Fixed Spectrum Access policy adopted by the FCC, government organizations and other regulatory bodies. From the studies conducted by the Federal Communication Commission in 2002 [4], spectrum utilization level ranging from $15 - 85\%$ was observed for spectrum bands below 3GHz and even lower ranges for higher frequency bands over a large spatial and temporal bases.

To mitigate this spectrum scarcity problem and increase spectrum utilization, a Dynamic Spectrum Access (DSA) Policy which permit unlicensed wireless users/devices to detect and utilize these temporarily unused portions of the radio spectrum of licensed user has been proposed. These temporarily unused portion of the spectrum is illustrated by figure 1.1; they are also referred to as spectrum holes/white space and may exist in time, frequency, and space domains.

Cognitive Radio (CR) is the enabling technology for DSA policy. A CR enabled device can opportunistically utilize the spectrum hole of the licensed user as long as they do not cause any harmful interference to the legacy spectrum users' communications.

Several researchers have identified and proposed the application of CR as a reliable wireless technology for smart grid communication [6][7]. Part of the benefits identified, includes: enhanced spectrum efficiency, cost effective communication and mitigation of some limitations of conventional wireless technologies currently in use for smart grid communication.

To fully realize the benefits of CR for SG, several challenges need to be addressed since the CR user is a visitor in the radio spectrum of the licensed user and can only use the spectrum when the primary user(PU) is absent and must vacate the channel when the

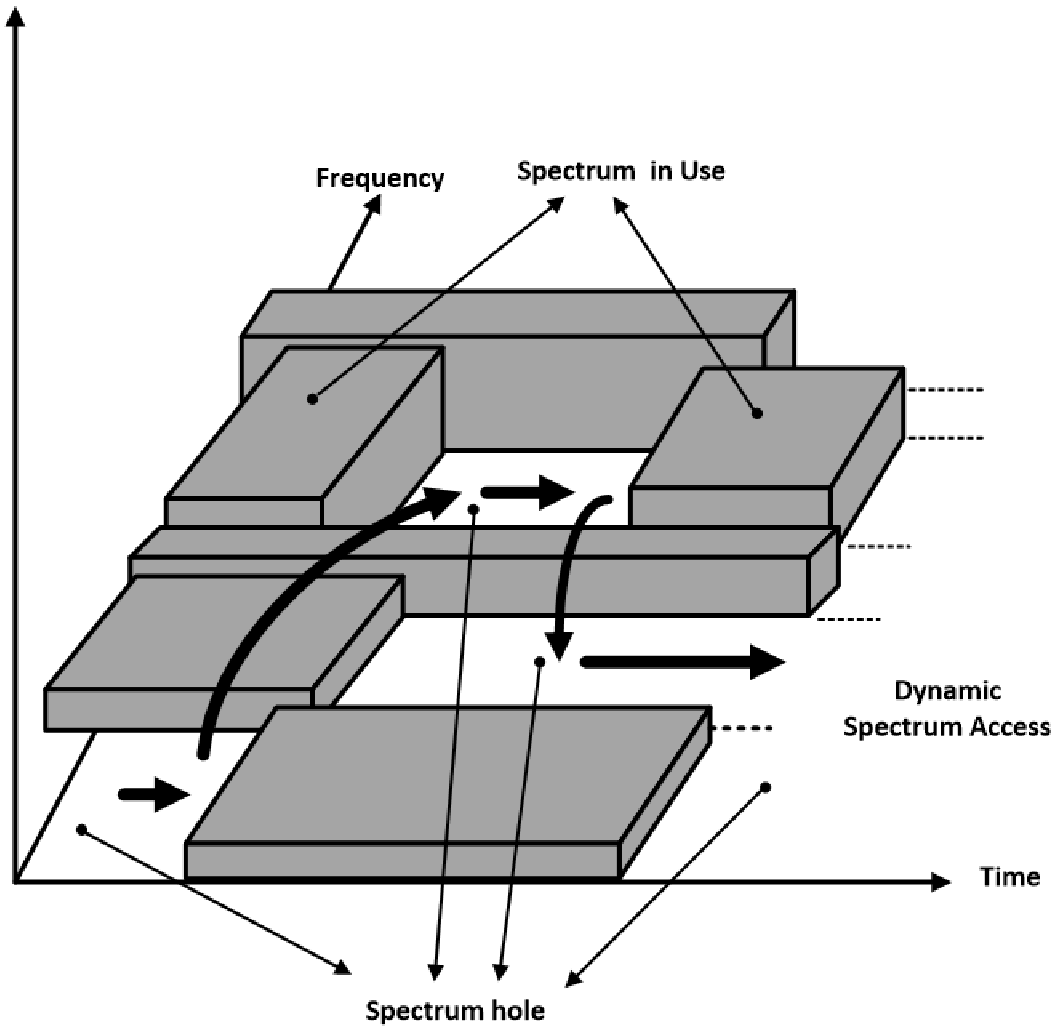



**Figure 1.1:** *Spectrum Hole Concept*
[5]

PU returns. Addressing and mitigating the negative effects of spectrum handoff, as one of the challenges in cognitive radio network, is still an open research area.

## 1.2 Research Motivation

The smart grid neighborhood area network demand frequent, reliable and real time transmission of energy and other service-related data between smart meters and central data access collection point. Most of the wireless communication technologies adopted for communication between these devices face the challenge of radio spectrum scarcity, congestion, cost, etc. Utilizing CR technology can mitigate these challenges and improve the communication between these devices.

Secondly, to utilize cognitive radio successfully, one of the major issues to be addressed is efficient handoff to reduce interference to primary user while maintaining secondary user communication.

Other researchers in [8][9] have developed spectrum handoff schemes to manage the issues addressed above using spectrum handoff with back up channel solutions. However, the proposed backup solutions have only relied on the unlicensed, industrial scientific and medical(ISM) spectrum bands. These channels have some limitations which if addressed will enhance the performance of the spectrum handoff scheme and consequently improve secondary user communication.

## 1.3 Statement of Problems

The use of Cognitive Radio as a wireless communication technology can significantly improve spectrum efficiency and data transmission in smart grid communication network by allowing smart grid devices (secondary users) to temporarily access the primary user's unutilized licensed spectrum band. When the primary user appears in the channel occupied by the secondary user, the secondary user has to vacate the channel to avoid interference to primary users and handoff to another free channel to continue a seamless communication. However, multiple and random appearance of PUs in the licensed spectrum band. will result into multiple handoffs which can cause a considerable performance degradation in the secondary and disruption primary user communication. Several works have been done to manage the problem of interference and mitigate the impact to the primary user as a result of the secondary user sharing its channel; however reducing the effects of multiple spectrum handoff on the secondary communication and helping the interrupted secondary users find a suitable target channel to complete its transmission remains a key challenge and an open research area.

## 1.4 Research Goals and Objectives

### 1.4.1 Main Research Goal

The goal of this research is to develop a spectrum handoff scheme to improve secondary user communication in a Cognitive Radio-based Smart Grid Neighborhood Area Network

### 1.4.2 Research Objectives

In order to achieve the goal for this research, the following objectives are formulated:

- To propose a spectrum handoff scheme that will reduce the effect of multiple handoff on secondary user communication.
- To model the secondary user communication scenario based on the proposed spectrum handoff scheme in terms of blocking probability, link maintenance probability and Link failure probability.
- To simulate, analyze and compare performance metrics of the proposed to existing model(s).

## 1.5 Research Questions

The following question are addressed in this research work:

- How can the effects of multiple handoff due to sudden and random reappearance of PUs in licensed channels occupied by SU be mitigated
- What is the role of spectrum handoff scheme in a CR communication and how can spectrum handoff improve secondary user communication performance.
- How does spectrum handoff metrics affect the performance of the SU communication?

## 1.6 Research Roadmap

In order to achieve the main goal of this research through the objectives specified, the following steps were employed:

1. Propose a spectrum handoff scheme for a Cognitive radio – based smart grid neighbourhood area network. This involved two sub steps:
    - Formulation of a system model - This involved constructing a framework that describes the operating network environment of the cognitive radio network and a set of assumptions that determine the behaviour of the system.
    - Formulation of the spectrum handoff scheme - A spectrum handoff scheme with backup channels is formulated using licensed and unlicensed channel with aim of achieving the objectives stated above.
2. Mathematical Model – Due to the uncertain behavior of PUs, spectrum handoff schemes are based on predictive and probabilistic approach and are generally evaluated based on performance metrics of the system. Mathematical expressions for performance metrics such as blocking probability, link maintenance and link failure are derived for evaluation of the formulated spectrum handoff scheme.
3. Simulation of the formulated model - In order to effectively evaluate the performance of the cognitive user communication, the derived mathematical models for the blocking, link maintenance and link failure probabilities were simulated using MATLAB simulation tool.

4. 4. Analysis of Spectrum Handoff Scheme – Based on simulation result for chosen network parameters, the performance of the cognitive radio user communication was analyzed based on the blocking probability, link maintenance probability and link failure probability. The performance of this spectrum handoff scheme is also compared with existing scheme(s).

## 1.7 Dissertation Organization

The rest of this dissertation is organized as follows:

**Chapter 2:** This chapter presents a background on smart grid, smart grid communication networks and cognitive radio as an applicable wireless communication technology for smart grid neighborhood area network. The concept of spectrum handoff in cognitive radio is reviewed and related works presented.

**Chapter 3:** In this chapter, the formulated spectrum handoff scheme with respect to the goal of this work is presented. Mathematical derivations of the spectrum handoff metrics used for evaluating the performance of the secondary communication based on the proposed handoff scheme are also presented.

**Chapter 4:** Simulation results of the derived mathematical models of spectrum handoff performance metrics are presented using the discrete event simulator-Matrix Laboratory (MATLAB) package tool. Analysis, evaluation and discussion of the performance of the spectrum handoff scheme based on the simulation results are also presented in this chapter.

**Chapter 5:** This ending chapter provides a conclusion for this research work and outlines some direction for future research.

# 2

# BACKGROUND AND LITERARTURE REVIEW

A key component for realizing the smart grid is a reliable, scalable and cost effective communication infrastructure. Apart from reliability, cost and scalability, a major challenge facing wireless communication for smart grid is availability of radio spectrum. The discussion in this chapter presents a concept of the smart grid, an overview of the SG communication network and wireless communication technologies in the first three sections. Cognitive radio and its application for SG is presented in the next three sections, the last sections is a review of spectrum handoff in CR network.

## 2.1 Concept of Smart Grid

The current electricity grid is faced with a lot of problems and is unable to cope with increasing demand for electricity. It's initial design, response capability, little or no end-user interaction and other factors have made it challenging for it to cope with the dynamics of the 21st century power demands [10]. The SG is a modernization program to transform the current electricity grid into an intelligent grid by combining various aspects of engineering, communication and management that will provide a more efficient supply of electricity, improved customer interaction and greener environment [11]. Major feature difference between the existing and the smart grid are highlighted in table 2.1 while figure 2.1 shows a conceptual model of SG.

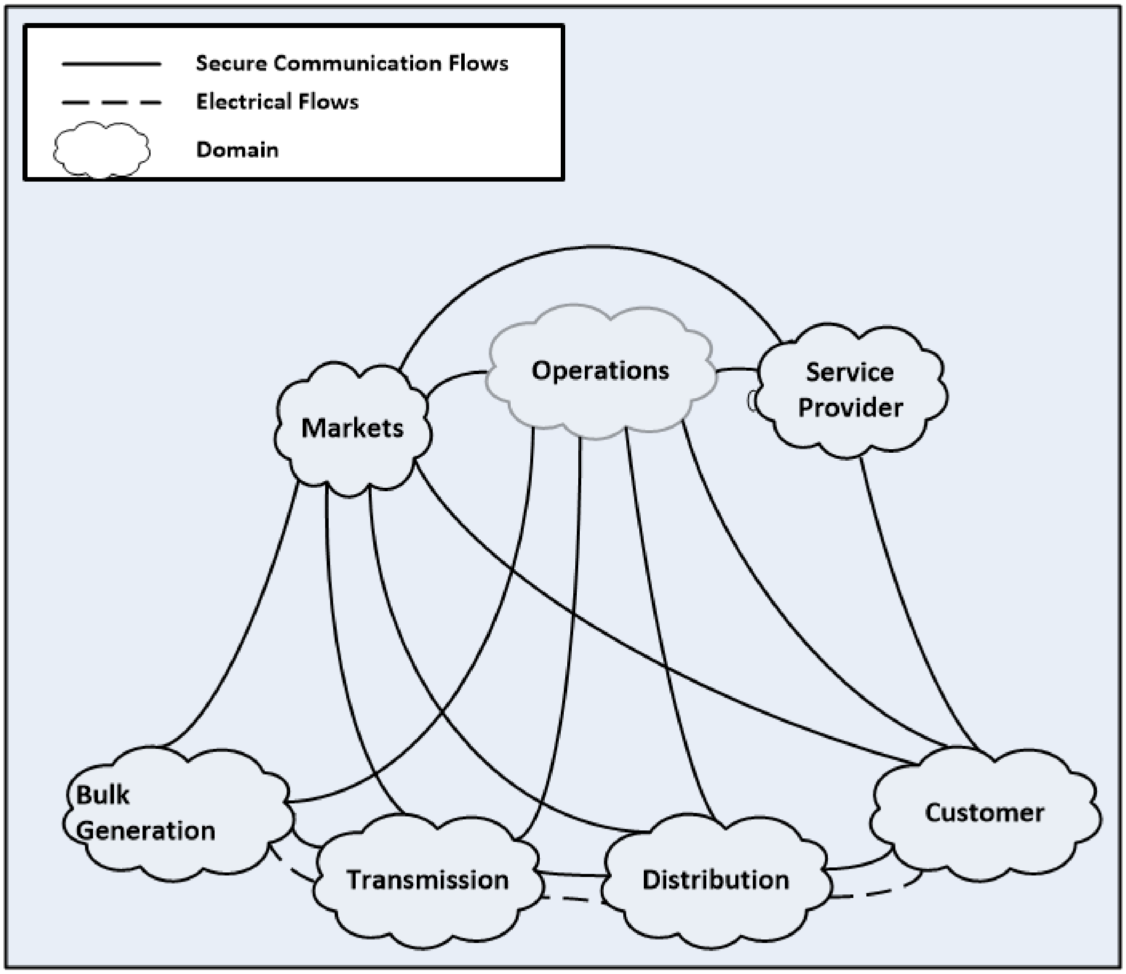



**Figure 2.1:** *A conceptual model of the smart grid [10]*

(h)

**Table 2.1:** *Comparing Existing Grid vs Smart Grid[12]*

| CONVENTIONAL GRID VS SMART GRID | | |
|---|---|---|
| . | Conventional Grid | Smart Grid |
| Information Flow | One Way | Two Way |
| Electricity Generation | Central | Distributed |
| Integrated DERs | Seldom | Often |
| Grid Topology | Radial | Network |
| Monitoring | Blind | Self-Monitoring |
| Healing | Manual | Self-Healing |
| Testing | Manual | Remote |
| Control | Passive | Active |
| Environmental Friendly | No | Yes |

The major motivations for investing in the SG by governments, academia, industries, and other researchers includes:

1. To proffer solutions to the challenges and limitations of the current grid with respect to the 21-st century electricity demands.

2. The outstanding benefits of the smart grid to the utility providers, the consumers and the environment. These benefits are evident from improved system reliability, lower cost of electricity usage and maintenance, improved customer interaction through provision of timely electricity pricing information, reduced environmental hazards due to emissions form over dependence on fossil fuel , sustainable and efficient supply of electricity, security and safety due to reduction of injuries and losses on life and properties as a result of grid related issues [13].

In [14] the SG is described as a collaborative platform made up of five layers – the power system layer, the control layer, the communication layer, the security layer and an application layer. Of these layers, the communication layer is considered pivotal to the smartness of the grid and key research area of the SG.

## 2.2 Smart Grid Communication Network

To achieve the goals of the SG, a reliable, cost effective and secure communication infrastructure that will support a two-way information delivery between customers and power suppliers in the smart grid is imperative [15]. This communication infrastructure has been envisioned as a hierarchical communication structure that extends across the entire SG as shown in figure 2.2 and further subdivided into home area network (HAN), neighborhood area network (NAN) and wide area network (WAN) based on coverage area, data rate and range [16] as illustrated in figure 2.3

End-user appliances communicate with smart meters through HAN; HANs connect to a local access point called data collector units (DCU) through the NAN. Each DCU covers several surrounding HANs. The WAN connects several NANs to the utility's control center using a high-speed backhaul communication technology.

