Cognitive Radio for Broadband Access in Rural Africa and other Developing Countries

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Abstract

This thesis examines how Cognitive Radio (CR) can impact broadband access in rural Africa and other developing countries. We investigate how CR through dynamic spectrum access facilitates the efficient use of underutilized spectrum (white spaces) in rural areas. Until now much of the research and development of CR standardization is focussed on developed countries deployment scenarios e.g. IEEE 802.22, ACME-92, IEEE 80.11af standards in TVWS. Such countries have a highly developed infrastructure capable of supporting the use of real time database access, and a requirement for broadband data rates. Due to financial constraints and lack of supporting infrastructure in developing countries a different approach may be required to maximize the use of CR. This thesis identifies GSM white space as a potential candidate band for CR applications in rural Africa/developing countries. We use Monte Carlo simulation techniques as an analytical tool to assess the coexistence performance between CR systems and GSM. It is shown that the INR threshold below 30 dB corresponding to a -91 dBm signal detection threshold is required to fully protect GSM systems from excessive interference from CR systems. These values are relatively higher than the noise level which means simple sensing techniques such as energy detection can be employed by the CR systems to determine white space. This minimizes the complexity of CR by avoiding the use of complex sensing techniques and real time database access which may add cost, the critical factor for rural deployment. It is also shown that at GSM channel load below 0.5 Erlang CR systems can operate in the GSM band and achieve a coverage of up to 1 km at a transmit power of 800 mw (-1 dBW) without causing excessive interference on primary GSM users. This means that in areas where the GSM band is underutilized such as rural areas, CR systems can opportunistically exploit GSM white spaces. From the regulatory perspective it is found out that dynamic spectrum sharing policies are more adaptive to current trends in technological advancement, which means new technologies such as CR systems can be accommodated.

Keywords: Cognitive Radio, Dynamic Spectrum Access, GSM, TVWS

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Declaration

All work presented in this thesis as original is so to the best knowledge of the author.

References and acknowledgments to other researchers have been given as appropriate.

1 Introduction

1.1 Background

The penetration of broadband access in rural areas is very low due to the regulatory unavailability of suitable radio spectrum and supporting infrastructure. Most of the useful radio spectrum is currently occupied by licensed users for provision of other services such as GSM, WCDMA and TV. However, studies show that the utilization of this RF spectrum is not full to potential particularly in rural areas. The utilization of spectrum including that in urban area can be categorized in the following ways [1]:

1) Some frequency bands in spectrum are largely unoccupied most of the time
2) Some of the other frequency bands are only partially occupied
3) The remaining frequency bands are heavily used

The term spectrum hole or white space has been used in the literature to refer to the portion of the spectrum that is underutilized. By definition a spectrum hole (white space) is a band of frequencies assigned to primary user, but at a particular time and specific geographic location, the band is not being utilized by that user [2].

CR is regarded as most promising technology capable of dynamically accessing the underutilized spectrum (white spaces) without causing harmful interference to legitimate users and other secondary users. The use of white spaces is expected to accelerate the availability of broadband services particularly in rural areas.

1.2 Aim and Objectives

The aim of this thesis is to examine how CR can be developed for Africa to support rural broadband access.

Until now much of the research and development of CR standardization is focussed on developed countries deployment scenarios, e.g. the IEEE 802.22, ACME-92 standards in TVWS. Such countries have a highly developed infrastructure capable of supporting the use of real time database access, and a requirement for broadband data rates. Due to financial constraints and lack of supporting infrastructure in developing countries a different approach may be required to maximize the use of CR. It is expected that CR devices will need to be cost-effective, energy efficient and operate with minimum human intervention.

The main objective of this research is to review the existing alternative and provide the technical platform suitable for implementation of rural broadband access in developing countries using the cognitive radio techniques. This thesis identifies GSM white space as a potential candidate band for CR applications in rural Africa/developing countries. The fixed channel assignment schemes employed in GSM cells may provide an opportunity for CR devices to exploit the GSM white spaces. In addition, due to the robust interference mitigation mechanism of GSM systems the protection of the incumbent (primary user) through the use of real time database access systems and associated infrastructure may not be mandatory as in the case of TVWS. The main focus of this work is to investigate the coexistence performance of CR and primary users in the GSM band and derive the necessary operational constraints that may be necessary to impose on CR in order to facilitate their implementation, while providing maximum protection to incumbent. The benefits and drawbacks of CR in African deployment scenario will be evaluated, and compared with existing alternatives. From the regulatory perspective we examine the existing regulation and necessary changes needed for the use of CR in white spaces. We use Monte Carlo simulation techniques and MATLAB as analytical tools to assess the coexistence performance between CR systems and primary GSM users.

1.3 Thesis structure

This thesis is organized into seven chapters as outlined below

Chapter 2 presents background information on CR systems. This includes an overview of CR functionality together with the technical and regulatory challenges associated with the implementation of CR systems. The progress made by various international organizations on the work related to CR development and standardization is also provided. The established TVWS and the proposed GSM white space are also introduced in this chapter. Finally different propagation channel models are discussed with the aim of choosing an appropriate model to analyze coexistence performance of CR in the proposed GSM band.

Chapter 3 provides the simulation methodologies used to examine the coexistence performance between CR systems and primary user systems. The adopted simulation technique based on a statistical approach is highlighted and the key performance measures are discussed.

Chapter 4 examines the coexistence performance of CR in the GSM band based on the worst case scenario where it is assumed the GSM channels are all utilized. The aim of this investigation is to derive the operational constraints that must be imposed on CR to support coexistence without compromising the performance of primary user system.

Chapter 5 investigates a detailed coexistence performance of CR in the GSM band based on their traffic behaviour. Traffic models are developed for both systems and performance is measured when these systems are subjected to different channel loading conditions. The results of this analysis provide an insight on the operational limitations and requirements for coexistence in the GSM band.

Ideas for further work are presented in chapter 6 and finally chapter 7 provides a summary and conclusion.

2 Background Information

2.1 Introduction

In this chapter we present an overview of CR by highlighting key functionality and the concept of dynamic spectrum access. The applications of CR in the white spaces and their impact on rural broadband access will also be highlighted together with the comparison between established TVWS and proposed GSM white spaces. We will then address existing and emerging CR standards and compare them with the existing related standards. We will also give an overview of the progress made by various international organization in the work related to CR standardization. Technical and regulatory challenges associated with the use of CR in the white spaces and possible measures will also be discussed. Finally, we will look at different propagation channel models which provide means of analyzing performance of radio systems. In the later chapters propagation models will be used to examine the coexistence performance between primary systems (GSM) and secondary systems (CR systems).

2.2 Cognitive Radio Overview

The CR concept was coined by J. Mitola [19] and has the following formal definition according to the International Telecommunication Union [34]

"*CR system:* A radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment, establish policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained."

From the above definition CR has the following key functionalities [26]

Spectrum sensing: The CR regularly senses and monitors the RF environment for spectrum holes (white spaces)

Spectrum analysis: The characteristics of the sensed spectrum are evaluated and results e.g. capacity and reliability are forwarded to the decision making step.

Spectrum decision: based on analyzed RF information the CR will choose appropriate spectrum for use and adjust its operating parameters accordingly, e.g. bandwidth, transmission mode, data rate, modulation scheme, and transmission power.