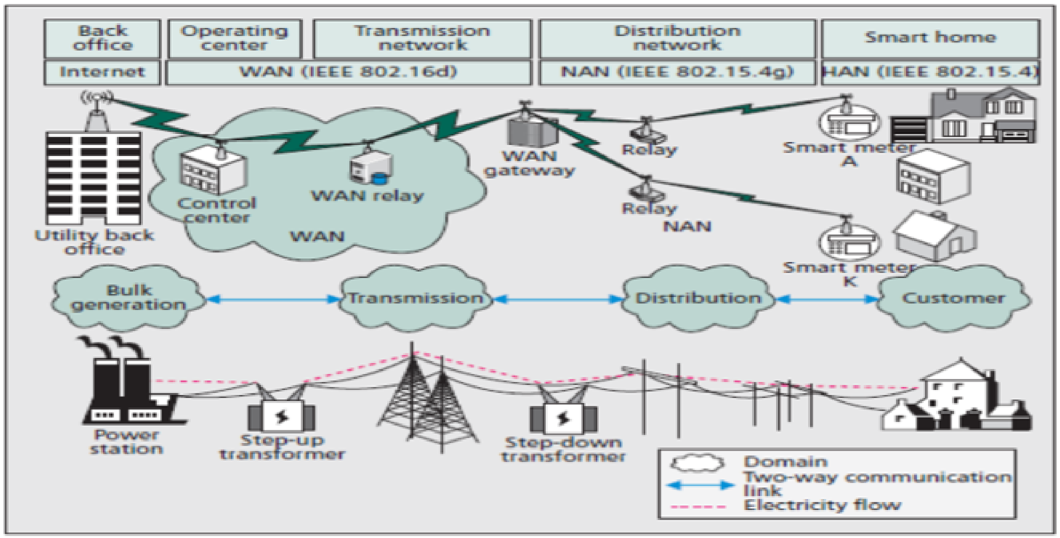



**Figure 2.2:** *A conceptual model of smart grid communication architecture*

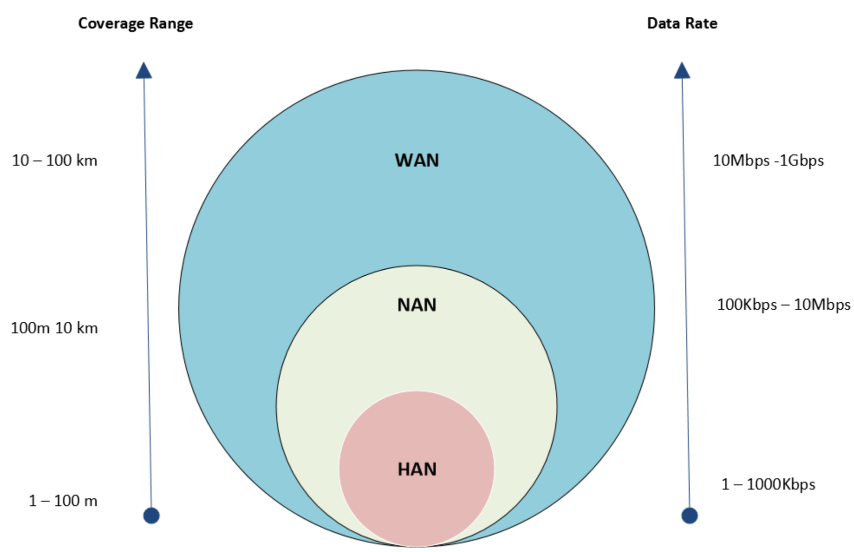



**Figure 2.3:** *Smart grid communication Network structure*

## 2.3 Smart Grid Neighborhood Area Network

NAN is the smart grid communication network that functions in the distribution domain of the smart grid and viewed as the last mile of the SG network. Its core function is to provide a communication link between a group of smart meters and the utility control center for information gathering and dissemination through a single data concentrator unit as illustrated in figure 2.4.

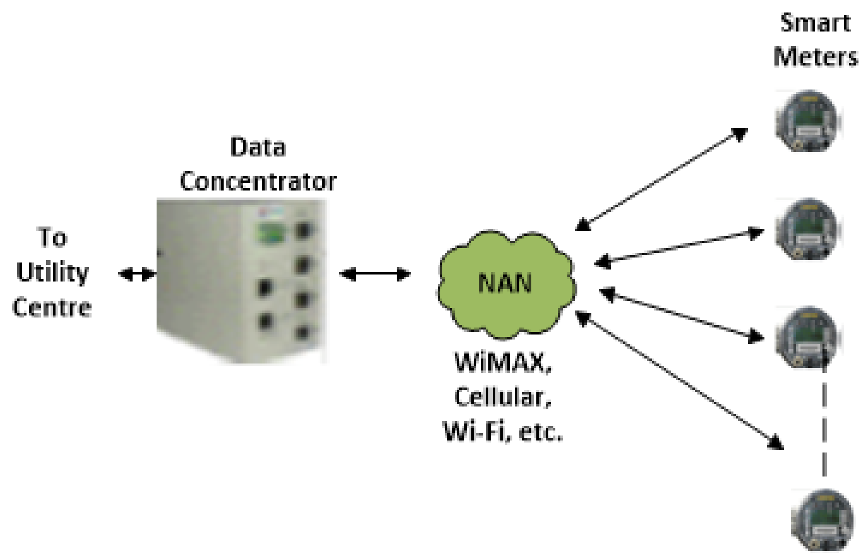



**Figure 2.4:** *Smart grid neighborhood area network*

The major components of this network are:

**Smart Meters** – Located at the user's premises; collects and transmit energy and other data from and to the users. It also serves as the HAN gateway.

**Data Concentrator Unit** – It interfaces between the Utility control center and multiple smart meters. It serves as gateway to the WAN. A single DCU can serve up to a thousand smart meter, however depending on the consumer/market concentration, smart meter groupings ; a DCU can serve between a 100 to 2000 smart meters [17].

**Communication network** - To provide two-way communication between the SMs and the DCUs. NAN can be implemented using wired or wireless communication technology [18]. In view of the huge number of nodes involved, the enormous and complex geological area covered by NAN, ease of installation and maintenance, the need for flexibility and reduction in total cost; wireless communication is viewed as a suitable communication technology for implementation of NAN[19][20].

## 2.4 Smart Grid Communication Technologies

Organizations including The Institute of Electrical Electronics Engineers (IEEE), International Electrotechnical Commission (IEC), and the National Institute of Standards and Technology (NIST) have been working on the standardization of smart grid communication system[21]. To provide efficient, reliable, and secure transmission of data, the SG communication infrastructure is expected to combine different communication technologies[3]. SG communication technologies can be broadly grouped as wired communication technologies (PLC, Ethernet, T1, etc.) and wireless (licensed or unlicensed) communication technologies. With the advancement in wireless communication technologies and need to reduce operational cost; there is a strong shift towards wireless communication technologies for various applications in the SG due to lower installation cost, higher mobility and real time capabilities associated with wireless communication technologies. Table 2.2 itemizes key wireless communication technologies in use for SG wireless communication.

**Table 2.2:** *Comparison of Key Wireless Technologies Used in SG[22][23]*

| WCS | Spectrum | Operating Frequency | Bandwidth | Data Rate(Mbps) | Range | Latency |
|---|---|---|---|---|---|---|
| IEEE802.11 a | Free -ISM | 5GHz | 20MHz | 6–54 | 120m | Up to 4ms |
| IEEE802.11 b | Free -ISM | 2.4 GHz | 22 MHz | 11-Jan | 140m | Up to 4ms |
| IEEE802.11 c | Free -ISM | 2.4 GHz | 20 MHz | 6–54 | 140m | Up to 4ms |
| IEEE802.11 n | Free -ISM | 2.4, 5 GHz | 20/40 MHz | 7.2-72.2/ 15-150 | 250m | Up to 4ms |
| IEEE802.11 ac | Free-ISM | 5GHz | 20/40/80/160MHz | 86.7/200/433.3/ 866.6 | 35m | Up to 4ms |
| IEEE802.15.1<br>Bluetooth | Free-ISM | 2.4-2.483GHZ | 1MHz | 24-Jan | 70m | Up to 10ms |
| IEEE802.15.4<br>ZigBee | Free-ISM | 2.4GHz, 915/868MHz | 5MHz, 2MHz, 600KHz | Up to 250Kbps | 10-100m | Up to 10ms |
| IEEE802.16<br>WiMax | Free-ISM | 2-6GHz | 1.25/5/10/20MHz | 70 | Ten of KM | Up to 10ms |
| IEEE802.20<br>Cellular (GSM,<br>GPRS,EDGE,3G) | Licensed | Cellular | 470-768 MHZ | Up to 56 | Hundreds of KM | Up to 10ms |
| Cellular (4G, LTE) | Licensed | Cellular | 700-2600MHz | 1Gbps | Hundreds of KM | Up to 5ms |

WCS - Wireless Communication Standard

## 2.5 Cognitive Radio Application in Smart Grid

Though the above wireless communication technologies can be used for transmission of data between smart grid components, the following are key limitations:

- Spectrum scarcity – with the proliferation of wireless devices contending for the limited radio spectrum, availability of radio spectrum is major challenge facing most of these technologies[24].
- These technologies operate only on specific range of spectrum as assigned by the regulatory authorities; thus this limits their extent of use for SG communication.
- Transmission of data in SG spans across the HAN, the NAN and the WAN, these networks cover a large geographical area with different communication requirement for applications running on these networks in terms of range, bandwidth, reliability as well as cost on the part of utility providers. This also places a limitation on the use of these technologies to achieve an efficient and reliably smart grid communication.

Cognitive radio technology is an intelligent wireless technology designed to address the problem of spectrum scarcity[3]; it can opportunistically use all available spectrum bands and provide a reliable communication across different geographical areas.. Cognitive Radio has been identified by various researchers as a viable technology to solve the issue of spectrum scarcity and other smart grid communication network problems [3][25]. Apart from being a panacea to the radio spectrum scarcity problem, other benefits of using cognitive radio in SG communication includes cost-efficiency, energy-efficiency, low interference level and increase interoperability. CR lets smart grid users to access spectrum bands optimistically.

The authors in [3] proposed the application of CR for backhaul communication in the SG wide area network and discussed the benefits of the proposed scheme in Urban and rural areas. In [26], a cognitive – radio – based communication architecture was proposed for the HAN, NAN and WAN of the smart grid. This was driven by the need to meet up communication challenges in the SG with respect to highly varying data traffic, explosive data volume, need for interoperability and QoS support.

# 2.6 Smart grid and Cognitive Radio

## 2.6.1 Radio Spectrum And Spectrum Access Policies

The primary resource for wireless communication is the electromagnetic spectrum; which is the portion of the frequencies laying between 30Hz and 300GHz. To cope with exponential increase in the limited spectrum demand and reduce interference, the Federal Communications Commission FCC broadly classified the radio spectrum as licensed and unlicensed bands and adopted the Fixed Spectrum Access (FSA) policy

### 2.6.1.1 Fixed Spectrum Access (FSA) Policy

In FSA exclusive rights to certain frequency bands are assigned to specific or class of users in temporal (over a period (i.e. decades) and spatial (for a large geographical region i.e. country wide) dimensions. The remaining portion is left for unlicensed use with equal rights. FSA works well if the demand for spectrum does not exceed the supply, however with the exponential growth and demand for spectrum, there appears a great famine of spectrum. The FCC report on spectrum utilization in November 2002[4] showed that a great portion of the licensed spectrum is under used. This suggests that the FSA is responsible for the perceived spectrum scarcity and not physical shortage of spectrum.

### 2.6.1.2 Dynamic Spectrum Access

In finding new ways to efficiently manage the utilization of radio spectrum, regulatory bodies have come up with the dynamic spectrum access (DSA) policy as a panacea to the dilemma between spectrum scarcity and utilization[27]. DSA is a spectrum sharing model which permits an unlicensed user (secondary user) to temporarily utilize part of the frequency assigned to a licensed user (primary user) when it is not utilized, on the bases they do not interfere with the primary user. Cognitive radio is the primary technology for implementing DSA. Two categories of users are present in DSA, the Primary User (PU) – assigned exclusive and pre-emptive right to a licensed spectrum band. The Secondary User (SU) – an unlicensed user enabled to use the PU's channels optimistically. The SU uses the spectrum holes (PU channels that are temporarily unoccupied in particular time and location) for its transmission and vacates these channels when the PU returns.

### 2.6.2 Cognitive Radio Overview

Cognitive radio is a new paradigm in wireless communications, presented first by Dr. Joseph Mitola in 1999[28]; it is now a major research topic which has gained the attention of various industries, regulators, and academia. It is a flexible and intelligent radio technology with cognitive capability and re-configurability. It is capable of detecting holes in a radio spectrum and re-configure or modify its transmission parameters to adapt the new radio environment. CR enables more communications to run simultaneously with improved performance in radio operation and without interfering with licensed users. The essential difference between CR and traditional radio technologies is its cognitive and re-configurability capabilities [29][30] ].

The prime objectives of CR are a highly reliable communication irrespective of the geographical location and time and an efficient utilization of the radio spectrum [28]. In a CR network, the licensed user is the primary user (PU) and has sole right and priority in the use of its channels. The cognitive radio user or secondary user (SU) is an unlicensed user with cognitive ability to access the spectrum the licensed spectrum in an opportunistic manner. The SU must vacate whenever the PU reappears the SU must vacate its channel to avoid interfering with the PU's transmission[31].

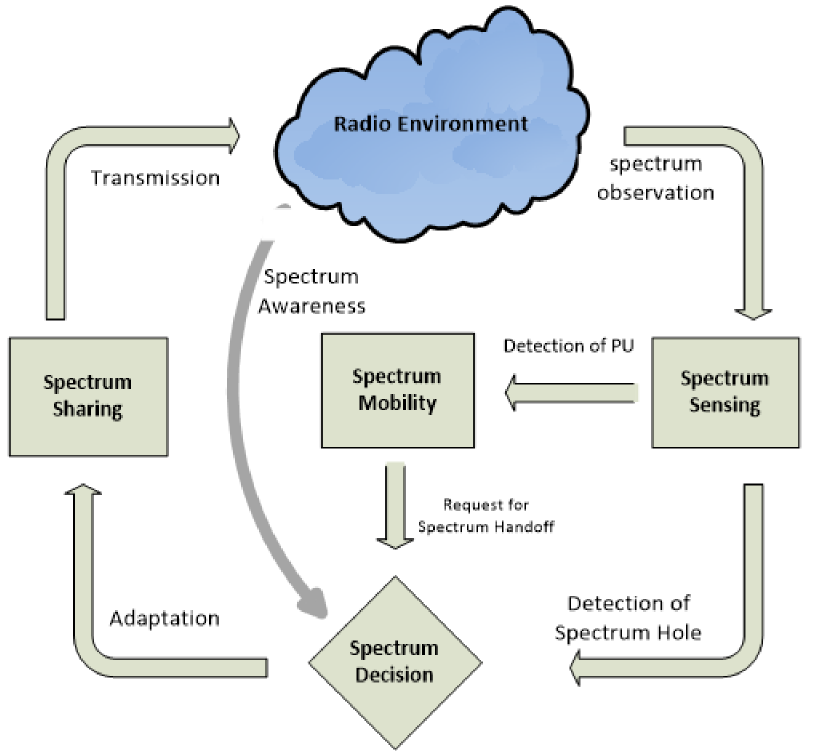



**Figure 2.5:** *Cognitive Radio Cycle*

Cognitive radios have four on-line tasks as they interacts through the RF environment[30]. These tasks are also referred to as CR radio cycle or CR management functions. They are: spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility as illustrated in figure2.5

**Spectrum sensing:** This is regarded as the first and most important phase in starting communication in a CR network[32]. In this phase the CR monitors the radio spectrum to identify spectrum holes and capture their information (out-bound sensing). They also monitor the spectrum band to detect the reappearance of PUs in the course of their transmission or degradation of the occupied channel condition in order to minimize interference to the PUs or maintain QoS requirement (in-bound sensing).

**Spectrum decision:** This phase uses the information obtain through sensing to selects the best channels out of the available spectrum holes and determines the transmission parameters. The three key steps in this function are: spectrum characterization, spectrum selection and CR reconfiguration of SU transceiver parameters to support communication[33]. Availability of spectrum, quality of service and cost of communication are also considered in the decision process.

**Spectrum sharing:** Coordination of access to spectrum holes with other user (cognitive and non- cognitive users) is handle at the third stage of the cognitive radio cycle[29].

**Spectrum mobility:** When the licensed user (PU) reappears or channel conditions fall below quality of service requirement, the cognitive radio user vacates the licensed channel, and transfer its service to another spectrum hole to maintain seamless communication[34].

## 2.7 Spectrum Handoff In Cognitive Radio

### 2.7.1 Spectrum Handoff Concept

Cognitive radio users use unoccupied channels of the primary user as its main operating channel. These free/unoccupied frequency channels of the primary user are referred to as spectrum holes[28].

A peculiar challenge in cognitive radio communication is that the spectrum holes occupied by the SU may not be available for the whole period of its transmission. At the return of the primary user, an SU occupying its channel has to vacate to avoid interfering the PU's traffic and switch to another available frequency band to continue its ongoing transmission. This transition of SUs from one frequency band to another is called Spectrum Handoff or Spectrum Handover[35]. Spectrum handoff is required to avoid primary user - secondary user interference, maintain seamless communication for the CR users, while maintaining the QoS requirements. Figure 2.6 illustrates the concept of spectrum handoff.

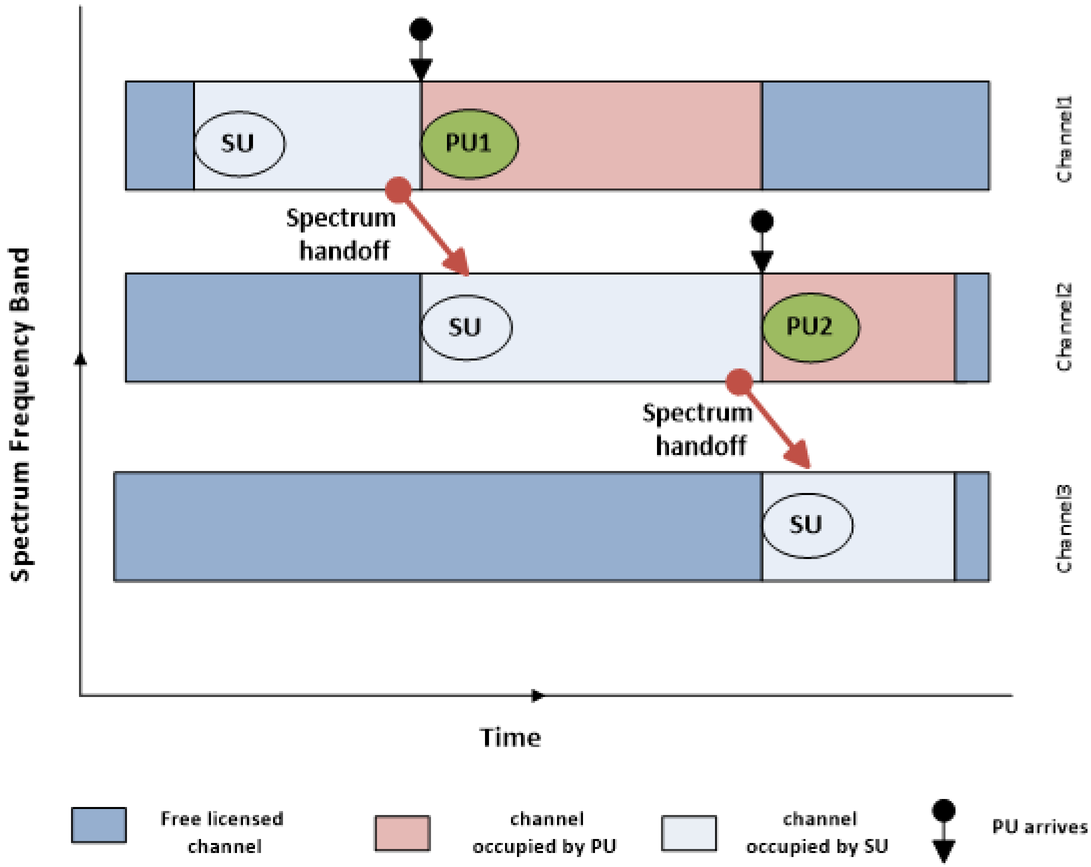



**Figure 2.6:** *spectrum Handoff Concept*

### 2.7.2 Spectrum Handoff Triggering

Spectrum handoff can be triggered by the following events as specified in [36–38]

1. **PU arrival in the licensed channel** - Unlike in other traditional wireless communication technologies, PU arrival is regarded as the most important parameter for the initiation of spectrum handoff in cognitive radio networks. It is the main parameter in timing-based spectrum handoff schemes

2. **CR user mobility** - When a CR in motion interferes with a PU currently using the same channel, spectrum handoff will be initiated.

3. **Degradation of the Signal quality**- When channel conditions of a channel used by SUs for communication falls below its QoS requirement, spectrum handoff is

triggered.

4. **Availability of free channels-** Especially in proactive spectrum procedures, the availability of free channels can influence spectrum handoff.

Fast and smooth selection of target channel for the vacating SUs to resume its ongoing transmission thereby evading performance degradation and reducing spectrum handoff time, is the prime aim for designing spectrum handoff schemes. These schemes are broadly classified, based on handoff triggering events. Table 2.3 summarizes these classifications [35, 38, 39].

**Table 2.3:** *Summarized Classification of Spectrum Handoff Schemes*

| Handoff Scheme Classification | Triggering Parameter | Channel Selection Criteria | Suitability |
|---|---|---|---|
| Time triggered | PU arrival rate | Time SU decides to select target channel (before or after PU arrival) | CR networks mainly depending on PU activities |
| CR user mobility triggered | CR user mobility | Motion of CR user with respect to spectrum pool and serving base station | CR cellular networks |
| Spectrum Sensing triggered | Pu arrival/Channel/degradation /availability of free channels | Effect of spectrum sensing method | General CRNs |
| Channel prediction probability triggered | Availability of free channels | Prediction of channel state and length of time the it is frees | General CRNs |

The procedure for spectrum handoff at the return of a PU to its channel, follows the order below and it is illustrated as shown in figure2.7:

1. Detection of PU and Preparation for Handoff.

2. Spectrum scanning and handoff decision.

3. Coordination, reconfiguration and spectrum handoff execution.

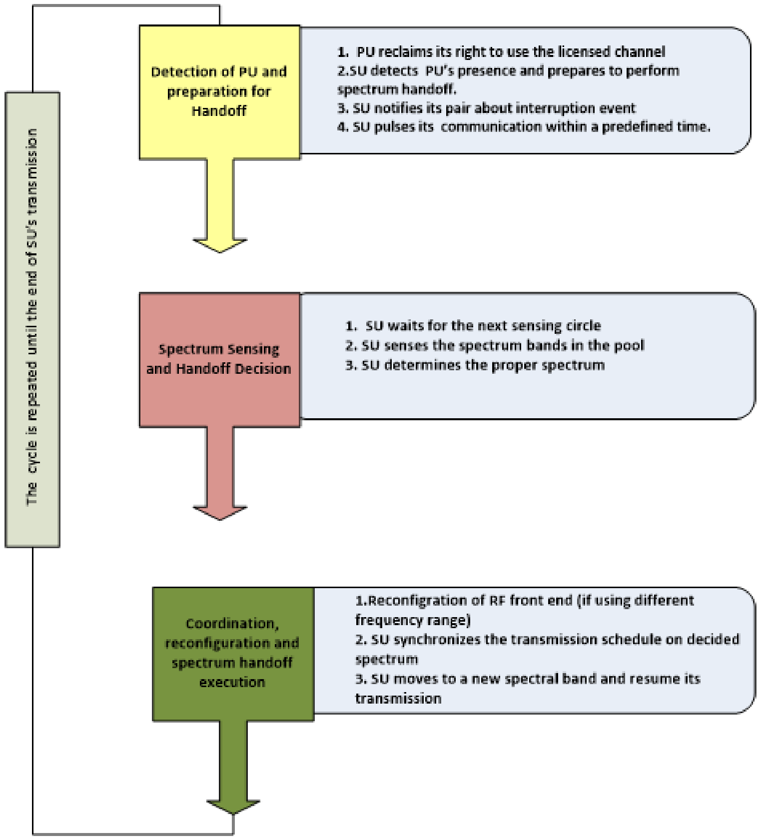



**Figure 2.7:** *Spectrum Handoff Process[40]*

## 2.8 Spectrum Handoff Performance Metrics

Efficient spectrum mobility can be accomplished by choosing an effective spectrum handoff strategy; spectrum handoff metrics/parameters are the indicators used to determine the effectiveness of designed spectrum handoff schemes. These parameters can be used for short term or long term evaluation of the handoff performance strategy[41].

1. **Link Maintenance Probability (LMP):** This is the probability that communication link of an SU in service, is successfully maintained when it vacates its current channel. The condition for a successfully link maintenance, is availability of a free channel for the SU to resume its communication, within allowable spectrum handoffs. LMP depends on the availability free channels in the system. For effectiveness,

this probability is expected to be high, the higher the better.

2. **Spectrum Handoff Latency:** It is referred as the cumulative delay or total time between the pausing and resumption of an SU's transmission at any given instance. It can be estimated from various parameters such as handoff set-up time, time to decide the best channel out of available channels, time to synchronize sensing and switching delay and delay due to inter cell resource allocation in the case of a cellular network. For real time multimedia services, handoff delay is very significant. For an effective SHO scheme, this parameter is expected to be minimal.

3. **Number of Spectrum Handoff:** This refers to the number of handoffs that occurs during one session of data communication in a CR network. For an efficient SHO scheme, this parameter is expected to be minimal.

4. **Number of handoff trials:** The total handoff trials that occur for an entire transmission period is another significant performance measure. Increase in the number of spectrum handoff trials increases secondary user's probability of maintaining an established link and the transmission time also. It can also be taken as channel switching rate, every time the channel switches, it includes some sort of delay and it decreases the capacity of network.

5. **SU non-completion probability:** This is the probability of an SU not completing its service.

6. **Collision Probability:** This is the probability of an interference between primary and secondary users at the return of a primary user to its channel which is in use by a secondary user. Collision probability value must be less for efficient spectrum usage and smooth handoff.

7. **Blocking probability:** This refers to the probability of SU not having access to the PU's channel due to non-availability of radio channel. For an efficient CR communication network, blocking probability should be low.

8. **Forced termination probability:** This is the probability of a cognitive radio user been forced to leave a channel for an arriving licensed user. This probability is

expected to be low.

9. **Effective Data Rate:**This parameter refers to the average of data transferred successfully between two CR users whose link is successfully maintained. The higher this parameter, the better.

## 2.9 Spectrum Handoff Scheme

Spectrum handoff schemes can be grouped based on the handoff triggering events. With respect to time triggering, spectrum handoff schemes are grouped into four, namely: non-handoff, pure reactive handoff, pure proactive handoff, and hybrid handoff strategy[38] as illustrated in figure 2.8. In these schemes, the target channel selection process is related to spectrum sensing and handoff times; Spectrum sensing as well as handoff can be done prior to or after the handoff triggering event[42].

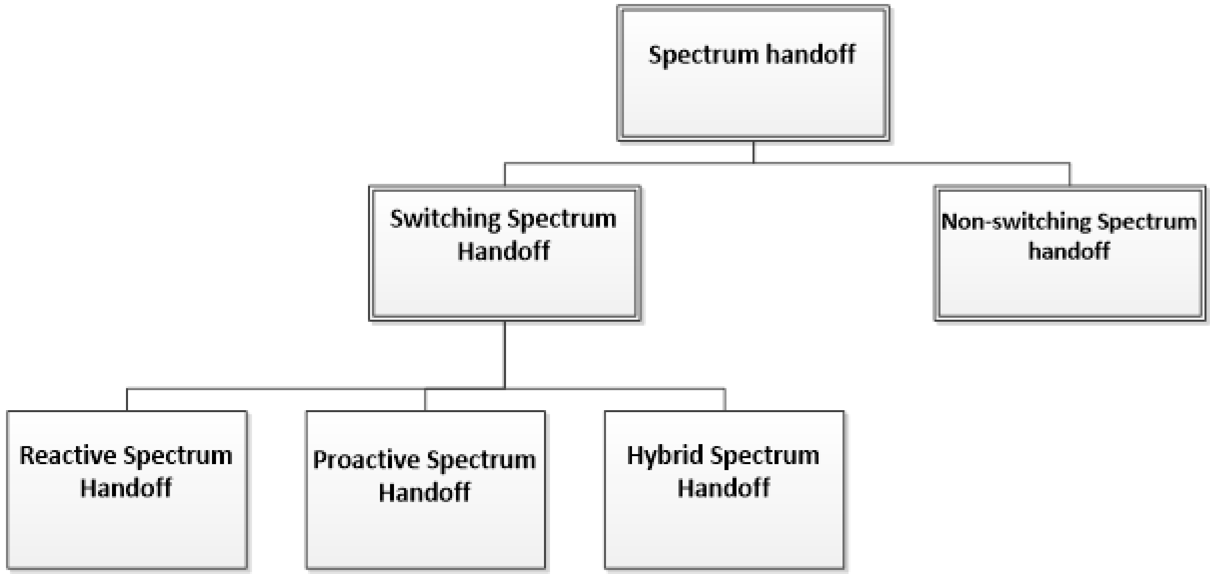



**Figure 2.8:** *Classification of Spectrum handoff Schemes*

### 2.9.1 Non - Handoff Scheme

For non- handoff or non-switching spectrum handoff scheme, the SU remains idle in the original channel and selects the current channel as its next target channel when handoff triggering event (reappearance of PU) takes place. The SU resumes data transmission after the PU completes its transmission [37]. This process reoccurs until SU completes its transmission in this channel. The waiting time of the interrupted SU, is the busy period of the PU in the same channel. The disadvantage of this scheme is that it increases the SU's latency. This makes it unsuitable for delay sensitive applications since it will fail to meet QoS requirements and short PU data transmission.

### 2.9.2 Pure Reactive Handoff Scheme

In this scheme, the selection of target channel and the decision to handoff are done after a handoff triggering event has occurred. The target channel selection follows an on-demand method. When interrupted by reappearance of the PU, SU senses, moves and resumes its transmission in the new channel. This process reoccurs until the SU completes its transmission. Some characteristics of this scheme includes; high handoff latency due to sensing time, precise target channel selection because sensing of target channel is done in real time[43]. Reactive spectrum handoff strategy performs better than the proactive strategy for short sensing time, however when the sensing time is long, the proactive strategy performs better[44].

The authors in [44] analyzed channel utilization and extended data delivery time are affected by decision manner of a reactive handoff scheme in cognitive radio network. This analysis considered different PU and SU traffic arrival rates and service time distributions. They concluded that results from their analysis can ease the formulation of SU admission control protocol and provide basis for evaluating if data delivery time can be effectively shortened by a spectrum sensing technology under different time distributions. In [43] the authors presented a mixed preemptive/non-preemptive resume priority queuing model. The model was aimed to reduce SU delay time in a reactive handoff scheme combined with random target channel. A reduction in in SU delay time is observed in this model compared to other models.

### 2.9.3 Pure Proactive Handoff Scheme

Backup target channel selection and handoff action are performed before the handoff triggering event occurs. SU predicts the arrival of the PU based on long term statistics/ knowledge of PU traffic model and leaves the channel in advance[45]. Merits of this scheme are, low handoff latency and the probability of multiple spectrum handoffs being minimized. The disadvantages are that the selected target channel may become obsolete due to the preselected channel already being occupied by another user. Degrade of overall spectrum mobility performance due to poor prediction of PU traffic model.

A proactive spectrum handoff framework for CR ad hoc networks was proposed in [45]. Their design included channel switching policies and network coordination and distributed channel selection schemes to address PU/SU communication issues. They considered the performance of their proposed model with respect to throughput and collision rates, based on simulation results, they concluded that their model performed better than a reactive spectrum handoff approach. A Target Channel Sequence Selection Scheme for Proactive-Decision Spectrum Handoff proposed by [46]. This scheme minimized frequency of handoff failure and optimized performance with respect to the expected number of handshake trials till success. The authors in [39] evaluated the performance of proactive spectrum handoff Performance, result of their proposed algorithms showed that proactive spectrum always outperformed the reactive in terms of high capacity and lower collision rates.

### 2.9.4 Hybrid Handoff Scheme

This scheme adopts the pure proactive scheme's target channel selection approach and the handoff decision approach of the pure reactive scheme. It has less handoff latency, but target channel can be obsolete.

Authors in [47] proposed an algorithm that combines proactive and reactive decision methods and analyzed the total service time of the cognitive user. In their algorithm, depending on the PU arrival rate, there is a toggle between the proactive and the reactive decision modes. Compared to either pure proactive or reactive mode, SU total service time is considerably reduced using the proposed hybrid handoff algorithm. To maximize SU quality of experience for multimedia applications in a CRN, a mixed preemptive/non-preemptive resume priority M/G/1 queuing model was proposed in [48]. In this scheme , the target channel was selected and sensed proactively and while the handoff decision was done reactively depending on the varying channel conditions and QoS requirements.

**Table 2.4:** *Summary of Time Triggered Spectrum Handoff Schemes*

| Handoff Scheme | Main Idea | Dependency | Handoff Latency | Strengths | Weakness |
|---|---|---|---|---|---|
| Non-Handoff | Stay and wait | PU activity | Unpredictably High | Very low PU interference level | Very High SU interference |
| Pure Reactive | Reactive Sensing Reactive Action | Spectrum Sensing | Medium | Accuracy selected target channel | Slow response |
| Pure Proactive | Proactive Sensing Proactive Action | Backup Channel relevance,Accurate PU traffic model | Very low | Predicts the arrival of PU on the channel, Fast response with reduced collision rate | Obsolete target channel selection, High computational requirements, Poor mobility performance due to poor prediction of PU traffic model |
| Hybrid | Proactive Sensing,Reactive Action | Backup Channel relevance | Low | Fast response | 'Outdated target channel selection |

## 2.10 Spectrum Handoff Strategies

Several spectrum handoff strategies have been developed based on the above broad time-based classifications some of which are:

### Fuzzy Logic based schemes

Using this approach, Pushp and Awadhesh in [49] proposed a spectrum handoff scheme that employed fuzzy logic and neural network to determine quality PU channels based on three parameters – PU interference , PU cannel bit error rate and signal strength. Selection of these channel in the spectrum handoff process improved channel utilization and reduced number of spectrum handoff. In [50] the authors proposed a fuzzy logic-based solution which was employed to determine the quality of PU channel in terms of PU activities and Signal-to-Interference-plus-Noise ratio of each PU channel. This information was used by CR users to decide the best (not just the available) PU channel as target channel during spectrum handoff decisions. The proposed spectrum handoff scheme improved the SU communication by reducing the frequency of channel switching and consequently improving the throughput of the SU network. CR handoff decision precision was improved in [51] using a fuzzy logic based handoff strategy.

**Guard Channel Approach**

A novel Hybrid Guard Channel Strategy (HGS) scheme was proposed in [52] to improve QoS of CR – based NAN domain using guard channel strategy. Some licensed spectrum bands are leased/purchased from a telecommunication provider, and these bands were used as licensed access for the HAN gate ways (HGWs) to ensure the QoS of data communications. Compared to conventional solutions, this scheme attained better dropping probability. In [53] TV band guard channels were employed for this scheme with decrease in total service time was accomplished.

**Power Controlled Based Spectrum Handoff Scheme**

This scheme which was proposed in [54] improved spectral efficiency, reduced number spectrum handoff, and enhanced effective data rate by intelligently changing the transmit power of the SU.

**Markov Model Based Schemes**

using a three-dimensional Markovian model, authors in [35] proposed a handoff scheme for an ad hoc CR network operating in an heterogenous spectrum environment. This scheme improved the SU non-completion probability. In [55] a similar scheme was proposed to analyze SU performance in terms of non-completion probability. Their result showed that for lower arrivals and higher service rates of PUs, SUs and CUs link maintenance was higher.

**Queueing Theory Based**

Spectrum Handoff techniques based on queueing theory have been proposed by several authors to enhance SU communication in cognitive radio-based networks. In [56] authors Proposed a preemptive resume priority (PRP) M/G/1 queuing network model. Extended data delivery time were estimated for different proactive target channel selection scenarios. The effect of multiple handoff delay due to various sources are examined.

**Spectrum handoff Using backup Channels**

Cognitive radios use the licensed channels as their core communication channels. This scheme aims at maximizing spectrum usage, reduce the number of spectrum handoffs and improve other SU traffic performance by incorporating the unlicensed spectrum channels in the handoff strategy. Mohamed A. Kalil and two others in [8] presented a mathematical model to analyzed the performance of this scheme. They observed that the use of backup channel performed better than the classical scheme which uses no backup channels. Their analysis was in terms of number of spectrum handoff and link maintenance probability. In [57] authors proposed a spectrum handoff scheme using the unlicensed channels as backup channels for CRNs in centralized and ad hoc scenarios. From their analysis SU performance of the with respect to blocking probability, link maintenance and dropping probabilities in both centralized and non-centralized scenarios performed better than the classical scheme (without a backup). Also, they observed that the non-centralized scheme was more effective with better SU service completion but with higher handoff trials. Salah Mohammed in [58] proposed a spectrum handoff scheme which used the unlicensed channels as backup. In this scheme, using retrial queueing theory, preference was given to handoff secondary user over non-handoff secondary users. Evaluation of the SU performance showed an improvement of handoff delay and better SU communication.