Spectrum sensing is a fundamental step in the cognitive cycle [26]. Sensing reliability and sensing efficiency are key factors that determine the system performance of CR. High spectrum sensing reliability means more spectrum access opportunities while high spectrum sensing accuracy means less interference to legitimate users [35]. In the next section we present common spectrum sensing techniques employed by CR systems.

2.2.1 Spectrum Sensing

There are several classifications of sensing techniques. In IEEE 802.22, the first established WRAN cognitive standard, sensing techniques are classified as signal specific or blind [7]. A signal specific sensing technique is based on the features of a certain signal type such as pilot, field sync, segment sync or cyclostationary. In a blind sensing approach the detection does not depend on the specific features of a signal e.g. energy detection.

Sensing can also be classified into groups [26] [35] [36]. Such groups include primary transmitter detection, primary receiver detection, interference management and cooperative sensing as presented in the following:

Primary Transmitter detection: Detection is performed based on the sensed primary transmitter signal. Three schemes are generally employed for primary transmitter detection; matched filter detection, energy detection and cyclostationary detection. In matched filter detection the prior knowledge of the characteristics of primary user signal is known by the CR. Energy detection is used when the characteristics of the primary user signal is unknown by the CR. In case of cyclostationary detection the CR detects the cyclostationary features of modulated primary signals through analysis of the spectral correlation function. The comparison of these primary detection schemes is highlighted in the table 2-1.

Sensing scheme	Advantages	Disadvantages
Matched filter	Optimal performance Low computational cost	Require prior information of the primary user
Energy detection	Do not require prior information Low computation cost	Poor performance for low SNR Cannot differentiate users
Cyclostationary	Robust against interference	Require partial prior information High computational cost

Table 2-1: Summary of the advantages and disadvantages of primary transmitter sensing schemes

Primary receiver detection: The primary user signal is detected based on the local oscillator leakage power of the primary user receiver RF front end. This approach is suitable when the primary user receivers are within the communication range of the CR and primary transmitter signals are far away to be detected reliably [26]. In these cases primary receiver detection can be considered as a robust one

Interference temperature management: In this approach an upper limit interference power is imposed such that CR does not cause harmful interference to primary users. Unlike in other schemes the CR does not have to sense and wait for spectrum opportunities but they are restricted by some operating constraints (e.g. power) necessary to protect primary users. The disadvantage with this approach is that the CR devices cannot transmit at high power even if the primary user is completely idle at a given time and location. Additionally, it can be difficult to accurately determine the interference temperature limits.

Cooperative detection: In this technique, sensing is based on coordination among multiple CRs or using external detection agents such as sensor networks. Different approaches have been suggested to perform cooperative sensing, including centralized detection, External detection and distributed detection [26]. In centralized detection a central unit collects the sensed information related to spectrum occupancy from participating CR devices and aggregates this information to obtain the spectrum occupancy status. The aggregated information is then broadcast and the CRs adapt their operational parameters according to the received information. Another way is using external detection where separate sensor networks determine the spectrum occupancy and disseminate this information to CR devices which adapt their transmission parameters according to the received information. Unlike centralized and external detection, in distributed detection, CR devices make their own decision based on their individual sensed information and information received from other interacting cognitive devices.

The advantages of cooperative sensing include improved reliability and sensing accuracy, and it also helps to overcome the hidden terminal problem [35]. This is possible because the CR users rely on collaborated sensing information rather than on their own to information determine spectrum occupancy**.** However, collaboration involves use of network resources (e.g. bandwidth) which can create network traffic overload and can add additional cost from establishment of sensor networks (in case of external detection) and central units in case of centralized detection. Moreover, it may take a longer time to process the coordinated sensing information than the required sensing time resulting in detection delay. Detection delay is a critical issue since the primary user situation may have already changed during the decision process.

2.2.2 Dynamic Spectrum Access

CR is viewed as the emerging technology that facilitates efficient use of spectrum. Through dynamic spectrum access techniques, CR opportunistically makes use of the spectrum holes (white spaces) without causing harmful interference to the incumbent. The concept of dynamic spectrum access and spectrum hole/white space is illustrated in figure 2-1. At any time instant several non- contiguous spectrum regions are left unused. These unused portions can be used by secondary users while simultaneously ensuring that primary user's rights are not violated.

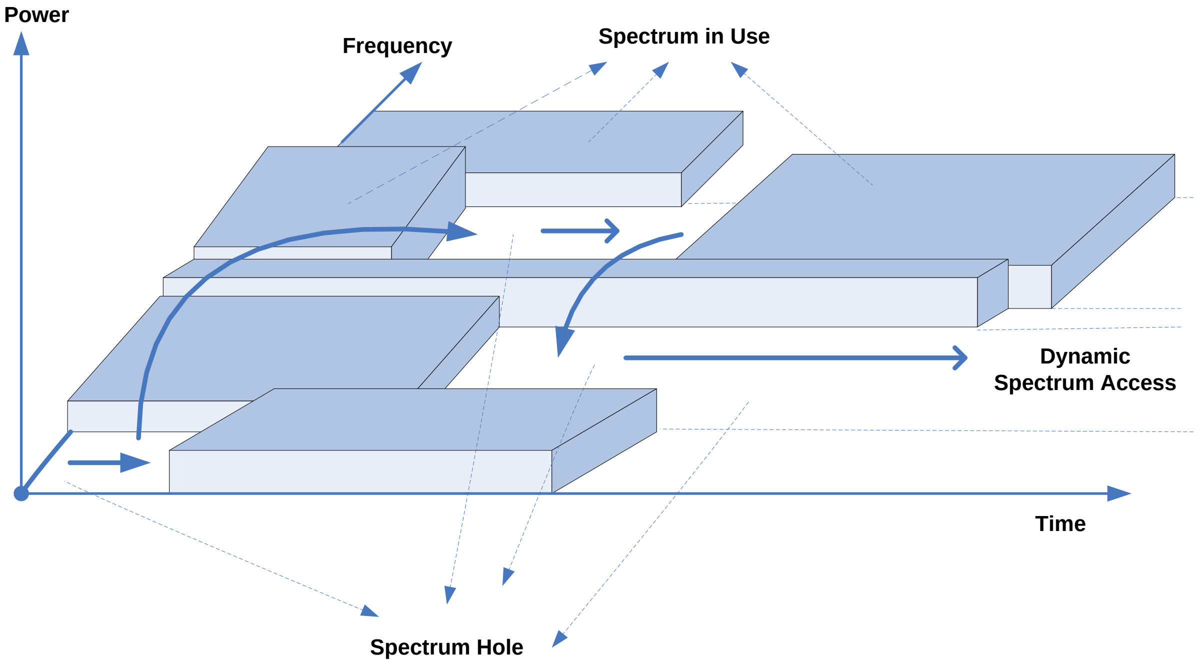


Figure 2-1: Dynamic access and white spaces/spectrum holes [32]