For application to SG, a power scheduling scheme driven by CR was proposed for efficient CR communication and optimal power distribution in [7]. The authors also modeled the behavior of power scheduling using CR technology, simulation results evaluated over chosen performance metrics showed that this scheme can significantly evade power wastage. Authors in [25][59][6][60][61][62][63] addressed various issues of CR-based SG with respect to spectrum sensing, interference, power scheduling, spectrum sharing and test beds. Spectrum handoff in CR based is still a well unexplored area that needs to be given more attention.

In this work the basic principles of the backup channel-based spectrum handoff scheme proposed by [57] will be adopted and improved upon to address spectrum handoff issue in a CR-based SG NAN communication network.

# 3

# SPECTRUM HANDOFF SCHEME MODELLING

## 3.1 Introduction

*An efficient spectrum handoff scheme is key to improving spectrum handoff management process and performance of the CR network. In this chapter a spectrum handoff scheme using the backup channel strategy is proposed for a smart grid cognitive radio-based neighborhood area network. The backup strategy is proposed to utilize both licensed and unlicensed channels for backup instead of just the unlicensed channels, as utilized in earlier works. This chapter is subdivided into three main sections. Section 1 describes the adopted system model; section two focuses on formulation of the spectrum handoff scheme to meet the goals in this research. The final section presents the mathematical models for spectrum handoff performance/evaluation parameters such as blocking probability, link maintenance probability and link failure probability.*

## 3.2 System Model

The system model is illustrated in figure 3.1; it is an ad hoc cognitive network consisting of smart grid neighborhood area network (NAN) nodes (Smart Meters and Data Concentrator Units fitted with cognitive capability), opportunistically sharing a heterogeneous spectrum environment. The spectrum environment consists of three spectrum pools:

1. Spectrum pool 1 (SP1) – A licensed spectrum pool with C1 number of channels belonging to licensed (primary) users such as TVs, radar or satellite.
2. Spectrum pool 2 (SP2) – A leased licensed spectrum pool with C2 number of channels, leased by the utility provider form a licensed spectrum owner to enhance the performance of its communication.
3. Spectrum pool 3 (SP3) – An unlicensed spectrum pool with C3 number of channels such as an IEEE 802.11x wireless LAN.

Three types of users are present in this cognitive radio-based network:

**The Primary User (PU)** – Owns the licensed channels in SP1 and has pre-emptive right to it. Uses only SP1 for transmission.

**The Secondary/ Cognitive User (SU)** – Smart grid NAN nodes fitted with cognitive radio technology. Can use both licensed and unlicensed channels for their communication. The SU uses spectrum holes in SP1 as its main operating channel and vacates these channels when the PU returns. SP2 is dedicated for use of handoff SUs only. SU uses SP3 as a classical user.

**The Classical User (CU)** - are non-cognitive unlicensed users, they can only access the unlicensed spectrum band (SP3).

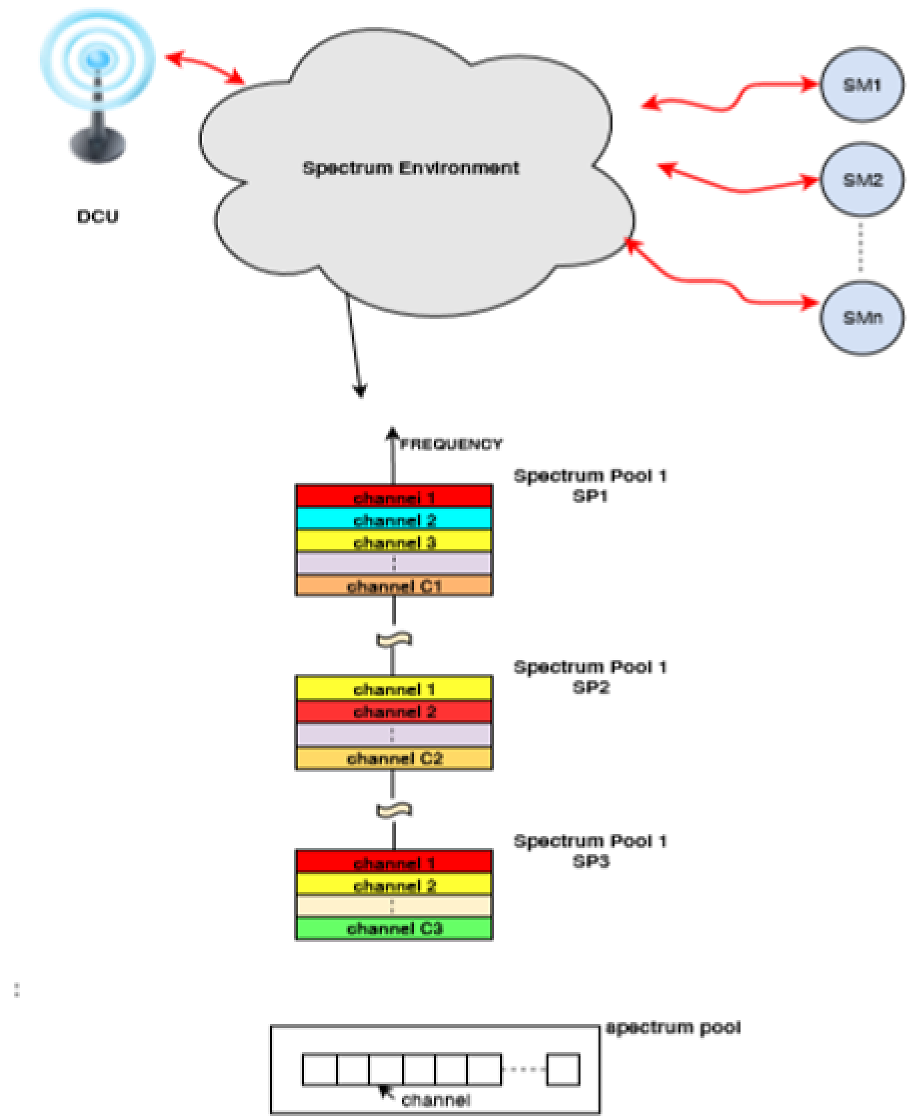



**Figure 3.1:** *System Model for spectrum handoff scheme*

### 3.2.1 System Model Assumption

Analytical models for a real-world application are made with some assumption for ease of mathematical computation, the assumption for this system model are as follows:

1. All nodes are statistically identical and independent of each other.

2. PUs, SUs and CUs arrivals follow the Poisson arrival point process with arrival rates of $\lambda_{pu}$, $\lambda_{su}$ and $\lambda_{cu}$ respectively.

3. The message lengths (call holding times) $\mu_{pu}$, $\mu_{su}$ and $\mu_{cu}$ of the PU, SU and CU respectively are exponentially distributed.

4. SU starts its transmission from SP1 and blocked calls are cleared.

5. The SU (NAN node) uses SP1 as its main operating channel, SP2 and SP3 are used as backup channels.

**Table 3.1:** *Comparison of Spectrum Pool Parameter*

| | Spectrum Pool | | |
|---|---|---|---|
| User Parameter | Licensed Spectrum Pool | Leased Licensed Spectrum Pool | Unlicensed Spectrum Pool |
| PU arrival rate | $\lambda_{pu}$ | PU will not access | PU will not access |
| SU arrival rates | $\lambda_{su}$ | Handoff SUs only | Handoff SUs only |
| CU arrival rate | Access denied | Access denied | $\lambda_{cu}$ |
| PU Service rate | $\mu_{pu}$ | PU will not access | PU will not access |
| SU Service rate | $\mu_{su}$ | $\mu_{su}$ | $\mu_{su}$ |
| CU Service rate | Access denied | Access denied | $\mu_{cu}$ |
| Access priority | PUs have more preference | Only for handoff SU | SUs and CUs equal preference |

## 3.3 Proposed Spectrum Handoff Scheme

The proposed spectrum handoff scheme for the smart grid neighborhood area network nodes is as illustrated in figures 3.3 and 3.4. It is a spectrum handoff scheme with backup channels. In this handoff scheme, priority is given to handoff cognitive radio user traffic. The SUs uses SP1 as its main operating channels; while the leased and the unlicensed channels in SP2 and SP3 respectively are used as backup channels for handoff SUs. Spectrum handoff occur only in SP1.

### 3.3.1 Description of Existing Spectrum Handoff Scheme Based on Backup Channel

In [57][64] authors proposed a spectrum handoff scheme with backup channels for a CR networks operating in an heterogeneous spectrum environment, in opportunistic (ad-hoc) and centralize scenarios. Figure 3.2 Illustrates their designed CR spectrum handoff scheme for an ad-hoc scenario.

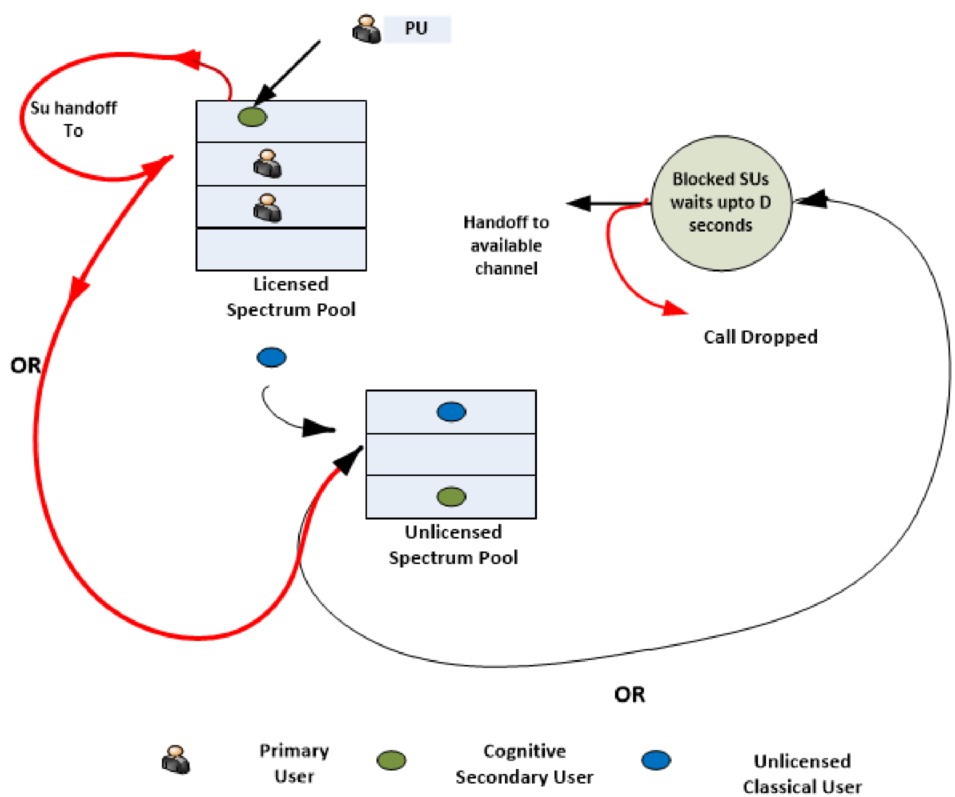



**Figure 3.2:** *Existing spectrum handoff scheme with backup channel scenario*

In this scheme, the CR user operates in an heterogenous spectrum environment consisting of two spectrum pools. The first, a pool of licensed spectrum with $C_1$ channels belonging to primary user and the second, a pool of unlicensed spectrum with $C_2$ channels free for unlicensed usage. In this scheme the SU uses the PU's licensed spectrum pool as its main communication channel; performs spectrum handoff to another free channel when a PU reclaims its channel. Free channels in the unlicensed spectrum pool are used as backup channels for handoff SU users only when there is no free PU channel to handoff to. If the hand off users finds no free channel, a delay period is observed for D seconds after which the call is dropped. The performance of this scheme was characterized by three metrics viz: Blocking probability, Link maintenance probability and link failure probability. These metrics were modeled as:

Blocking Probability:

$$\frac{\rho 1^{C_1}}{C_1!}\frac{\rho 2opp^{C_2}}{C_2!}\left[\sum_{i=0}^{C_1}\frac{\rho^i}{i!}\right]^{-1}\left[\sum_{j=0}^{C_2}\frac{\rho 2opp^j}{j!}\right]^{-1} \tag{3.1}$$

Link maintenance Probability:

$$Pv_{opp}[(1 - P_{b1}) + P_{b1}(1 - P_{b2}) + P_{b1}P_{b2} (1 - \alpha^{C_1-1} - \beta\gamma^{C_2})] \tag{3.2}$$

Link Failure Probability:

$$Pv_{opp}P_{b1}P_{b2}\alpha^{C_1-1}\beta\gamma^{C_2} \tag{3.3}$$

Simulation results comparing the performance of the CR network with the backup situation (OSB) and the classical or CR network without backup channels (OS) showed that their proposed spectrum handoff scheme improved the performance of the classical situation with respect to the above metrics.

### 3.3.2 3.3.2 Motivation for Backup Strategy

Earlier spectrum handoff schemes with backup channels, utilized the unlicensed channels only as backup channels [9][64][65]. In this proposed scheme, both licensed (leased licensed channel- SP2) and unlicensed channels are utilized for backup to improve overall system performance, mitigate backup channel availability issues and improve communication especially for real-time or mission critical data.

For SG applications, wireless communication using the unlicensed channels utilizes industrial, scientific and medical (ISM) frequency bands which include frequencies between 902 to 928 MHz, 2.400 to 2.4835 GHz and 5.725 to 5.875 GHz. These bands have limitation on operating power level; bands are overly congested (due to emergence of several wireless communication standards operating in this band) with high likelihood of harmful interference [66] and may become unsuitable for future mission critical data transmission in SG [67]. Moreover, the availability of free channels in the unlicensed spectrum band as a backup channel for handoff SUs is uncertain since all users have equal priority. Finally, the propagation characteristics of unlicensed channel is much lower as compared to the licensed channel. With the emergence of more smart grid services and the need for more real time data transmission, utilities will need a better business case and more bandwidth than unlicensed spectrum can provide. In this scheme, these disadvantages of complete reliance on unlicensed channels for backup are mitigated by employing a few dedicated licensed channels as backup channels in addition to the unlicensed channels.

### 3.3.3 Description of Proposed Spectrum Handoff Scheme

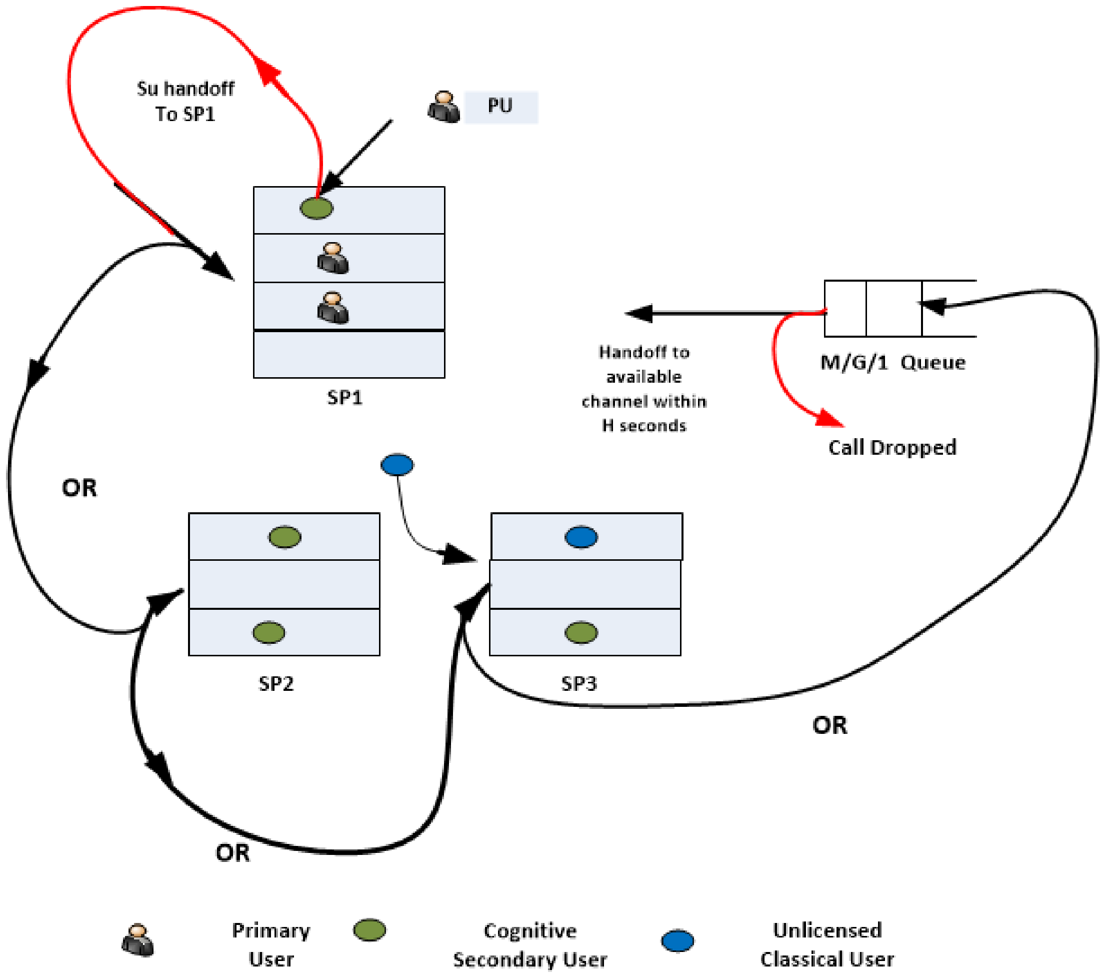
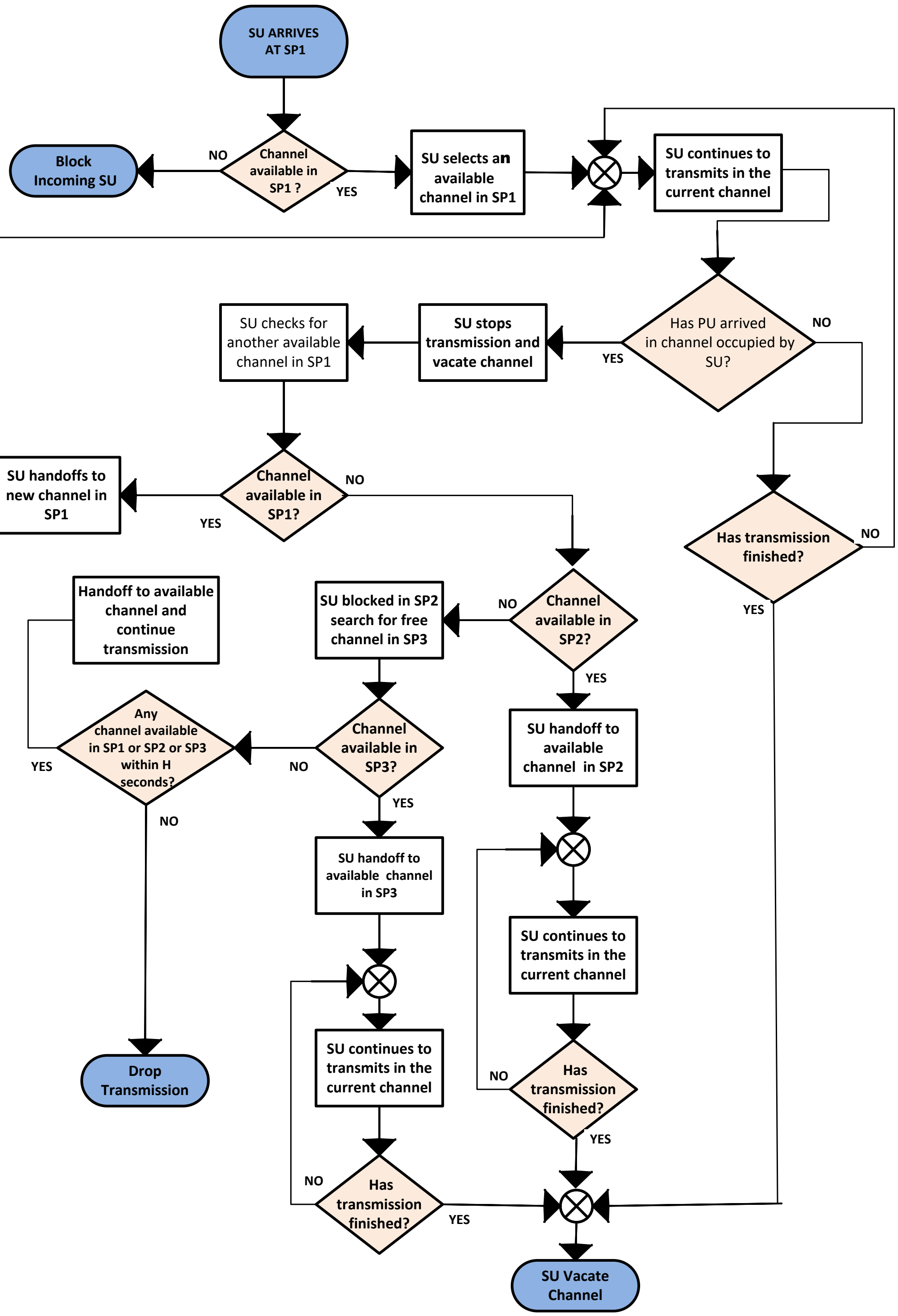



**Figure 3.3:** *Proposed Spectrum Handoff Scheme*


SU ARRIVES AT SP1
Channel available in SP1 ?
NO
YES
Block Incoming SU
SU selects an available channel in SP1
SU continues to transmits in the current channel
Has PU arrived in channel occupied by SU?
NO
YES
SU stops transmission and vacate channel
SU checks for another available channel in SP1
Channel available in SP1?
NO
YES
SU handoffs to new channel in SP1
Has transmission finished?
NO
YES
Channel available in SP2?
NO
YES
SU blocked in SP2 search for free channel in SP3
SU handoff to available channel in SP2
Channel available in SP3?
NO
YES
Any channel available in SP1 or SP2 or SP3 within H seconds?
YES
NO
Handoff to available channel and continue transmission
SU handoff to available channel in SP3
SU continues to transmits in the current channel
SU continues to transmits in the current channel
Has transmission finished?
NO
YES
Has transmission finished?
NO
YES
Drop Transmission
SU Vacate Channel

The scheme operates as follows:

- The SU starts its transmission in SP1. It is admitted only if there is at least one free channel in SP1 otherwise it is blocked.
- The SU continues its transmission and completes its service in SP1, if no PU arrives within the service period of the SU.
- The SU pulses its transmission when a PU arrives on the same channel it is transmitting in, vacates the channel and performs an intra-pool handoff to another free channel in SP1, else it is blocked in SP1.
- The handoff SU blocked in SP1 performs an inter pool handoff to SP2 if it finds a free channel in SP2 and continue its transmission uninterrupted. It is blocked in SP2 if there is no free channel.
- A blocked SU in SP2 will access SP3 if there is at least a free channel and continue its transmission uninterrupted. If there is no free channel in SP3, the SU will wait for a maximum period of H seconds in a queue for a channel to become available in SP1 or SP2 or SP3. Adopted queueing discipline and length is FCFS ( First Come First Served), M/G/1 queue.
- The SU will be admitted into any channel that becomes available within H seconds; else it is dropped (transmission terminated) if no channel become available after H seconds.

## 3.4 Mathematical Formulations

### 3.4.1 Introduction

*In this section mathematical expressions to represent the performance metrics of the proposed spectrum handoff scheme are derived. The metrics include SU Blocking probability, Link maintenance probability and link failure probability for the system operating in an opportunistic manner. The concept of overflow system in a teletraffic loss system is* *adopted to characterize the traffic of the handoff cognitive radio user with respect to the above metrics. Erlang B formula, Poisson process and Exponential Distribution are key mathematical concepts applied for the derivation of these performance metrics.*

In teletraffic engineering, probability theory is applied to telecommunication systems for the purpose of planning, making predictions on network performance, etc. The objectives of this theory include:

- To use mathematical models to make traffic (the statistical or stochastic properties of arrival and call holding times) measurable.
- Derive relationships between number of resources (trunks, channels, etc.), the random demand and quality of service of the system. This derivation help decide on the performance of the system (e.g. blocking probability, average waiting time, fraction of calls that overflow, etc.)

Teletraffic networks are handled as:

1. Loss System - where calls that cannot handed immediately (blocked calls) are rejected from the system.
2. Delay System - where call that cannot handed immediately (blocked calls) are queued

An overflow system is a teletraffic loss system in which blocked calls are transferred or overflow to an alternative route thereby reducing the likelihood of calls being dropped. A call blocked in the alternate route is rejected and cleared.The handoff traffic pattern of an SU in a spectrum handoff scheme operating in a backup scenario can be described as an overflow traffic system.

In modelling the SU traffic performance with respect to spectrum handoff scheme operating in a backup scenario, reviewed existing schemes which followed the teletraffic principles omitted the bursty nature of the handoff SU traffic, this gives an overall blocking probability less than the actual The proposed scheme is carefully modelled as an overflow system with mixed renewal and Poisson inputs; attention is also paid to the bursty traffic nature of the SU handoff traffic overflowing from the primary to the secondary systems.

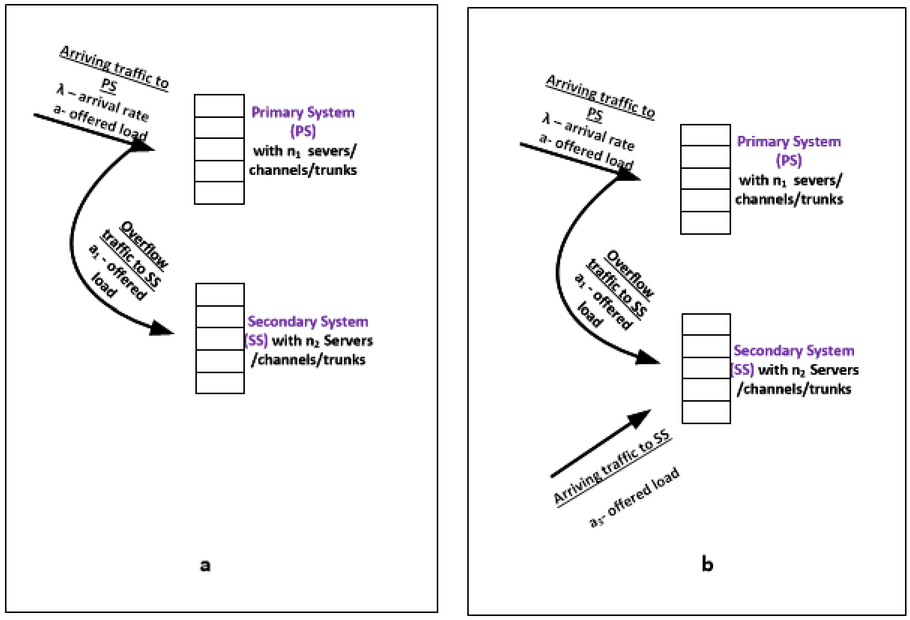



**Figure 3.5:** *Overflow in a loss system with mixed inputs*

Figure 3.5 illustrates overflow traffic in a switched circuit system in which traffic to the secondary system in (a) is a renewal traffic while traffic input in (b) is a mixed renewal and Poisson traffic.The network consists of a primary system of $n_1$ servers/channel/trunks and secondary system with $n_2$ servers. Both forming an $n = n_1 + n_2$ overflow system. All incoming traffics are directed to primary servers with an offered load (traffic intensity) of **a**. If all primary servers/channels are busy, the traffic overflows to the secondary servers with traffic intensity $a_1$. The arrival process of the overflow traffic is an interrupted Poison process (IPP). The arriving request is completely blocked if all secondary servers are busy.

The Poisson traffic into the primary group is characterized by the mean value of offered traffic (a), the capacity of the primary group(n), and peakedness factor(z). The interrupted Poisson traffic is characterized by mean value of the overflow traffic(b) and the peakedness factor(z).The peakedness factor of a traffic, is ratio of the variance to the mean value of its offered traffic. It is given as:

$z = \frac{\sigma^2}{m}$

$z = 1$ for Poisson traffic

$z < 1$ for serviced traffic in the primary group

$z > 1$ for Interrupted Poisson traffic

The traffic of a basic circuit switched network compares to the cognitive radio handoff traffic for the proposed spectrum handoff scheme as illustrated in Figure 3.6.

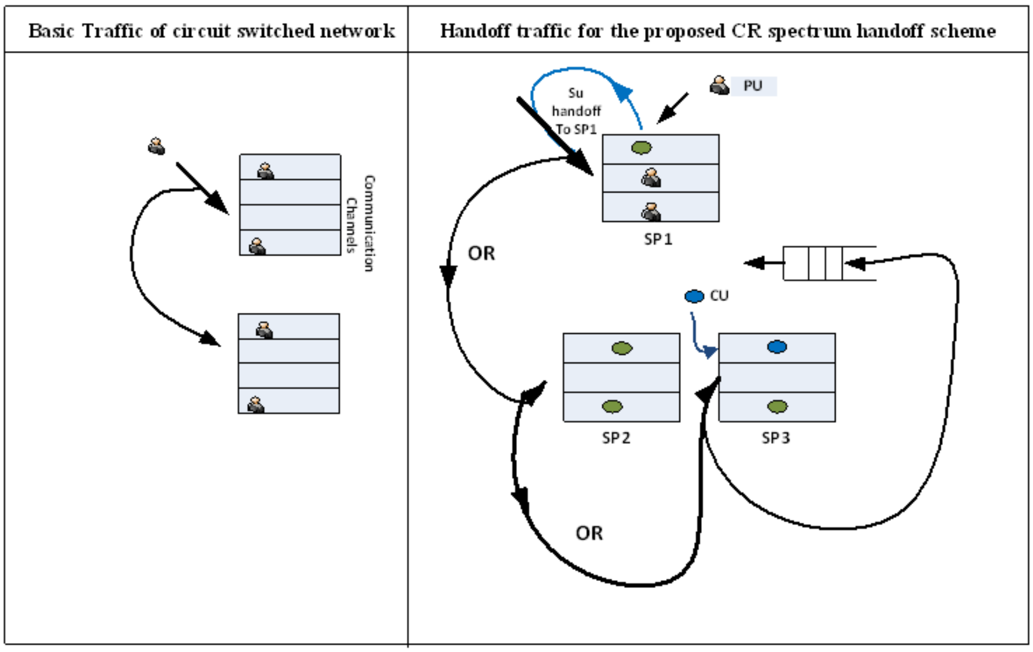



**Figure 3.6:** *Handoff traffic as an overflow traffic system*

#### 3.4.1.1 Basic System Parameters

Let:

Number of licensed channels in SP1 = $C_1$

Number of leased licensed channels in SP2 = $C_2$

number of unlicensed channels in SP3 = $C_3$

Number of active PUs in SP1 at any time = k where $0 \leq k \leq C_1$

Number of SUs in SP1 at any time = n where $0 \leq n \leq C_1$

Number of SUs in SP2 = m where $0 \leq m \leq C_2$

Number of classical users CUs in SP3 = r where $0 \leq r \leq C_3$

Number of SUs in SP3 = q where $0 \leq q \leq C_3$

The arrival and departure of the PUs, SUs and CUs follow the Poison process

#### 3.4.1.2 SU Admission and blocking criteria

- SU will be admitted in SP1 if

$$k + n < C_1 \tag{3.4}$$

  otherwise it will be blocked.

- A handoff SU will be admitted in SP2 if

$$m < C_2 \tag{3.5}$$

  but blocked otherwise

- A handoff SU from SP1, blocked in SP2 will be admitted in SP3 if

$$r + q < C_3 \tag{3.6}$$

  otherwise it will be blocked

### 3.4.2 Primary System Traffic Analysis

#### 3.4.2.1 Steady state probability in spectrum pool 1

The number of PU present in SP1 varies with time. At a random point in time, the state of statistical equilibrium for which there are $k$ PUs in SP1 defines the steady state probability of SP1. This probability is derived by the Erlang's loss formula in [68] as:

$$Pk = \frac{\frac{a^k}{k!}}{\sum_{i=0}^{C_1} \frac{a^i}{i!}} \qquad 0 \leq \ k \ \leq \ C_1 \tag{3.7}$$

Where $a$ is the Poissonian traffic offered to SP1 by the arriving PUs and given as $\frac{\lambda_{pu}}{\mu_{pu}}$

#### 3.4.2.2 Blocking Probability of PU in SP1.

An arriving PU will be blocked (i.e. denied service) in SP1 if all radio channels are busy at the time of arrival. The blocking probability is a function of the number of available channels and offered (traffic) load. It can be derived using the Erlang B formula.

A new PU will be blocked when $k = C_1$

The blocking probability Pb1 of PU in SP1 according to Erlang B is

$$Pb_1 = E\left(C1, \quad a\right) = \frac{\frac{a^{C1}}{C1!}}{\sum_{i=0}^{C1} \frac{a^i}{i!}} \qquad 0 \leq \quad k \quad \leq \quad C_1 \tag{3.8}$$

### 3.4.3 SU Vacating Probability Pv in SP1

When a PU arrives the licensed channel and choses a channel occupied by an SU, the SU has to vacate the channel to avoid interference to the PU. The probability $Pv$, that an SU vacates a channel in SP1 is equivalent to the probability that a PU arrives SP1 and selects the same channel occupied by the SU as illustrated in figure 3.7.

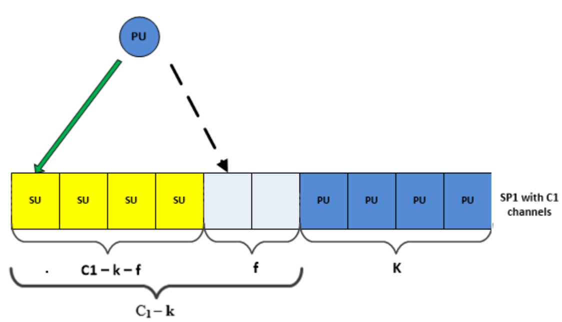



**Figure 3.7:** *PU Reclaiming A Channel (Proposed Scheme)*

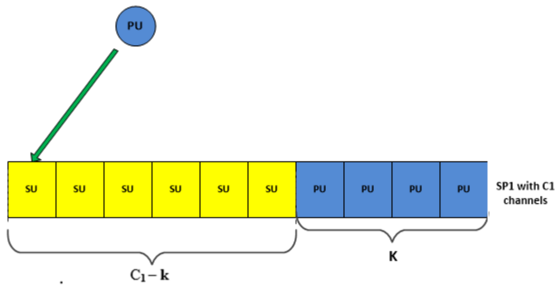



**Figure 3.8:** *PU Reclaiming A Channel (Existing Scheme)*

This probability has been derived by authors in [41][57] and [64] as:

$$Pv = \frac{\sum_{k=0}^{C_1-1} \sum \left\lfloor \frac{1}{(C_1-k)} \right\rfloor P\ k}{1\ \ - Pb1} \tag{3.9}$$

These authors assumed that at the arrival of the PU, all channels not occupied by PUs, are occupied by SUs as illustrated in figure 3.8. They did not consider that, some of these channels can be free at the arrival of the PU as illustrated in figure 3.7. One of the disadvantages of this assumption, is that, it depicts that at every arrival of a PU, an SU must vacate the licensed spectrum and perform spectrum handoff. However, if an arriving PU selects a free channel, the SU need not vacate and spectrum handoff will not be performed. In order to improve the modelling of the SU vacating probability, the possibility of having SUs or free channels in the licensed spectrum pool is considered in modelling this scheme

In this work, this probability is derived as follows:

Let the system state be k, with a state probability P(k) upon the arrival of a PU where $0 \leq k \leq C_1 - 1$ (i.e. there must be at least one SU in the system for handoff to take place)

The probability that an arriving PU reclaims a particular channel (occupied by SU or free) is $1/(C_1 -$ k). Spectrum handoff will only occur when PU reclaims a channel occupied by an SU.