2.3 Related work-Coexistence performance of cognitive radio

The main focus of this work is to examine the coexistence of CR systems with the view of maximizing the use of CR in rural area particularly Africa and other developing countries. Until now much of the research work have been focused on TVWS [3] [4] [7] [11] [13] [16] [27] [39].The studies in the TVWS have resulted in the establishment of TVWS standards IEEE 802.22 for WRAN applications particularly in rural areas broadband connectivity. Compared to TVWS, very few studies have been made in other bands and no coexistence standards have been established. In [59] spectrum sharing studies between Cognitive Radio and GSM uplink band has been made. These studies investigate the channel capacity (bps/Hz) of cognitive radio user under different constraints and interference scenario. The studies however do not take into account the GSM power control mechanism which plays an important role in interference mitigations. Users traffic behaviours are also not considered which make it difficulty to reflect the practical systems. In addition the studies highlights channel capacity of cognitive radio systems under different GSM power, GSM channel occupancy , CR power limits and log-normal fading spread but doesn’t derive the required performance constraints required to fully protect the incumbent (GSM). In [60] femto cell based CR architecture for enabling dynamic spectrum access in next generation cellular broadband networks operating at 2.1 GHz band have been studied. The femto cell is primarily used for indoor application covering few meters. In this study the probability of false detection is measured as a function of throughput and it is shown that with the better sensing capability cognitive radio discovers the spectrum opportunities more efficiently and hence improving CR throughput and spectrum access which also result in less interference to primary user. Our work is based on the cognitive radio coexistence performance in the GSM downlink band. We investigate the key performance indicators and derive the cognitive radio performance constraints required to fully protect the primary users (GSM) while maximizing the use of white space. Our results will be compared with the already established TVWS from which extensive work has already been done.

2.4 Cognitive Radio Technical Challenges

CR systems are expected to significantly improve spectrum utilization efficiency through dynamic spectrum access mechanism however deployment of these systems may be faced with technical and operational constraints. These difficulties includes hidden terminal problem, and security concerns over the online database access. The discussion of these challenges and suggested measures is presented in the following.

2.4.1 The hidden terminal problems

A CR device works on the principle that it senses the environment before transmission in order to avoid interference by using the unutilized RF channels/frequencies. The presence of an obstacle (e.g. tree, building etc) between the transmitters may lead to misdetection of the RF signal. This phenomenon is known as shadowing which can result in the hidden terminal problem and is illustrated in figure 2-2. The CR B cannot detect primary transmitter A due to shadowing and both transmitters (Node A & Node B) may use the same frequency at the same time causing interference on the primary receiver (Node C). The shadowing can significantly deteriorate the performance of legitimate primary systems which are required to be protected all the time against interference.

Several solutions have been suggested each of which reduces the appeal of CR. One of the solutions is to have an ubiquitous network of beacons that is able to broadcast all transmissions at every location. The CR will then consult this network to determine the unutilized frequencies. The problems associated with this approach is the cost involved with development of such infrastructure may be too high to make business sense, and spectrum resources will have to be committed for CR devices to be able to communicate with this network, somewhat violating the whole meaning of CR. Another solution is to employ a cooperative sensing where nearby nodes communicate with each other and exchange information so that each can have a composite view of the environment. The problems with this approach may be the willingness of network operators to use their own device resources to facilitate connections of other networks and also if the number of CRs in the area of interest are sufficient to provide the full coverage. Online database access has also been considered as the solution where CR systems are required to consult these databases and obtain all information necessary for their coexistence with primary users. Such information may include a list of available frequencies and transmission power requirement.

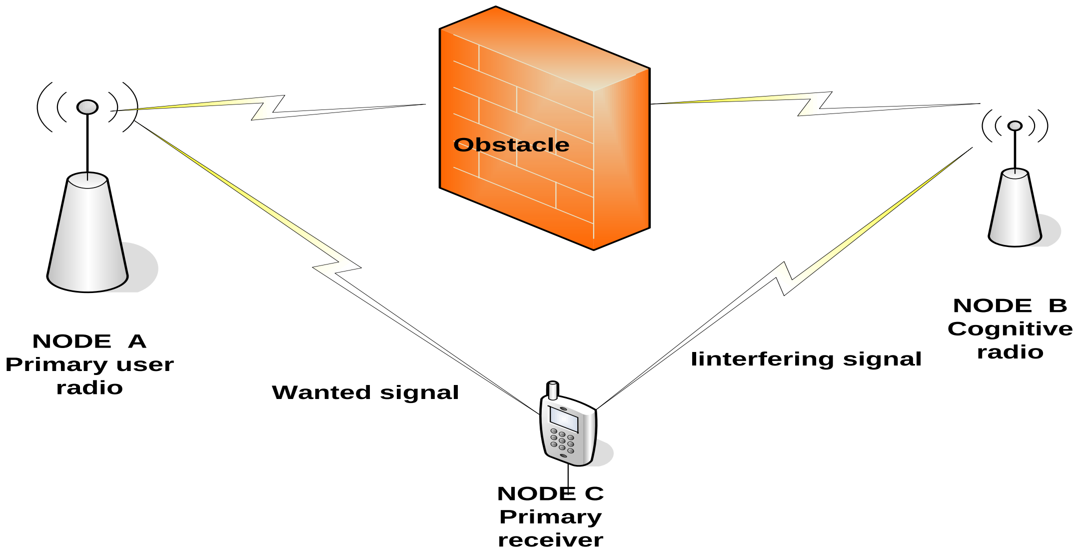


Figure 2-2: Effect of the hidden terminal problem

2.4.2 Security Issues

As mentioned above, prior to transmission CR devices may be required to access online centralized database containing the list of all frequencies in use and power requirements. Availability of these databases over the Internet makes them vulnerable to attacks such as spoofing. CR devices may also be hacked and loaded with unauthorized software which could alter the legitimate information obtained from the database causing them to operate on different frequencies and power level. Industry and regulators are aware of these threats and are working to find possible solutions [21]. Several authentication mechanisms such as PKI and the reputation protocol have been suggested [38].

2.5 Regulatory Challenges for Cognitive Radio Systems

For CR to fully support dynamic spectrum access, appropriate regulatory policies must be in place to facilitate the operation of these radios in white spaces. The existing regulatory approach may not meet all the necessary requirements needed to fully support these new technologies. Regulators across the globe have been reviewing their regulations in order to accommodate these new technologies and associated services. Existing regulation and their shortcomings together with new regulatory approaches are discussed. Some of the already practiced regulatory approaches supporting dynamic spectrum access are also presented.

2.5.1 Existing Spectrum Management Practices and Need for a Change

Command and control approach: This has been the traditional spectrum management model for almost 100 years [10]. In this model the spectrum is regulated by frequency where the RF spectrum is divided into frequency bands. Users are then assigned specific RF channels for specific service. The user has the exclusive usage of the assigned RF channels during the entire period of the License (authorization to use frequency). This approach is technological and service based for example, in Europe the band 890-915 MHz and 935-960 MHz is reserved for mobile services using GSM standards. The advantages of command and control approach are that it facilitates harmonization of spectrum use across multiple countries which can bring about economics of scales, international roaming and reduced interference [10].