Let the number of free channels $= f$

Then the number of channels occupied by SU is given by $n = C_1 – k – f$

The Probability of an arriving PU reclaiming a particular channel occupied by an SU is given as:

$$\sum_{k=0}^{C_1-1} \sum_{f=0}^{C_1-k-1} \left\lfloor \frac{1}{[(C_1 - k) - f]} \right\rfloor \tag{3.10}$$

The SU vacating probability is equivalent to the probability that a PU arrives at SP1 which is in state k and selects an SU on the condition that the incoming PU is not blocked. This probability is derived as:

$$Pv = \sum_{k=0}^{C_1-1} \sum_{f=0}^{C_1-k-1} \left\lfloor \frac{1}{[(C_1 - k) - f]} \right\rfloor Pk. \left[ \frac{1}{1 - Pb1} \right] \tag{3.11}$$

1-Pb1 represent the condition that the incoming PU is not blocked.

### 3.4.4 3.4.3 Secondary System Traffic analysis

The SU handoff traffic pattern for the proposed model presented in section 3.3.3 is illustrated in figure 3.9

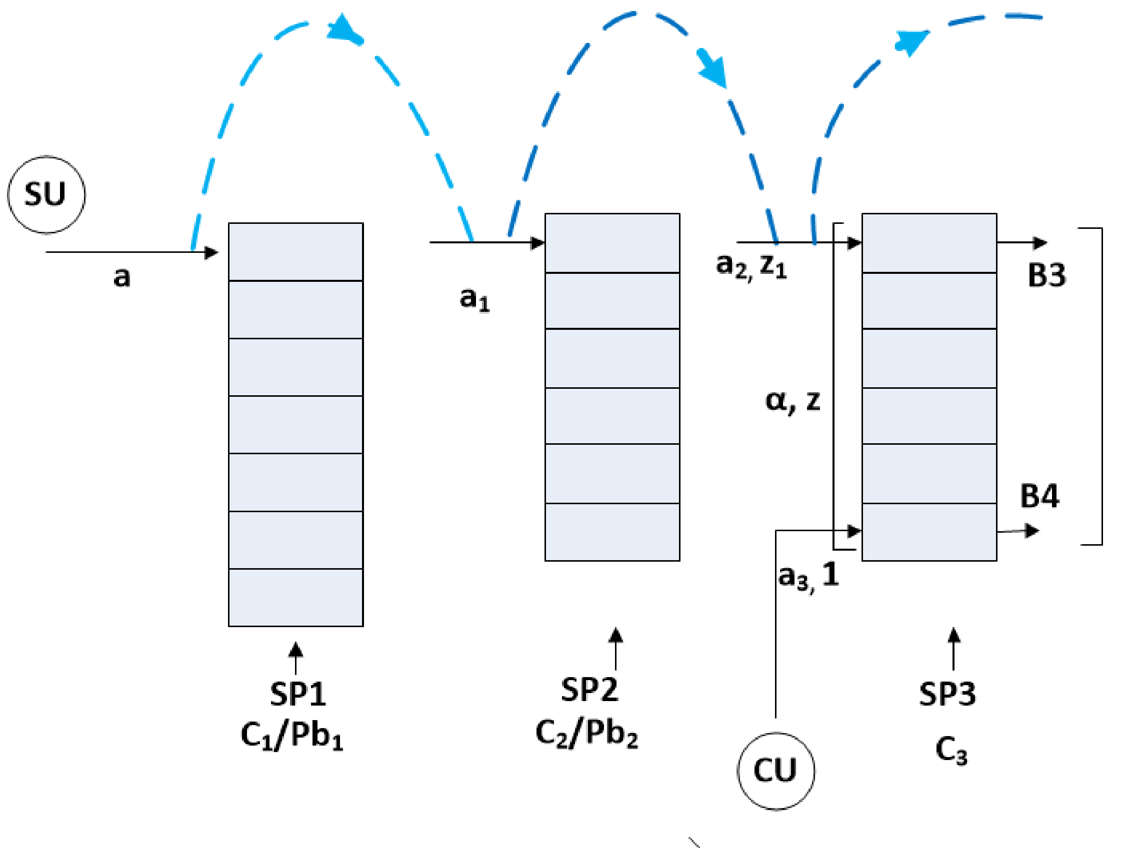



**Figure 3.9:** *SU Handoff overflow traffic pattern*

$SU_1$ is an SU which vacates SP1 due to PU arrival and offers an initial handoff traffic with intensity **a**, to the primary system (SP1).We assume that the arrival rate of the arriving PU and the departure rate of the vacating SU are the same (i.e. birth rate equal to death rate). In future work a different rate can be considered. **a1** and **a2** are the intensities of the traffics overflowing into SP2 from SP1 and into SP3 from SP2 respectively. **a3** is the traffic intensity of the incoming CU while $\alpha$ is the total intensity offered to SP3.

#### 3.4.4.1 The blocking probability of an SU vacating SP1 in SP2

The traffic intensity $a_1$, of the traffic overflowing from SP1 to SP2 is an interrupted Poisson and not a pure Poisson traffic as derived by existing works. It is derived with reference to [68] as:

$$a1 = \ a.E(C_1,\ a) = a.Pb_1 \tag{3.12}$$

and the blocking probability in SP2 is derived as:

$$Pb_2 = \frac{E(C_1 + C_2,\ \ a)}{E(C_1,\ \ a)} = \frac{1}{Pb_1}.\frac{\frac{a^C}{C!}}{\sum_{i=0}^{C}\frac{a^i}{i!}} \qquad\qquad C = C_1 + C_2 \tag{3.13}$$

#### 3.4.4.2 The blocking probability of SU in SP3

The traffic into SP3 from SP2 is an overflow (interrupted Poisson/renewal) traffic with intensity $a_2$, peakedness factor $z_1$. The CU traffic into SP3 is a random (Poisson) traffic with intensity $a_3$ and Peakedness factor 1. These parameters are derived with reference to [68] as:

$$a_2 = a1.Pb_2 = a.E(C_1 + C_2, \quad a) \tag{3.14}$$

$$z_1 = 1 - \ a_1 + \frac{a}{(C_1 + 1 - a + a_1)} \tag{3.15}$$

$$a_3 = \frac{\lambda_{cu}}{\mu_{cu}} \tag{3.16}$$

The combined traffic into SP3 is considered a renewal traffic with traffic intensity $\alpha$ and peakedness factor z. These parameters are derived with reference to [69] as:

$$\alpha = a_2 + a_3 \tag{3.17}$$

$$z = \frac{a_3 + a_2 z_1}{\alpha} \tag{3.18}$$

The separate and joint blocking probabilities in SP3 are given as $B_3$ (blocking probability due to handoff SU), $B_4$ (blocking probability due to incoming CU), and **B** (blocking probability due to both CU and SU). These blocking probabilities in the secondary system are obtained below, with reference to [69] as:

$$B^{-1} = \sum_{j=0}^{C_3} \left[ \frac{\binom{C_3}{j}}{\prod_{r=1}^{j} \left\{ \frac{\alpha}{r} + \frac{(z-1)(\alpha+3z)}{r-1+\alpha+3z} \right\}} \right] \tag{3.19}$$

$$B_4 = \left[ 1 + (z-1)\frac{C_3}{\alpha} . \frac{(\alpha + \mathbf{3z})}{C_3 \ - \ 1 + \alpha + \mathbf{3z}} \right]^{-1} B \tag{3.20}$$

$$B_3 = \left[ 1 + (z_1 - 1)\frac{C_3}{\alpha} . \frac{(\alpha + \mathbf{3z})}{C_3 \ - \ 1 + \alpha + \mathbf{3z}} \right] B_4 \tag{3.21}$$

The blocking probability of the handoff SU in SP3 is $Pb_3 = B_3$. The blocking probability for the overall system derived as:

$$PB = Pb_1 Pb_2 Pb_3 = \frac{\frac{a^C}{C!}}{\sum_{i=0}^{C} \frac{a^i}{i!}} . \left[ 1 + (z_1 - 1)\frac{C_3}{\alpha} . \frac{(\alpha + \mathbf{3z})}{C_3 \ - \ 1 + \alpha + \mathbf{3z}} \right] B_4 \tag{3.22}$$

### 3.4.5 Link Maintenance Probability

When an SU vacates SP1, the link is successfully maintained if it finds a free channel in SP1 or in SP2 or SP3 to continue the ongoing transmission.

Let P(LM) = Link maintenance probability

The probability of SU vacating a channel in SP1= $Pv$

The probability of SU being blocked in SP1 = $Pb_1$

The probability of handoff SU being blocked in SP2 = $Pb_2$

The probability of handoff SU being blocked in SP3 = $Pb_3$

The link is successfully maintained based on the following events:

1. SU vacates a channel in SP1 and finds another free channel in SP1 - *lm1*

$$P(lm1) = Pv(1 \ - \ Pb_1) \tag{3.23}$$

2. SU vacates a channel in SP1; cannot find a free (i.e. is blocked in SP1) but finds a

free channel in SP2. - *lm2*

$$P(lm2) = PvPb_1(1 - Pb_2) \tag{3.24}$$

3. SU vacates a channel in SP1; is blocked in SP1; Is blocked in SP2 but finds a free channel in the SP3 - *lm3*

$$P(lm3) = PvPb_1Pb_2(1 - Pb_3) \tag{3.25}$$

4. SU vacates a channel in SP1; is blocked in SP1; Is blocked in SP2; is blocked in SP3 but a channel becomes available within a period of H seconds - *lm4*

$$P(lm4) = PvPb_1Pb_2Pb_3P_{(w \leq H)} \tag{3.26}$$

where $P_{(w \leq H)}$ is the probability of a channel becoming available in SP1 or SP2 or SP3 within H seconds. Figure 3.10 illustrates a blocked SU waiting to access a channel that becomes free within H seconds.

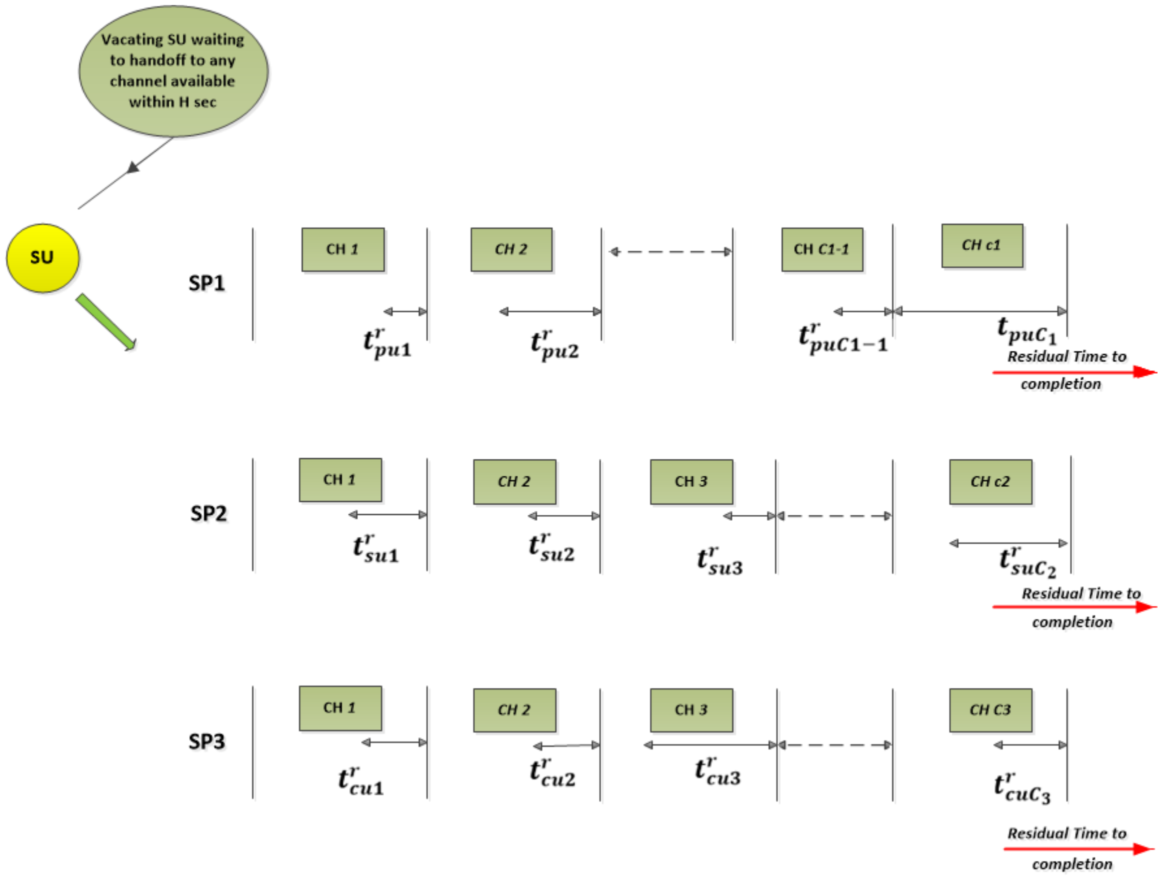



**Figure 3.10:** *Illustrating SU waiting time for free Channel within H seconds*

$T_{pu}$ = random variable (RV) of the service period of PU in SP1 with mean service time of $1/\mu_{pu}$, probability density function (pdf) $f_{T_{pu}}$(t) and cumulative distribution function (CDF) $F_{T_{pu}}$(t)

$T_{su}$= RV of the service period of SU in SP2 with mean service time of $1/\mu_{su}$, pdf $f_{T_{su}}$(t) and CDF $F_{T_{su}}$(t)

$T_{cu}$ = RV of the service period of users (SU and CU) in SP3 with mean service time of $1/\mu_{su} = 1/\mu_{cu} = 1/\mu$, pdf $f_{T_{cu}}$(t) and CDF $F_{T_{cu}}$(t)

$T^r_{su}$= RV of the residual service period of SU in SP2 with values of

$t^r_{su1}$, $t^r_{su2}$, $t^r_{su3}$, . . . . $t^r_{suC_2}$, pdf $f_{T^r_{su}}$(t) and CDF $F_{T^r_{su}}(t)$; $t^r_{sui}$ represent the ith term in $T^r_{su}$

$T^r_{cu}$= RV of the residual service period of users (SU and CU) in SP3 with values of

The relationship between the pdfs and CDFs of service period and the residual service period are as follows:

$$f_T(t, \mu) = \mu e^{-\mu t} \qquad t \geq 0, \mu \geq 0 \tag{3.27}$$

$$F_T(t, \mu) = 1 - e^{-\mu t} \qquad t \geq 0, \mu \geq 0 \tag{3.28}$$

$$f^r{}_T(t) = \frac{F'\left(t\right)}{E\left[_{t_s}\right]} = \frac{1 - F_{T_s}\ \left(t\right)}{E\left[_{t_s}\right]} = \frac{e^{-\mu t}}{\frac{1}{\mu}} = \mu e^{-\mu t} \tag{3.29}$$

$$F^r{}_T(t) = 1 - e^{-\mu t} \tag{3.30}$$

Let

$U_1$ = minimum value of $T^r_{pui}$ in SP1

$U_2$ = minimum value of $T^r_{sui}$ in SP2

$U_3$ = minimum value of $T^r_{cui}$ in SP3

The probability that the waiting time for a channel to be available in SP1 or SP2 or SP3 is $\leq$ H is given as:

$$\begin{aligned} P_{(w \leq H)} &= P((U_1 \cup U_2 \cup U_3) \leq H) \\ &= 1 - P\left[(U_1 \cup \bar{U_2} \cup U_3\ )' \leq H\right] \\ &= 1 - P\left(U_1{}' \leq H\right) P\left(U_2{}' \leq H\right) P\left(U_3{}' \leq H\right) \\ &= 1 - \left(1 - P\left(U_1 \leq H\right)\right)\left(1 - P\left(U_2 \leq H\right)\right)\left(1 - P\left(U_3 \leq H\right)\right) \end{aligned} \tag{3.31}$$

$$
\begin{aligned}
P\left(U_1 \leq H\right) &= P\left(min\ T^r_{pui} \leq H\right) \\
&= P\left(min\left(t^r_{pu1}, t^r_{pu2}, ..t^r_{puC_1-1} t^r_{puC_1}\right) \leq H\right) \\
&= 1 - P\left(min\left(t^r_{pu1}, t^r_{pu2}, ..t^r_{puC_1-1} t^r_{puC_1}\right) > H\right) \\
&= 1 - P\left(t^r_{pu1} > H\right)\left(t^r_{pu2} > H\right)\ldots\left(t^r_{puC_1-1} > H\right)\left(t^r_{puC_1} > H\right) \\
&= 1 - [1 - F_{T^r_{pui}}(H)]^{C_1-1}[1 - F_{T_{pu}}(H)] \\
&= 1 - e^{-\mu H C_1 - 1} e^{-\mu H} = 1 - e^{-\mu H C_1 - 1 + 1} = 1 - e^{-\mu H C_1}
\end{aligned}
\tag{3.32}
$$

$$
\begin{aligned}
P\left(U_2 \leq H\right) &= P(min T^r_{sui} \leq\ H) \\
&= P(min\left(t^r_{su1}\ t^r_{su2},\ t^r_{su3},\ ....\ t^r_{suC_2}\right)\ \leq\ H \\
&= 1 - P(min\left(t^r_{su1,}\ t^r_{su2},\ t^r_{su3},\ ....\ t^r_{suC_2}\right)\ >\ \ H \\
&= 1 – P(\ t^r_{su1} >\ \ H) P(t^r_{su2} >\ H),\ ....\ P(t^r_{suC_2} >\ \ H) \\
&= 1 - [1 - F_{T^r_{su}}(H)]^{C_2} \\
&= 1 - e^{-\mu C_2 H}
\end{aligned}
\tag{3.33}
$$

$$
\begin{aligned}
P\left(U_3 \leq H\right) &= P(min t^r_{cui} \leq\ H) \\
&= P(min\,(t^r_{cu1}\ t^r_{cu2},\ t^r_{cu3},\ ....\ t^r_{cuC3})\ \leq\ H \\
&= 1 - P(min\left(t^r_{cu1,}\ t^r_{cu2},\ t^r_{cu3},\ ....\ t^r_{cuC3}\right)\ >\ \ H \\
&= 1 – P(\ t^r_{cu1} >\ \ H) P(t^r_{cu2} >\ \ H),\ ....\ P(t^r_{cuC3} >\ \ H) \\
&= 1 - [1 - F_{T^r_{cu}}(H)]^{C_3} \\
&= 1 - e^{-\mu C_3 H}
\end{aligned}
\tag{3.34}
$$

By replacing (3.32),(3.33), and (3.34) in (3.31),

$$
P_{(w \leq H)} = 1 - e^{-\mu C_1 H} e^{-\mu C_2 H} - e^{-\mu C_3 H} = 1 - e^{-\mu H (C_1 + C_2 + C_3)} \tag{3.35}
$$

With reference to (3.23),(3.24),(3.25), and (3.26), the SU Link maintenance probability for the system is given as:

$$P(LM) = P(lm1) + P(lm2) + P(lm3) + P(lm4) \tag{3.36}$$

$$\begin{aligned} P\left(LM\right) &= Pv\left[\left(1 - Pb1\right) + Pb1\left(1 - Pb2\right) + Pb1Pb2\left(1 - Pb3\right) + Pb1Pb2Pb3P_{(W \leq H)}\right] \\ &= Pv\left(1 - Pb1Pb2Pb3 + Pb1Pb2Pb3P_{(w \leq H)}\right) \end{aligned} \tag{3.37}$$

### 3.4.6 Link Failure Probability

The link fails when a SU vacates the licensed channel and cannot find a channel to maintain the link

$$P(LF) \ = \ Pb1 \ Pb2Pb3P_{(w>H)} \tag{3.38}$$

where $P_{(w>H)}$ is the probability of no channel becoming available within H seconds after the SU is blocked in SP3.

$$P_{(w>H)} = 1 – P_{(w \leq H)} \tag{3.39}$$

$$P(LF) \ = \ Pb1Pb2Pb3\left(1 \ - \ P_{(w \leq H)}\right) \tag{3.40}$$

# 4

# RESULTS AND DISCUSSION

*This chapter focuses on analyzing the performance of the proposed spectrum handoff scheme and comparing it with an existing scheme in terms of their Blocking, Link Maintenance and Link Failure Probabilities. Using the MATrix LABoratry (MATLAB) simulation tool, simulated results of these parameters are presented, analyzed and compared.*

## 4.1 Simulation Result

Simulation parameters given in table 4.1 are adopted in order to benchmark with the existing scheme. Simulation results of blocking probabilities, link maintenance probabilities and failure probabilities for different network scenarios are presented in this section.