Under the command and control approach, the control of interference has been imposed through imposing technical and operational limitations such as power, location, frequency etc and in case of frequency sharing it has been performed in a coordinated manner between the users. This method is regarded as a form of static control, as it does not give flexibility in accessing the spectrum. Even though spectrum is allocated to users some spectrum occupancy measurements such as those presented [28] have indicated that large portions of spectrum are unoccupied most of the time. Some of the other portions are only partially occupied, with only a small portion of the spectrum being heavily occupied. The static control approach was suitable when demand of spectrum was low, and the number of services was few, but in recent years there has been skyrocketing demand for usage of spectrum due to emerging technology and services and these have necessitated the need for change in the current approach. There has been evidence that the current methods are failing to maximize the economic value of the spectrum [10] as highlighted in some examples below

- There has been spectrum access difficult for new applications or technologies, e.g. iBursts cellular technology and Mobile TV systems [10]. While it is not guaranteed there would be value added, but their difficulty in entering the market may be a sign of an excessively rigid systems.
- Despite the availability of efficient technologies, some applications, e.g. aviation radar have been authorized to use spectrum for free and for many years, and they have not modernized their systems indicating there is not enough drive to do so [10].
- Some allocated spectrum has remained unused for many years, e.g. spectrum allocated to ERMES paging systems or the TFTS in flight phone system. Suggesting that it could have been put to an alternative use to add some value for this scarce resource [10].
- In the US the command and control approach governance of public safety spectrum has been questioned due to low non peak time utilization rates [24]

Owing to above constraints, dynamic spectrum control has been considered as ideal approach especially in high spectrum utilization demand like wireless broadband applications. The advancement in technologies such as CR (CR) and Software Defined Radio (SDR) have the potential to provide real time spectrum access negotiation and transaction, and thus enable dynamic spectrum access. CR is capable of sensing its environment including spectrum use and presence of other radio and adapts their operational characteristics to avoid interference. Such capabilities could improve spectrum utilization efficiency through dynamic real-time control of interference instead of the current static control approach [19].

The need for change arises from the fact that traditional command and control approach may be too restrictive to cater for current trends. This has prompted regulators across the globe to review regulatory policy on spectrum licensing to accommodate these new changes. A market driven approach has been considered as suitable model for the current pace in technological advancement and emerging services. Under this scheme the ownership and use of spectrum can change in the course of license operation. Other features include transparent and open spectrum allocation mechanism such as auction and introduction of secondary market (spectrum trading) where a licensee may lease part of their spectrum to another entity. Some of the key advantages of market driven approaches include promoting coexistence of different systems in a situations where interference can be mitigated. This may make it easier for new entrants to enter the market and acquire spectrum through secondary trading, promote competition and incentive to use new technologies and services due to spectrum liberalization.

Exclusive use model: In this model the users are exclusively assigned specific RF channels and are not restricted on the services they provide. However, certain operational rules (e.g. emission limits) are imposed to ensure that they do not cause interference to neighboring users**.** The advantage of this approach is it gives flexibility for users to use technologies and services of their choice. On the other hand if the spectrum is underutilized by the licensee it could lead to wastage of this scarce resource due to exclusivity. Permission for secondary usage on these bands through dynamic spectrum access will improve spectrum utilization efficient and pave the way for emerging technologies and new services.

License exempt model: This is also referred to as spectrum commons: Under this scheme a certain portions of spectrum is reserved for common use and users do not require license to operate in these bands. Devices operating in these bands are normally low power devices and certain emission rules are provided to ensure they do not cause interference to legitimate users. License exempt users are not guaranteed any interference protection right or the exclusive use of the RF channel [24]. Examples of license exempt service include cordless phone and wireless LAN such as Wi-Fi.

2.6 Examples of Established Regulation in TVWS

Since the TV band is a licensed band, the introduction of secondary usage needs new regulation to protect the incumbent. For this, regulatory bodies such as FCC, OFCOM, CEPT and some government agencies have made rules regulating TVWS, and other countries like China, Germany, Japan, France are interested and plan to make rules on using spectrum more efficiently [3]. Outlines of some of these rules are given below

2.6.1 FCC rules

Under the FCC rules the TV band is unlicensed for secondary usage. Unlicensed devices that could be used in this band are categorized into two groups a low power unlicensed devices such as Wi-Fi cards in computers and wireless LAN. The second group is unlicensed high power fixed wireless devices. Both of these devices must have sensing and geo-location/database access capabilities and are type approved by the FCC. Portable devices are classified into mode I which is under control of device employing geo-location/database access and mode II which must support geo-location/database access by itself. In all devices the geo-location accuracy should be within +/- 50 meters and the devices must be capable of sensing ATSC digital TV, NTSC analogy TV and wireless microphone signals. The FCC has also specified the separation distance protection contour requirement from which the unlicensed devices must keep away from TV service contour edge. Technical and operational requirements for TV unlicensed devices [29] are shown in tables 2-2, 2-3, 2-4 and 2-5 below.

Antenna height (m)	Separation (km)	
	Co-channel	Adjacent channel
Less than 3	6.0	0.1
3 to 10	8.0	0.1
10 to 30	14.4	0.74

Table 2-2: Minimum separation distance between TV unlicensed devices an TV service contour edge

Signal type	Signal strength
ATC	-114 dBm, average of 6 MHz bandwidth
NTC	-114 dBm, average over 100 kHz bandwidth
Wireless microphone	-114 dBm, average over 200 kHz bandwidth

Table 2-3: Sensing Thresholds (referenced to an omni-directional receive antenna with gain of 0 dB)

Transmit Power	Maximum 1 W 40 mW if on adjacent channel
EIRP	Maximum 4 W
Transmit-power control	Required
Bandwidth	Unlimited

Table 2-4: RF parameters for high power fixed devices

EIRP	Maximum 100 mW with geo-location and sensing maximum 50 mW with only sensing
Transmit power control	required
bandwidth	unlimited

Table 2-5: RF parameters for portable devices

2.6.2 OFCOM

In 2009, Ofcom proposed three approaches for unlicensed devices access in the TV band. The proposed methods include sensing, geo-location/database access and beacon. Ofcom recognizes that each method has its advantages and drawbacks.

- Sensing has the capability of determining the white spaces but the hidden terminal problem may cause interference to the incumbent
- Geo-location requires online database access and frequent updates of the database by the license holders and
- Beacons require infrastructure to transmit and a database to store the information.

Ofcom thinks that the beacon approach is inferior to other two and will not be taken for further consideration. Ofcom requirements for geo-location and sensing are shown in table 2-6 and 2-7.

Recently Ofcom has decided to make TVWS license exempt on condition that they do not cause harmful interference to primary users. To ensure protection of existing users notably TV broadcasters and wireless microphone, white space devices will be required to consult a list of database hosted online and will notify one of the databases of its location and update regularly. The database will then return detailed lists of frequencies and power levels it is permitted to use. Ofcom’s next step is to consult on a draft Statutory Instrument to make white space devices license exempt [21].

Ofcom expects that White Space technology could be launched in the UK in 2013 and is also considering the future use of other White Spaces such as those in the band currently used by FM radio services.

Cognitive parameter	**Value**
Assume 0 dBi antenna	-114 dBm in 8 MHz channel (DTT) -126 dBm in 200 kHz channel(wireless microphone)
Transmit power	13 dBm (adjacent channels) to 20 dBm
Transmit-power control	Required
Bandwidth	Unlimited
Out of band performance	Less than -44 dBm
Time between sensing	Less than 1 second
Maximum continuous transmission	400 milliseconds
Minimum pause after transmission	100 milliseconds

Table 2-6: Ofcom requirement for spectrum sensing [6]

Cognitive parameter	**value**
Location accuracy	100 meters
Frequency of database access	To be determined
Transmit power	As specified by the database
Transmit-power control	required
Bandwidth	unlimited
Out-of-band performance	Less than -44 dBm
Maximum continuous transmission	400 milliseconds
Minimum pause after transmission	100 milliseconds

Table 2-7: Ofcom requirement for spectrum geo-location [6]

2.6.3 CEPT Regulations

CEPT has taken various initiatives in tackling the CR regulations issues. Groups within CEPT dealing with different aspects of CR have been established. The names and functions of these groups are outlined in the following

TG4: this group was mandated to establish harmonized European decisions on the use of digital dividends. The group was established in 2007 and completed its work in February 2010. Two key results that came out were the identification of the upper part of UHF band V as a possible harmonized band for the digital dividend in Europe and the use of the reverse duplex in the digital dividend spectrum.

CPG PTA: This group is responsible for preparation for WRC-2012. In addressing the WRC-2012 agenda items 1.19 CEPT is of the opinion that frequencies or frequency bands for a particular applications can be harmonized regionally by regional telecommunication organization or on world basis in the ITU recommendations approved and developed in a normal way unless exceptional is justified.

SE42: WAPECS (Wireless Access Policy for Electronic Communication Services) - The purpose of SE42 group is to develop the list of least restrictive technical conditions in the following frequency bands; 174 – 240 MHz, 470 – 862 MHz, 880 – 915 / 925 – 960 MHz, 1710 – 1785 / 1805 – 1880 MHz, 1900 – 1980 / 2010 – 2025 MHz, 2500 – 2690 MHz, 3.4 – 3.8 GHz. In WAPECS the operators will have freedom to choose from any access technology and service.

SE43: The objective of this group is to look at the best use of CR in the TV band. SE43 is mandated to define the technical and operational requirements for the operation of CR systems in the white space of UHF TV broadcasting band such that incumbent radio services systems are sufficiently protected and investigate the consequential amount of spectrum potentially available as white space.

2.7 White spaces and Rural Broadband access

The CR through utilization of white spaces may provide cost-effective technological means of bridging the digital divide in rural and underserved areas. Statistics indicate that the internet broadband access in rural area is very low compared to urban areas [12]. Low income, low population density and lack of supporting infrastructure are some of the stated contributing factors. The CR devices are expected to dynamically access the white space on license exempt basis or at a much lower spectrum fees compared to licensed bands. These devices are also expected to be low cost, low power and intelligent devices with minimum human intervention and capable of operating in wide range of frequencies. These CR features may significantly lower deployment and operation cost resulting in availability of affordable services in rural and underserved area.

In rural areas demand for spectrum is often less critical but requirement for coverage is of paramount importance due to sparse population. Until now the focus of regulators and industry players has been on the TVWS in the frequency range of 470 MHz-862 MHz from which standards like IEEE 802.22 have been developed and other standards, e.g. IEEE 802.11af are under development. This may be due to ongoing worldwide migration from analogue TV to more spectrum efficient digital television technology which has made it possible to free some spectrum and increased white space in TV UHF band [12].

The technical and operational requirement for devices operating in TVWS may be difficult to achieve in developing countries. The need for establishment of state of the art real time database management systems and associate infrastructure may be challenging in developing countries due to cost and other requirements, e.g. it may be difficult to get up to date network information all the time due to power unreliability experienced in these countries. As an alternative, GSM white space in frequency range 890-960 MHz and 1710-1880 MHz is proposed. Comparison between GSM and TVWS will be discussed and potential applications of CR in white spaces will be highlighted in the following.

2.8 Comparison between GSM White Space and TV White Space

Studies show that the spectrum utilization for both GSM and TV in rural areas is low compared to urban areas. Both TV and GSM RF bands offer excellent coverage compared to other higher frequency bands e.g. WiMax at 2.5 GHz and Wi-Fi at 2.4 GHz.

The TVWS devices, e.g. IEEE 802.22 operate on a condition that they have sensing, geolocation and online database access capabilities. These requirements may increase CR complexity and the need for infrastructure to support the real time incumbent's database access. The deployment cost associated with such arrangement can be higher and can become a stumbling block for rural broadband access particularly in developing countries. In WRAN applications the minimum separation distance required for cochannel and adjacent channel sharing with incumbents is likely to be greater due to interference susceptibility of TV receivers. E.g. in IEEE 802.22 for co-channel sharing separation distance between 6-10 km is required between CR and TV service contour. This means that the presence of TV services may have bigger impact on the coverage of secondary services compared to GSM band. On the other hand the TVWS may offer better data rates because there is more bandwidth than in the GSM band.

One of the big challenges in TVWS is the detection thresholds imposed on the cognitive devices. For example Federal Communication Commission (FCC) requires that all cognitive devices operating in TVWS must be capable of detecting incumbent signals at -114 dBm. Such a signal level is well below noise level so the sensing must be performed at negative SNR. One of the drawbacks of operating at this SNR level is that synchronization is not practical. Successful signal detection is usually achieved when reliable synchronization is obtained. In addition, the use of a simple energy detection technique such as an energy detector is rather difficult because energy detectors do not work with very negative SNR levels due to noise uncertainty [39]. This means that for reliable sensing, using complex sensing techniques such as cyclostationary detection that rely on specific signal features must be employed. This may add CR complexity and cost.

Unlike the TVWS the requirement for real time database access, infrastructure may not be mandatory particularly in low power applications because of the robust interference mitigation mechanism of the GSM systems. The various interference mitigation techniques employed by GSM includes channel quality monitoring, power control and frequency hopping. The channel quality is monitored by measuring certain performance parameters, e.g. SINR, BER and through the use of a control channel base station and mobile station exchange information before connection is established. Power control has also been used as an interference control method where the base station or mobile device within its operating range adjusts its power depending on the quality of the channel. Frequency hopping is usually applied in high traffic loading conditions, e.g. urban areas where channel assignment is done in a random order in each base station in a predefined time intervals. In this arrangement the interference is significantly minimized by averaging out the total interference among all users.

Another advantage of using the GSM white space is both primary users and secondary users can coexist in the same service area. This may be beneficial to secondary users who can share the available GSM infrastructure, e.g. towers and microwave links. Moreover, the incumbent may utilize the white space to offer secondary services such as fixed broadband services using the existing infrastructure. Such an approach may significantly reduce the operational and deployment cost of CR systems.

The choice between the two white spaces will depend on the user requirements for example, GSM white spaces could be used in situations where it is difficult to achieve real time database access infrastructure required by devices operating in TVWS. On the other hand TVWS can be utilized when users have supporting infrastructure to facilitate real time database access and much higher data rates.

2.9 Potential Applications of Cognitive Radio in White Spaces

Additional services could be provided in white spaces by devices employing the CR techniques. As already emphasized, the CRs opportunistically utilize white space under condition that they do not cause harmful interference on primary users. Since the focus until now has been on TVWS most of the suggested applications have been centred on the TVWS. However, these applications could as well be applied to proposed GSM white spaces. The emerging white space applications are outlined below.

Wide area coverage in rural areas (e.g. IEEE 802.22): There is more white space in rural areas which could be used for fixed wireless broadband covering a distance of up to tens of kilometres [4].

Enhanced Wi-Fi like application (e.g. IEEE 802.11af): low power devices could be used in unlicensed TVWS/GSM white space to provide broadband services over short distances, e.g. Wi-Fi hotspots in wireless local area networks (LAN) [27].

Backhaul for wireless LAN/Wi-Fi: When Wi-Fi such **as IEEE** 802.11af or IEEE 802.11a/b/g/n is installed, e.g. in airports, hotel, campuses or business the main challenge is usually the internet connectivity to the Wi-Fi access points. The time and cost associated with cable connectivity could be significantly reduced by using TVWS as a backhaul for access point. This is because TVWS and GSM white space RF signal provide better coverage and also have better penetration inside walls and buildings.