**Table 4.1:** *simulation parameters*

| Parameter | Symbol | Value(s) |
|---|---|---|
| PU arrival rate | $\lambda_{pu}$ | 0.0 – 0.7 / second |
| PU service rate | $\mu_{pu}$ | 1/180 second |
| CU arrival ratee | $\lambda_{cu}$ | 0.15/second |
| SU service rate | $\mu_{su}$ | 1/180 seconds |
| CU service ratee | $\mu_{cu}$ | 1/180 seconds |
| Number of channels in SP1 | $C_1$ | 12 |
| Number of channels in SP2 | $C_2$ | 3, 6 |
| Number of channels in SP3 | $C_3$ | 6, 10 |
| Maximum waiting time in queue | H | 9, 18 seconds |

## 4.2 Simulation Result of Blocking Probability

The simulation results of SU blocking probability are presented in figures **??** and 4.2, as a function of the primary user arrival rate. The performance of the proposed handoff scheme is compared to the performance of existing scheme described in section 3.3.2. The impact of PU arrival rate and variation in number of backup channels on the blocking probability are also examined and discussed.

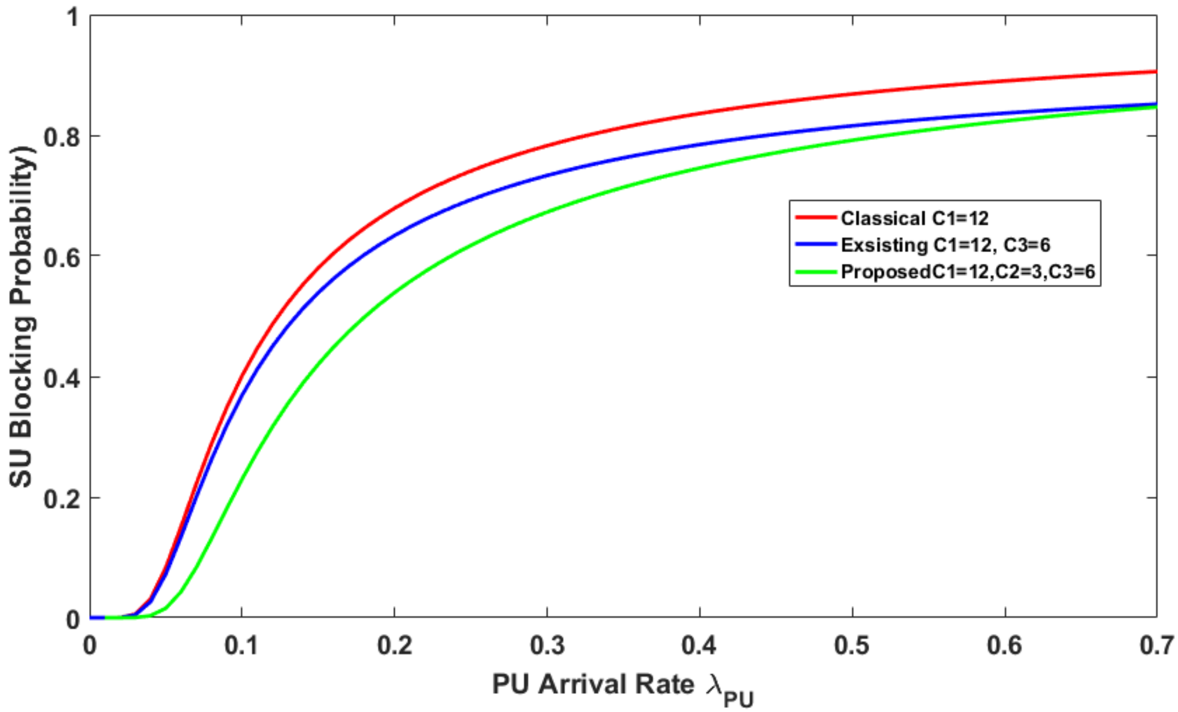



**Figure 4.1:** *SU Blocking Probability of Classical, Existing and Proposed Schemes in Terms of PU arrival rates Scenario 1*

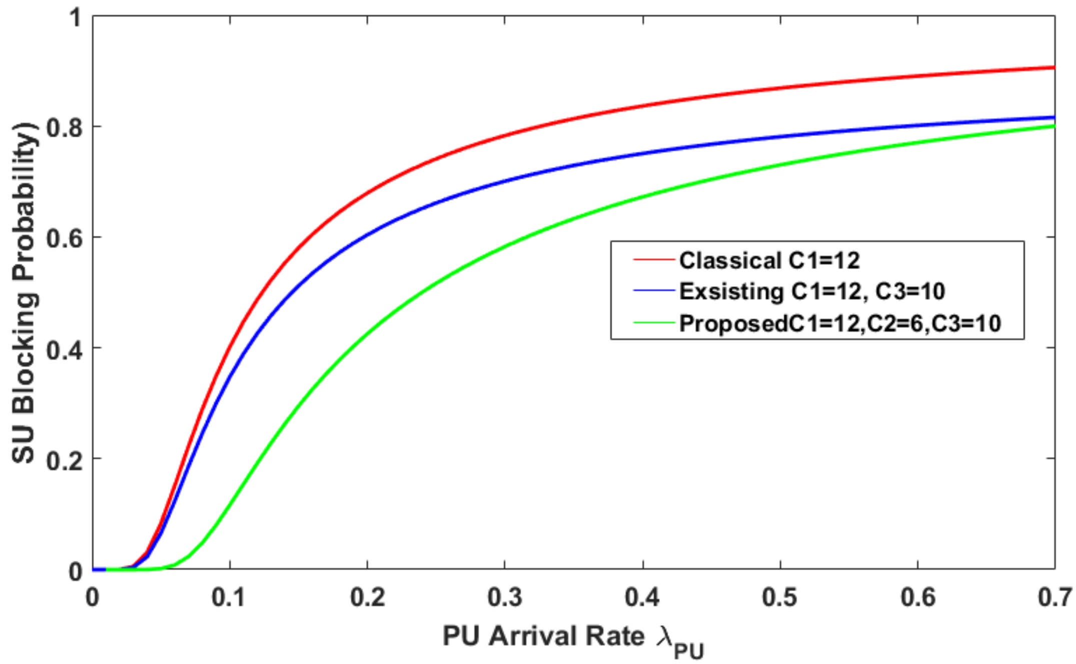



**Figure 4.2:** *SU Blocking Probability of Classical, Existing and Proposed Schemes in Terms of PU arrival rates Scenario 2*

**Table 4.2:** *Evaluation and Comparison of SU Blocking Probability for Proposed and Existing Spectrum Handoff Schemes*

| **SU Blocking Probability** | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | **Performance(%)** | |
| Scenarios | Varring Parameter | PU Arrival rate | Classical | Existing | Proposed | Existing | Proposed |
| S1 - (C1=12 C2=3 C3=6) | Number of Channels | 0.7 | 0.91 | 0.85 | 0.85 | **6.0** | **6.5** |
| S1 - (C1=12 C2=3 C3=6) | Number of Channels | 0.3 | 0.78 | 0.73 | 0.67 | **6.3** | **14.1** |
| S1 - (C1=12 C2=3 C3=6) | Number of Channels | 0.2 | 0.68 | 0.63 | 0.54 | **6.7** | **20.6** |
| S2 - (C1=12 C2=6 C3=10 ) | Number of Channels | 0.7 | 0.91 | 0.82 | 0.80 | **9.9** | **11.7** |
| S2 - (C1=12 C2=6 C3=10 ) | Number of Channels | 0.3 | 0.78 | 0.70 | 0.58 | **10.5** | **25.6** |
| S2 - (C1=12 C2=6 C3=10) | Number of Channels | 0.2 | 0.68 | 0.60 | 0.43 | **11.1** | **37.4** |

**Classical**- No Backup Situation;**Existing**- Backup with Unlicensed Channels Only. **Pro-**

**posed** -Backup Using Licensed and Unlicensed Channels

**Discussion**

From the results in figures **??** and 4.2, which are further analyzed in table**??** , it is clearly observed that:

1. The blocking probabilities in both existing and proposed schemes are affected by variations in the number of backup channels and PU arrival rates. With increase of in number of backup channels, blocking probabilities reduce (i.e. it is improved) this is because handoff SUs which are blocked from accessing the PU channels in SP1, finds an increased number of channels to continue and complete their transmission; consequently, the number of SUs blocked reduces. Blocking probability increases with reduction in number of backup channels. As the PU arrival rate increases, the number of PU channels that are busy, due to PU activities, increases; the number of channels available for vacating SUs to handoff to decreases, so the blocking probability increases. Blocking probability decreases when the PU arrival rate decreases.

2. With respect to the evaluation of blocking probabilities for the existing and proposed spectrum handoff schemes; For scenario 1(C1 = 12, C2 = 3; C3 = 6), at Pu arrival rates of 0.7, 0.3 and 0.2 users per second, existing scheme reduces (improves) the blocking probability of the classical situation by 6.0%, 6.3% and 6.7% while the proposed scheme improves it by 6.5%, 14.1% and 20.6% respectively. For Scenario 2 (C2 = 6; C3 = 10) at a PU arrival rates of 0.7, 0.3 and 0.2 users per second, the existing scheme improves the system blocking probability by 9.9%, 10.5% and 11.1% while the proposed scheme improves it by 11.7%, 25.6% and 37.4% respectively.

With reduction in the number of blocked SUs, the proposed system improves the quality of service of the SU communication.

## 4.3 Simulation Results for Link Maintenance Probability

Figures 4.3 and 4.4 are simulation results of SU link maintenance probability as a function of the primary user arrival rate. The performance of the proposed handoff scheme is compares to that of the existing with respect to their link maintenance probabilities. Also, the impacts of number of backup channels and waiting time H, on the SU maintenance probability are examined.

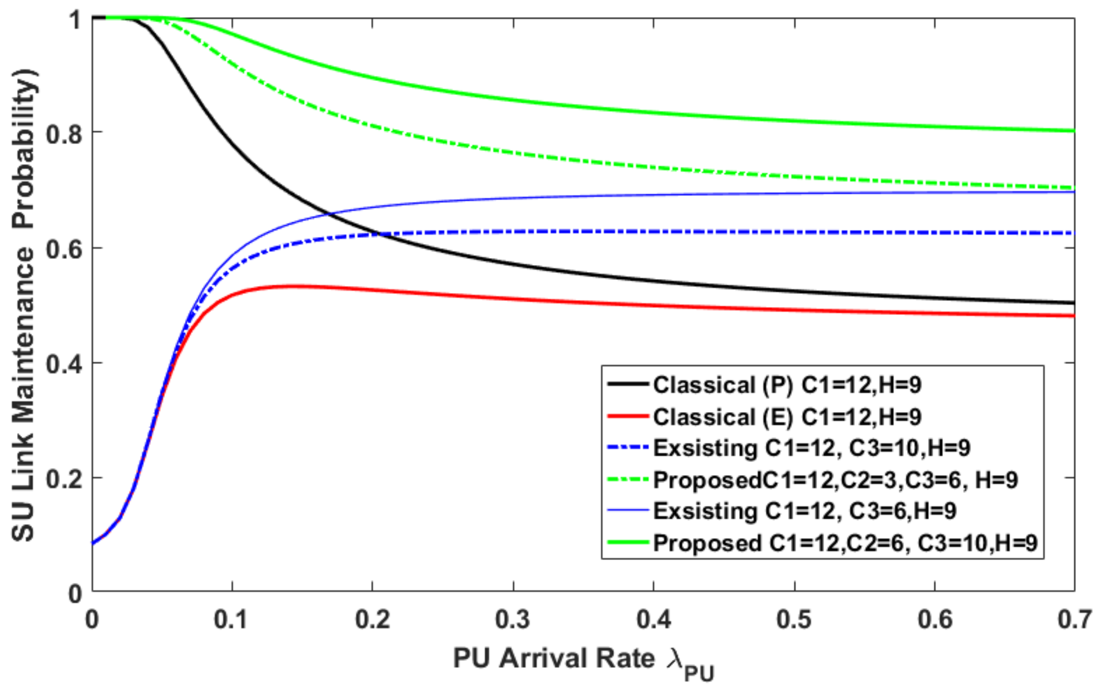



**Figure 4.3:** *Comparison of link maintenance Probability for Classical, Existing and Proposed Spectrum Handoff Schemes*

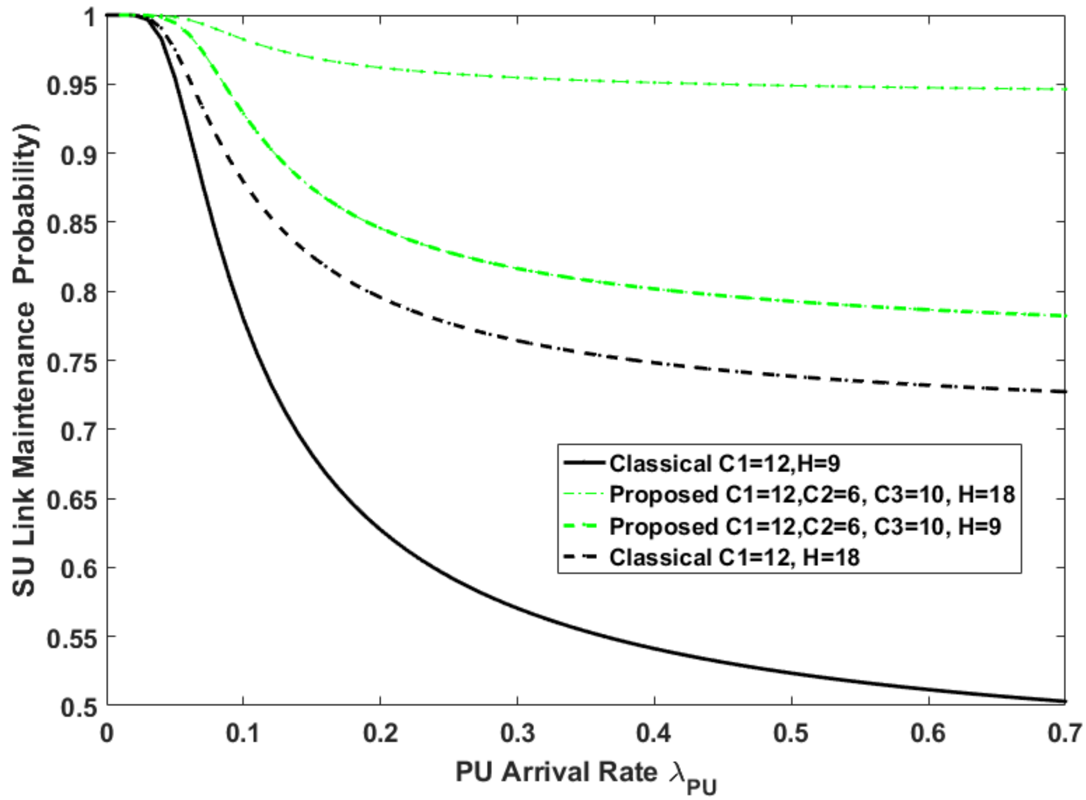



**Figure 4.4:** *Impact of Waiting Time H, on SU Link Maintenance Probability*

**Table 4.3:** *Evaluation of Link Maintenance Probability for existing and proposed schemes*

| **SU Link Maintenance Probability** | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | **Performance (%)** | |
| Channel Scenario | PU Arrival rate | Classical (E) | Classical (P) | Existing | Proposed | Existing | Proposed |
| S1 - (C1=12 C2=3 C3=6 H=9) | **0.30** | **0.48** | **0.57** | **0.63** | **0.76** | **31.25** | **34.14** |
| S1 - (C1=12 C2=3 C3=6 H=9) | **0.70** | **0.48** | **0.50** | **0.62** | **0.70** | **29.01** | **39.88** |
| S2 - (C1=12 C2=6 C3=10 H=9) | **0.30** | **0.51** | **0.57** | **0.69** | **0.86** | **34.44** | **50.23** |
| S2 - (C1=12 C2=6 C3=10 H=9) | **0.70** | **0.48** | **0.50** | **0.70** | **0.80** | **44.84** | **59.58** |

**Classical (E)** - No Backup Situation for Existing Scheme, **Classical (P)** - No Backup Situation for Proposed Scheme, **Existing** - Backup Using Unlicensed Channels Only,**Proposed**- Backup Using Licensed and Unlicensed Channels

**Discussion**

The following observations are made from the SU link maintenance probability simulation results presented in figures 4.5 and 4.4 and further analyzed in table**??**.