Remote monitoring: TVWS/GSM white space could provide a communication link between monitoring stations and remote devices such as equipment, sensors, meters etc. Some of the examples are Connectivity for security cameras, remote monitoring of a power plant and monitoring patients in locations where signal loss is severe but connectivity is achievable with TVWS/GSM white space.

Public safety networks: Public safety organs, e.g. Police, fire, search and rescue and emergency medical services rely heavily on the use of wireless networks as a means of day to day communication and in an event of emergency. These networks can support services like voice, text, pictures transfer, database access, video streaming and other wide band services. However, the radio frequency allocated for public safety use has become heavily congested especially in urban area [9]. In addition interoperability of these safety agencies is often difficult due to multiple frequency bands, incompatible radio equipment and lack of standardization. The above challenges can be eased through the application of CR. With CR, public safety users can use additional spectrum such as

TVWS/GSM white space. CR can also improve device interoperability through spectrum agility and interface adaptability.

2.10 Standardization and International Activities on CR

As an emerging technology, standardization of CR systems not only ensures these devices support interoperability among heterogeneous systems while offering different applications and services, it also means that they are recognized worldwide. Economies of scale as result of standardization will also lower production cost of CR devices and their associated services. Implementation of these systems could be more beneficial to end users especially in rural and underserved areas where the income is generally low as the services could be offered at affordable price. The CR standards are being developed and few have been finalized notably IEEE 802.22. Some of the key international standardization organizations taking part in development of CR standards include IEEE, ITU, ETSI, Wireless Innovation Forum formerly known as SDR forum and ECMA. The established and potential cognitive standards along with various activities carried out by the international organization are highlighted in the following:

2.10.1 IEEE 802.22 standards

Finalized in 2011, IEEE 802.22 is the first established CR standard for wireless regional area networks (WRAN) operating in the UHF television band on a secondary basis. It is designed for last-mile service in low populated areas especially rural area. It makes use of the TVWS on non interference basis through spectrum sensing, geo-location and real time primary user’s database access. The CR base station covers an area between 30 km (typical) to 100 km and the network is designated to provide the minimum throughput of 1.5 Mbps for the downstream and 384 kbps for the upstream [7]. In additional to conventional PHY and MAC layer functionalities, new features have been included in IEEE 802.22 standard. These features are highlighted in the following:

- Spectrum Manager (SM): The SM uses the input from the spectrum sensing and geo-location and the primary user database to determine the TV channel for WRAN base station and the EIRP threshold for a particular WRAN terminals. The SM is located in the MAC layer, and it interfaces with the Physical Layer Management Entity (PLME) to control the local sensing and geo-location functions and the station management entity to access the primary user database.

- Spectrum Sensing (SS): The function of spectrum sensing is to analyze the spectrum in the interested channels to determine which channels are occupied by incumbents. In 802.22 standards both the base station (BS) and user terminal must have sensing capabilities but the final decision on channel selection is done by the BS.
- IEEE 802.22.1 beacon: In addition to sensing the primary user the WRAN devices are required to detect the IEEE 802.22.1 beacon which is transmitted to signal the presence of wireless microphones. The beacons contain the information of the microphone such as location, signature and certificate to ascertain that protection is needed. The beacons are transmitted at the channel occupied by microphones 77 kHz bandwidth in the 6 MHz TV channel at the nominal digital TV pilot frequency.

2.10.2 IEEE 802.11af

The workgroup IEEE 802.11af was created in January 2010 to develop Wi-Fi like standard based on CR technologies in the TVWS. The objective of this group is to modify both the 802.11 physical layers (PHY) and the 802.11 Medium Access Control Layer (MAC), to meet the legal requirements for channel access and coexistence in the TVWS [8]. The work of IEEE 802.11af is still ongoing.

2.10.3 ECMA-392 standards

Published in December 2009, ECMA-392 is the first CR standard for personal/portable devices to exploit the TVWS. This standard specifies the PHY and MAC for operation in TV band with several features such as flexible network formation, adaptation to different regulatory requirements and support for real time multimedia applications [13]. Some of the applications ECMA-392 is expected to support, includes in home HD video transmission, campus wide area coverage and interactive TV broadcasting.

2.10.4 IEEE 802.16h

This standard is an amendment to IEEE 802.16 to cater for a mechanism to enable the coexistence of license exempt systems based on IEEE 802.16 standards at 2.4 GHz and 5 GHz, and to facilitate the coexistence with primary users through mitigation of potential of frequency interference caused by such systems sharing the same frequency bands.

2.10.5 IEEE 802.19

IEEE 802.19 is the wireless coexistence Technical Advisory Group. The purpose of this group is to develop the mechanism for coexistence between different IEEE 802 standards networks operating in common white space. This group held its first meeting in January 2010.

2.10.6 SCC-41

The IEEE standards coordinating committee 41(SCC 41) Dynamic Spectrum Access Networks (DySPAN) was formed from the previous IEEE P 1900 standard committee with the aim of developing supporting standards in the field of spectrum management and advanced radio system technologies such as CR systems and related technologies. SCC 41 has six working groups 1900.1, 1900.2, 1900.3 and 1900.4, 1900.5, 1900.6 dealing with different project as outlined in the following [17]

- IEEE working group 1900.1 is responsible for establishing technically precise definitions and explanation of key concepts in fields of CR, policy defined radio adaptive, software defined radio and related technologies.
- IEEE working group 1900.2 is tasked with formulating the technical guidelines for analyzing the potential of coexistence or interference between radio systems operating in same frequency bands or between frequency bands.
- IEEE working group 1900.3 is responsible for specifying techniques for radio frequency testing and analysis to be used during regulatory compliance and

stakeholder evaluation of radio systems with the dynamic spectrum access capability.

- IEEE working group 1900.4 is the major working group and its function is to define the appropriate system architecture and protocols which will facilitate optimization of radio resource usage in heterogeneous wireless access networks.
- IEEE working group 1900.5 defines the policy language and policy architecture for managing CR for dynamic spectrum applications
- IEEE working group 1900.6 defines the spectrum sensing interface as well as data structures for dynamic spectrum access systems.

2.10.7 ETSI

The European Telecommunications Standards Institute (ETSI) is a recognized European Standards organization by European Commission (EC). ETSI is mandated to develop applicable standards for fixed, mobile, radio, converged, broadcast and internet technologies [5]. ETSI has established a technical committee for Reconfigurable Radio Systems (RRS) to examine the standardization and development of CR and software defined radios. ETSI RRS technical committee conducted a feasibility studies and in 2009 produced a report [20] which presents the recommended topics for standardization. The report laid foundation for development of RRS standardization which is ongoing.

2.10.8 Wireless Innovation Forum

The Wireless Innovation Forum (WIF), formerly known as SDR, is a non-profit organization committed to promoting the emerging wireless technologies takes strong interests in CR. There are three groups within WIF involved in CR activities. The first group is the Regulatory committee which aims at promoting the development of international regulatory framework supporting software download and reconfiguration mechanisms and technologies for SDR-enabled devices and services [5]. The second group, the CR Working Group (CWRG) works on harmonizing the meaning and implication of CR and related terms. The CWRG has recently completed a report

"Quantifying the benefits of CR". This report represents the results of the extensive survey conducted on open and public CR (CR) literature and has been approved by WIF. The third group Cognitive Applications Special Interest Group (CA-SIG) is responsible for identifying the wireless communication and control scenarios where CR and CR applications could provide better solution than the traditional approach. Its objective is to help identify which CRs applications are likely to emerge first.

2.10.9 ITU

Having about 192 member states and other membership from leading academic institutions and over 700 private companies ITU is regarded as single a global organization in that it embraces all players in the ICT sector. ITU allocates global radio spectrum including satellite orbits and develop technical standards that ensures network and technologies seamlessly interconnect, and strives to improve access to ICTs to underserved communities worldwide [12]. At the national level detailed regulations are established in harmony with the ITU regulations. Conformity with ITU regulation is usually based on goodwill [5]. Through its study groups the ITU-Radio communication Bureau (ITU-R) has initiated standardization activities on CR and cognitive networks. Following the ITU World Radiocommunication Conference (WRC-07) resolution 956, ITU-R study group 1 Working part IB was tasked to study the need for regulatory measures related to the application of software define radio (SDR) and CR systems (CR). The next conference WRC-12 will consider the results of the studies and take appropriate actions.

In 2007, ITU Radio communication Assembly (RA) issued a letter to ITU-R study group to study the question ITU-R 241-1/5 ''CR in land mobile services''. The key issues that were addressed include:

- What is the ITU definition of CR systems?
- What are the closely related radio technologies (e.g. smart radio, reconfigurable radio, policy-defined adaptive radio and their associated control mechanisms) and their functionalities that may be a part of CR systems?

- What key technical characteristics, requirements, performance and benefits are associated with the implementation of CR systems?
- What are the potential applications of CR systems and their impact on spectrum management?
- What are the operational implications (including privacy and authentication) of CR systems?
- What are the cognitive capabilities that could facilitate coexistence with existing systems in the mobile service and in other radiocommunication services, such as broadcast, mobile satellite or fixed?

The outcome of the above studies will be published in ITU-R recommendations and /or reports.

2.11 Comparisons of Cognitive Radio Standards with Related Existing Standards

Until recently IEEE802.22 is the first CR based standard that has been finalized and as already mentioned it will be operated in TVWS. Another promising standard which is still under development is IEEE 802.11af; the standard will also operate in TVWS spectrum on low power license exempt basis. Comparison of these most promising CR standards with their related existing IEEE standards is highlighted in the following

2.11.1 IEEE 802.22 and IEEE 802.16

IEEE 802.16 was developed to provide the infrastructure necessary to support both fixed and mobile wireless metropolitan access network in the range of 1-5 km radius. It operates on microwave frequencies above 2 GHz, e.g. WiMax at 2.5 GHz, 3.5 GHz and 2.3 GHz. IEEE 802.22 is intended for fixed wireless broadband services in rural areas covering a distance of up to 100 km. Table 2-8 below summarizes comparison of the two standards.

	IEEE 802.22	IEEE 802.16
Air interference	OFDMA	OFDMA, OFDM, single carrier
Multiple Antenna techniques	Not supported	Support Multiplexing, space time coding and Beam forming
Self coexistence	Dynamic spectrum assignment	Master frame assignment
Coexistence with incumbent	Spectrum sensing management, Geolocation management, incumbent database query and channel management	Not supported
Internetworking communication	Over the IP network	Over the IP network
OFDMA channel profile (MHz)	6,7,8 (according to Regulatory Domain)	28, 20, 17.5, 14, 10, 8.75, 7, 3.5, 1.25

Table 2-8: Comparison between IEEE 802.22 and IEEE 802.16 standards

2.11.2 IEEE 802.11a/b/n and 802.11af

Both of these standards are meant for low power devices supporting LAN operating in unlicensed frequency bands. IEEE802.11a/b/n operates on highly congested unlicensed frequency bands at 2.4 GHz and 5 GHz. The 802.11af standard is currently being developed to operate on a TVWS as a way of enhancing IEEE802.11 capabilities and providing an alternative means. IEEE 802.11af will employ both sensing and online database access to mitigate interference. These features are not available in existing IEEE802.11 a/b/n standards.

The diagram below illustrates how these IEEE standards are related

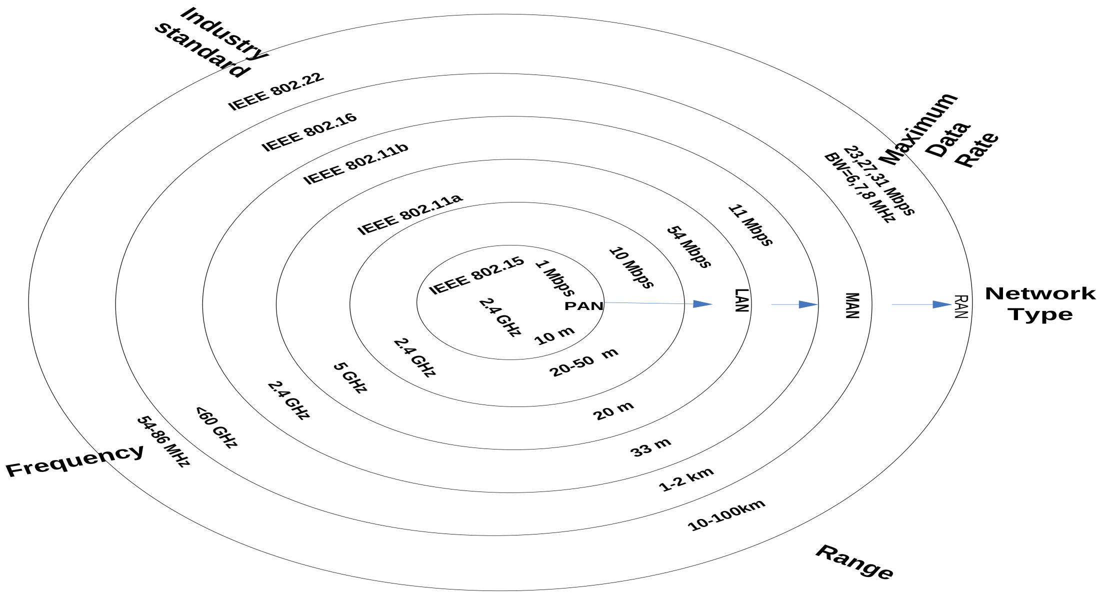


Figure 2-3: IEEE wireless Standards

2.12 Propagation Channel Models

In order to assess the coexistence performance of CR systems an appropriate propagation channel model has to be established. Choosing appropriate channel models is the key in accurately determining the interference behaviour of the wireless systems. Channel modelling provides a means of predicting the signal power losses between the transmitter and receiver.

The characteristics of the path are influenced by various factors including frequency, distance, antenna height and environment.

As the waves propagate they will suffer attenuation (path loss) due to frequency, distance, antenna height and environment. In addition, channels in mobile wireless systems may be subjected to phenomenon known as fading which is a result of reflection, diffraction, scattering of electromagnetic waves and clutter (e.g. tree, buildings, mountains etc) along the path.

If P_T is effective isotropic radiated power at the transmitter in decibel, P_{LOSS} is the total path loss in decibel then the received input power PR at the receiver can be expressed as [37]

$$P_R(dB) = P_T - P_{LOSS} + G_{R-}L_R \qquad (2.1)$$

$$Where\ \ P_T = P_{TR} + G_T - L_T \qquad (2.2)$$

$$And\ P_{LOSS} = Loss(Distance) + Loss(Shadowing) + Loss(Multipath)\ (2.3)$$

$Loss\,(Distance)$ accounts for large scale channel losses whereas $Loss\ (shadowing)\ and\ Loss(\ Multipath)$ accounts for small scale channel losses also known as fading.