1. SU link maintenance reduces with increase in PU arrival rates and increases as PU arrival rate reduces for the proposed scheme.

2. SU link maintenance probability (LMP) is affected by number of backup channels. The link maintenance probability increases (i.e. performance improves) as the number of backup channels increases. This is because there are more backup channels available for the vacating SUs to resume and complete their transmission. Also, LMP will reduce as number of backup channels decreases. The cost required for obtaining leased licensed channel in SP2 is a limiting factor to number of lines to be acquired.

3. The existing scheme improves the link maintenance performance of the classical CR network by 23.6% and 29.0% at PU arrival rates of 0.3 and 0.7 respectively for the network scenario S1 shown in table **??** while the proposed scheme improves the link maintenance of the classical CR network by 34.1 % and 39.9% at PU arrival rates of 0.3 and 0.7 respectively for network scenario S2. The above result shows that the proposed scheme outperforms the existing scheme in terms of link maintenance probability and consequently quality of service.

4. The directions of the curve plots obtained from the results of the existing and proposed schemes are different. The difference has been traced to the different consideration adopted for determining the vacating probabilities for both systems as explained in section 3.4.3

5. Results represented in figure 4.3 shows that the link maintenance probability improves (increases) as the waiting time H increases. More users (PU and SU) in service can complete their transmission and vacate their channels if the vacating SU waits longer, consequently link maintenance will be improved. The backdrop of the increase of waiting time could be increase in total service time.

## 4.4 Simulation Result of Secondary User Link Failure Probability

Results of the SU performance with respect of link failure probability (LFP) are presented in figures 4.5 and 4.6 . The proposed and the existing spectrum handoff schemes are compared with respect to their link failure probabilities in terms of PU arrival rates. Finally, the impact of number of backup channels, PU arrival rates and waiting time H, on the LFP are also analyzed.

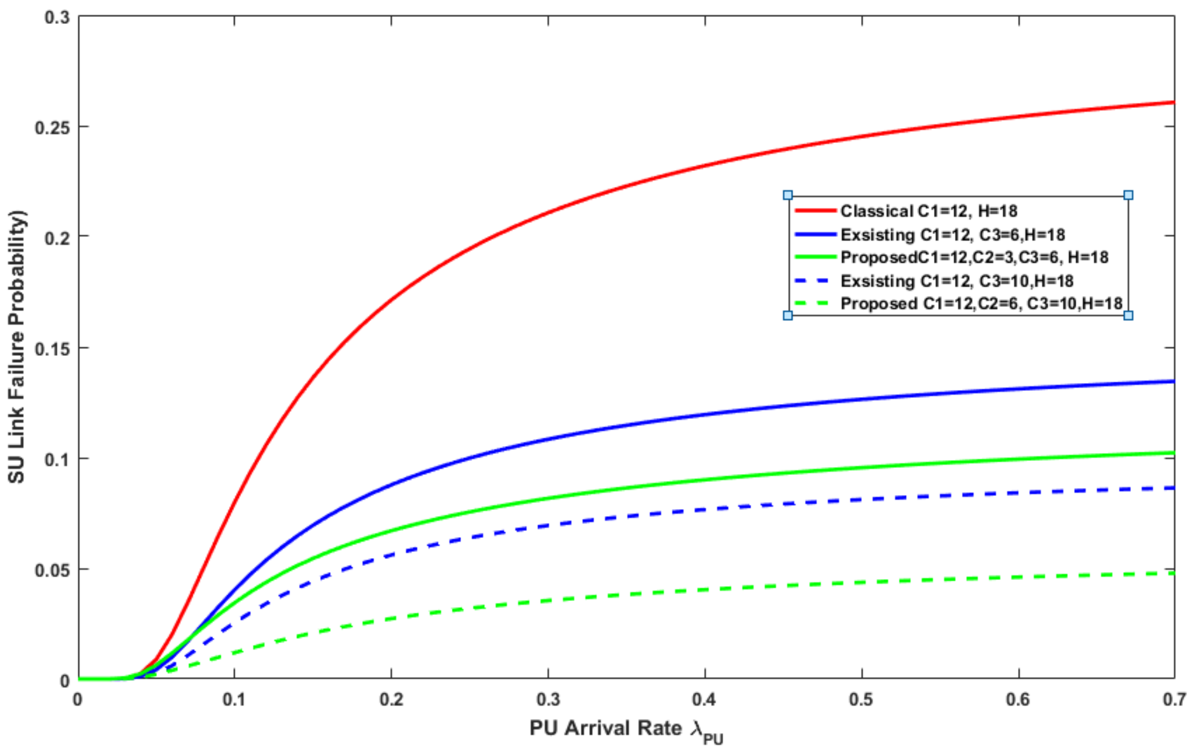



**Figure 4.5:** *SU Link Failure Probability of Classical, Existing And Proposed Spectrum Handoff Schemes in terms of PU arrival rate*

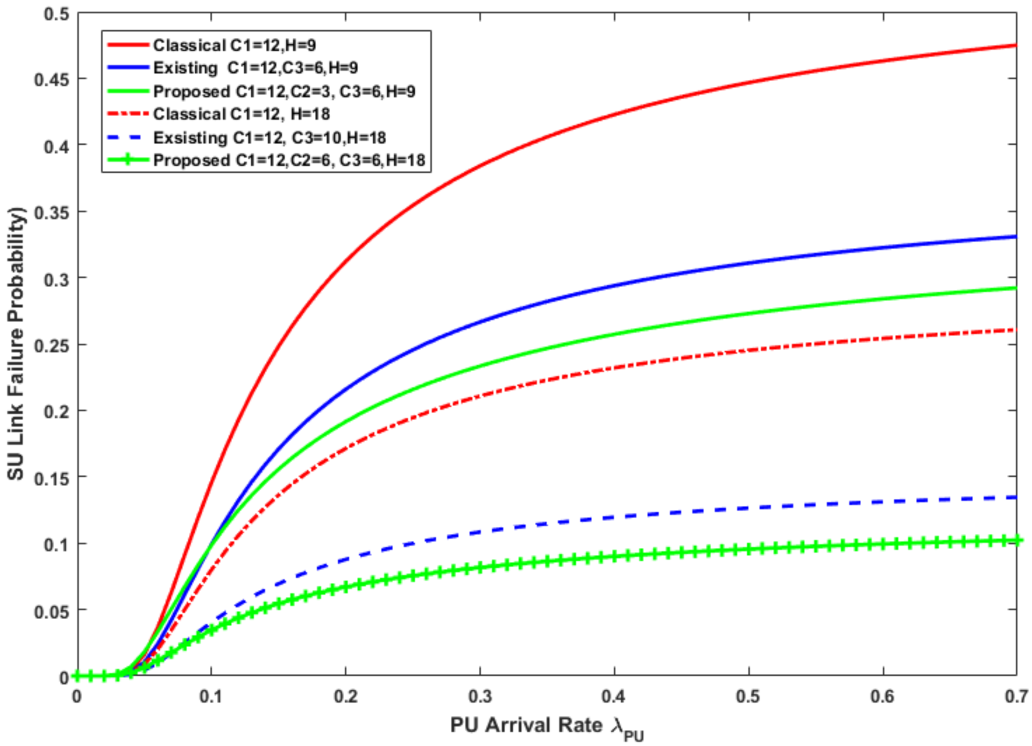



**Figure 4.6:** *Impact of waiting time on LFP For Classical, Existing and Proposed Spectrum Handoff Schemes*

**Table 4.4:** *Evaluation of Link Failure Probability for existing and proposed schemes*

| Link failure Probability | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | **Performance (%)** | |
| Scenarios | Varying Parameter | PU Arrival rate | Classical | Existing | Proposed | Existing | Proposed |
| S1 -(C1=12 C2=3 C3=6 H=18) | Number of Channels | 0.7 | 0.26 | 0.13 | 0.1 | **48.4** | **60.8** |
| S1 -(C1=12 C2=3 C3=6 H=18) | Number of Channels | 0.3 | 0.21 | 0.11 | 0.08 | **48.6** | **61.2** |
| S2 -(C1=12 C2=6 C3=10 H=18) | Number of Channels | 0.7 | 0.26 | 0.09 | 0.05 | **66.9** | **81.7** |
| S2 -(C1=12 C2=6 C3=10 H=18) | Number of Channels | 0.3 | 0.21 | 0.07 | 0.04 | **67.1** | **83.2** |
| S3 -(C1=12 C2=3 C3=6 H=9 | Handoff SU waiting time | 0.7 | 0.47 | 0.33 | 0.29 | **30.3** | **38.5** |
| S3-(C1=12 C2=3 C3=6 H=9) | Handoff SU waiting time | 0.3 | 0.38 | 0.27 | 0.23 | **30.6** | **39.2** |
| S4-(C1=12 C2=6 C3=10 H=9) | Handoff SU waiting time | 0.7 | 0.26 | 0.13 | 0.1 | **48.4** | **60.8** |
| S4-(C1=12 C2=6 C3=10 H=9) | Handoff SU waiting time | 0.3 | 0.21 | 0.11 | 0.08 | **48.6** | **61.2** |

**Classical**- No Backup Situation;**Existing**- Backup with Unlicensed Channels Only. **Proposed** -Backup Using Licensed and Unlicensed Channels

**Discussion**

The data obtained from the results in figures 4.5 and 4.6 are presented and evaluated in table 4.3. It shows that:

1. Link failure probability (LFP) is affected by number of backup channels. The link failure probability decreases (i.e. performance improves) as the number of backup channels increases. This is because there are more backup channels available for the vacating SUs to resume and complete their transmission so the number of failures will reduce. Also, LFP will increases as number of backup channels decreases. The cost of providing more leased licensed channel in SP2 is a limiting factor to number of lines to be acquired.

2. Link failure probability (LFP) is affected by the waiting time H. An SU which vacates SP1 and blocked in all available spectrum pools, will need to wait for H seconds before the Link fails. Figure 4.6 presents result of different waiting times for same number of backup channels for the proposed and existing schemes. The result shows that the link failure probability decreases (performance improves) as the waiting time increases.

3. Link failure probability reduces (improves) as PU arrival rate decreases.

4. The Existing scheme improves the LFP of the CR communication without backup situation (classical) by 48.4% and 48.6% while the proposed scheme improves the classical situation by 60.8% and 61.2% at PU arrival rates of 0.7 and 0.3 respectively; for channel combinations of $C_1 = 12, C_2 = 3, C_3 = 6, H = 18$. For channel combination of $C_1 = 12, C_2 = 6, C_3 = 10, H = 18$; the existing scheme improves the classical by 66.9% and 67.1% while the proposed scheme improves the classical by 81.7% and 83.2% for PU arrival rates of 0.7 and 0.3 respectively Also, for all considered scenarios with parameters as shown in table 4.4, the proposed scheme outperforms the existing scheme.

# 5

# CONCLUSION AND FUTURE WORK

*A brief review of the work done, result obtained and finding are reported in this chapter. Cost benefit analysis of the proposed scheme and recommendations leading to further research are also highlighted.*

## 5.1 Conclusion of Dissertation

This research, as defined by the objective, centered on proposing a spectrum handoff scheme to improve secondary user communication in a Cognitive Radio-based Smart Grid Neighborhood Area Network. The proposed scheme adopted and improved upon an existing scheme to address the issue of spectrum handoff for a CR-based communication in the neighborhood area network of the smart grid. Spectrum handoff is a prime concern in CRN.

The proposed scheme was described in chapter three and further modeled from the perspective of overflow system in a teletraffic loss system. Simulation results presented in chapter four, evaluated the performance of the proposed scheme in terms of blocking probability, link failure probability and link maintenance probability. The proposed schemes improved the blocking, link failure and link maintenance probabilities of the classical cognitive situation in which there is no backup provided for handoff users by up to 22.8%, 83.2% and 45.2% respectively depending on chosen network scenario. A comparison of the performance of the proposed and existing schemes showed that the proposed scheme outperformed the existing scheme in terms of the above performance measures (blocking, link failure and link maintenance probabilities) for all considered network scenarios.

Finally, though the proposed scheme outperforms the existing scheme as investigated above, the cost of leasing a few licensed channels is involved. For utilities intending to enjoy the benefits of this scheme at a reduced cost, the proposed scheme can be adopted for smart grid NAN, in densely populated or urban areas due to very high traffic in the unlicensed spectrum bands, while the existing scheme can be adopted for lightly populated or rural areas.

### 5.1.1 Contributions

- In modelling the SU traffic performance with respect to spectrum handoff scheme operating in a backup scenario, reviewed existing schemes which followed the teletraffic principles omitted the bursty nature of the handoff SU traffic, this gives an overall blocking probability less than the actual. In this work the bursty traffic nature was duly considered in modelling the SU traffic performance.
- In deriving the SU vacating probability from a licensed channel in SP1, existing schemes assumed that at the arrival of a PU to SP1, all channels not occupied by primary users are occupied by secondary users. In this work, SU vacating probability was derived considering the fact that at the arrival of a PU, licensed spectrum channels not occupied by primary users, can either be occupied by secondary user or are free.

## 5.2 Cost Benefit Analysis of Proposed Scheme

Cost benefit analysis (CBA) is an essential tool that aids organizations take business decisions based on the future value or benefits of embarking on a project. This is done by comparing the expected cost and benefits of embarking on the project with that of an alternative solution. In this section the CBA of adopting the proposed scheme for communication between NAN devices (smart meters and data concentrator units) is presented.

**Cost Involved**

The major costs involved for deploying the proposed and existing scheme are presented as follows:

**Table 5.1:** *Cost Requirement for Proposed and Existing Schemes*

| Performance Communication Cost | Existing Scheme | Proposed Scheme |
|---|---|---|
| Radio Spectrum License | Not required | Required |
| Hardware (Communication modem) | Required | Required |

Estimated Cost for spectrum lease - A utility provider can lease licensed spectrum channels from any licensed holder for a given period. For example, the FCC allows a utility provider to lease spectrum from the 2.5GHz EBS (Educational Broadcasting Service) licensed holder for a maximum period of 30 years. The spectrum lease value is rated by a normalized metric – "price per MHz-pop". This signifies the estimated cost for the EBS spectrum for each unit of population in the geographical service area per MHz spectrum. It is given as:

$$Price\ per\ MHz-pop\ = \frac{Total\ price\ for\ channels}{number\ of\ MHz\ channels\ X\ Population\ in\ geogrphical\ service\ area} \tag{5.1}$$

For a leasee utility provider, leasing six MHz channels for a geographical service area covering 2,000,000 population. Assuming a price of \$0.9 MHz-pop;

Total leasing cost will be $= 0.9x6x2000000 = \$10,800,000.00$

**Performance**

The benefits of the proposed scheme are tied to its improved performance on the SU communication and the value/cost saving this brings to the utility. From the results obtained in chapter 4, table 5.2 summarizes the performance that can be achieved depending on the network scenario.

**Table 5.2:** *Comparison of Performance Measures of Existing and Proposed Schemes*

| Performance Metric | Performance Improvement of Existing Scheme over the classical scheme | Performance Improvement of Proposed Scheme over the classical scheme |
|---|---|---|
| Blocking Probability | 11.1% | 37.4% |
| Link Maintenance Probability | 44.8% | 59.6% |
| Link Failure Probability | 67.1% | 83.2% |

Improved blocking and link maintenance probabilities improves Qos of communication network which results in improved transmission of metering, monitoring and operational data and this leads to a more efficient system.

Improved link failure probability reduces failure in timely transmission of mission critical data which can save the utility and consumer economic loss due to power outage. The average economic loss experienced by an average customer due to power outage as an outcome of reliability and power quality problems for a summer afternoon was assessed in [70]. Using the Tobit model, they estimated the loss as follows:

Residential customers - 3 x 38390 = $115,170

Small commercial/industrial customers - 1200 x 1600 = $1,920,000

Large commercial/industrial customers - 82,000 x 10 = $820,000

Total = $2,855,170

In 30 years, the total loss will be 30 x 2,855,170 = $85,655,100.00

**Table 5.3:** *Cost Benefit Analysis of Proposed Scheme*

| Item | Year 1 | Year 30 |
|---|---|---|
| Estimated Total Cost for leasing Radio Spectrum | $10,800,000.00 | $10,800,000.00 |
| Economic loss due to Outage | $2,855,170.00 | $85,655,100.00 |
| Cost saved/benefit due to Existing Scheme (67.1%) | $1,915,819.07 | $57,474,572.10 |
| Cost saved/benefit due to Proposed Scheme (83.2%) | $2,349,804.91 | $70,494,147.30 |
| Cost Saving of Proposed over Existing Scheme) | $433,985.84 | $13,019,575.20 |

Overall cost saved due to power outage only, exceeds the cost spent on spectrum leasing by about 27.9% from the above scenario.

## 5.3 Future Works

The following issues serves as future research areas for the proposed scheme:

1. It was assumed that the SU vacating a licensed channel due to a PU's arrival, re-offered a traffic of the same intensity as that of the PU reclaiming the channel. In future work a different traffic intensity can be considered

2. The transmitted data between smart meters and data concentrator units are of different priorities. This model did not distinguish or give some preference to real time or mission-critical data. In future work, traffic prioritization for different data type should be considered.

3. Increase in waiting time H, increases the link maintenance and link failure probabilities in this scheme. This increase may negatively affect other performance metrics which were not investigated in this work, e.g. extended service time, etc. In future work, algorithms that can help in determining a balance between increasing the waiting time to improve these parameters while staying within acceptable limits of other parameters can be considered.

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