P_{TR} Transmitter power, G_T antenna gains of the transmitter, L_T and L_R are antenna feeder losses in transmitter and receiver cables respectively.

The above expression is a **link budget** of the propagation channel which accounts for all losses and gains in a channel. By assessing the link budget it is possible to meet the requirement of the end to end communication systems, e.g. (e.g. sensitivity, signal to noise ratio, carrier to interference ratio). In the next section various existing large scale and small scale channel models will be explored and appropriate model will be adopted for later analysis of coexistence performance of CR systems.

2.12.1 Large Scale Channel Models

This deals with path loss due to distance, where the average received power are a function of the user with respect to distance from the base station and the obstacle between them. Large scale loss only changes when user moves at least few meters. Channel loss with distance is deterministic, non random and useful in determining how many transmitters are required to cover given area and how many interference is expected from other transmitters. Large scale is classified as empirical channel models and physical channels model. Physical models require detailed knowledge of the area to be covered such as terrain, building, trees etc. Empirical models require an extensive set of actual path measurements of a particular environment and appropriate function is fitted by averaging all the measurements. The model can then be used to design the systems operating in the same environment. The empirical models have found favour in both research and industrial communities owing to their speed of execution [37]. In this thesis only empirical models will be considered.

2.12.1.1 Basic Channel Models

Includes free space loss (FPL) which is dependent only on frequency and distance and planet earth loss (PEL) which is independent of frequency but takes into account the transmitter and receiver antenna height. Both of these models are considered to be ideal as they do not consider the environment effects on path loss. The expressions for these losses are

$$FPL(dB) = 32.4 + 20logR + 20logF \tag{2.4}$$

Where R is the propagation distance in km and F is the frequency (MHz) and

$$PEL(dB) = 40logr - 20logh_m - 20logh_b \tag{2.5}$$

Where r is the propagation distance in km and h_m and h_b are antenna heights of mobile/user station and base station respectively.

2.12.1.2 Clutter Factor Models

This is an extension of the plane earth model where an extra loss (dB) called clutter factor has been added. The clutter factor depends on frequencies and environment.

2.12.1.3 The Okumura-Hata Model

This is the most widely used model in radio frequency propagation for predicting the behaviour of cellular transmissions in city outskirts and other rural areas [37]. This model incorporates the graphical information from Okumura model and develops it further to better suit the need.

It is based on a large number of readings between 150 MHz and 1500 MHz in and around Tokyo. It is applicable for a distance above 1 km and base antenna height above the ground of 30 m to 200 m and mobile antenna height of 1 m to 10 m. This model is derived from three scenarios Urban, suburban areas and open areas as presented below;

Urban area $$Loss\ (dB) = A + BlogR - E \tag{2.6}$$

Suburban area $$Loss\ (dB) = A + BlogR - C \tag{2.7}$$

Open area $$Loss\ (dB) = A + BlogR - D \tag{2.8}$$

Where R is the propagation distance and A, B, C, D and E are parameters which are dependent on combination of mobile and base antenna height above the ground and frequency.

The urban values have been standardized by the **ITU** in the recommendation ITU-R P.529.

2.12.1.4 The COST- 231 Hata Model

This is an extension of Okumara-Hata model and it is designated to be used in the frequency band 500 MHz to 2000 MHz It also contain corrections for urban, suburban and rural (flat environment). Its simplicity and availability of correction factors has seen it widely used for path loss prediction. The path loss equation is of the form [23]

$$Loss(dB) = F + BlogR - E + G \tag{2.9}$$

Where $F = 46.3 + 33.9logf_c - 13.82logh_b$ (2.10)

$$E = (1.1logf_c - 0.7)h_m - (1.56logf_c - 0.8) \qquad (2.11)$$

f_c and R are frequency and distance respectively

$G = 0\,dB$ for medium-sized cities and suburb areas and $G = 3\,dB$ for metropolitan areas.

2.12.1.5 Stanford University Interim (SUI) Model

The SUI Model is based on extensive experimental data collected at 1.9 GHz in 95 macro cells across the United States. The model, adapted by the IEEE 802.16 group is the recommended model for fixed broadband applications [23]. SUI model is divided into three terrains namely A, B, C. Type A represents maximum path loss and is suitable for hilly terrain with moderate to heavy foliage densities. Type B is characterized with either mostly flat terrains with moderate to heavy tree densities or hilly terrains with light tree densities and type C represents minimum path loss and applies to flat terrain with light tree densities. SUI model can be used where the height of base station antennas range from 10 m to 80 m, where the receiving antenna height between 2 m and 10 m and the cell radius between 0.1 km and 8 km. The path loss equation is expressed as

$$PL = A + 10(log_{10}\left(\frac{d}{d0}\right) + X_f + X_h + s \;\; for\ d > d0 \qquad (2.12)$$

Where, d is the distance between the transmitter and receiver in meters, $d0 = 100\,m$ and s is a lognormally distributed factor that is used to account for the shadow fading owing to trees and other clutter.

The other parameters are defined as,

$$A = 20log_{10} \qquad (2.13)$$

$$\gamma = a - bh_b + \frac{c}{h_b} \qquad (2.14)$$

Where, the parameter h_b is the base station height above ground in meters and a, b, c are constants and their values depend on terrain type. The frequency correction factor is given by

$$X_f = 6.0 \log\left(\frac{f}{200}\right) \tag{2.15}$$

Where f is the frequency

2.12.1.6 ITU- REC-P.1546-4 Model

This propagation model is used for prediction of field strength in frequency ranges between 30-300 MHz it is intended for use between the distance of 1 to 1000 km and antenna height less than 3km over land, sea or mixed land/sea path. Determination of the base antenna height depends on the distance under consideration and may require geographical information if it is not known. One of the interesting features of this model is it produces similar results to the Okumura-Hata method for distances up to 10 km**.**

2.12.1.7 Winner II Channel Model

This model can be used for wireless systems operating in the frequency range 2-6 GHz with up to 100 MHz bandwidth [38]. It supports multi antenna technologies, polarizations, and multiuser, multicell and multi hop networks. The model path loss is of the form

$$Loss\ (dB) \ = \ Alog\ (d\ ([m])\ + B + Clog10\ (f_c\ [GHz])\ + X \tag{2.16}$$

Where d is the propagation distance and f_c is the system frequency.

A, B, C, X are fitting parameters and their values are provided and are based on applications scenario e.g. Urban, rural, suburban and whether it is line of sight (LOS) or Non line of sight (NLOS).

2.12.2 Small Scale Channel Models

These models deal with small changes in received power as the user moves much smaller distance typically few centimetres [37]. These variations in power (also known as fading) are losses due to shadowing and multipath. In shadowing or slow fading received power fluctuations are due to objects obstructing the propagation path as a result different locations with equal distance from the transmitter will receive different power. Multipath or fast fading occurs when the transmitted wave takes more than one path to receiver due to reflections and refractions as mobile user moves over small distances compared to shadowing correlation distance. Since both shadowing and multipath fading are random variables, their predictions are based on statistical approach. Shadowing is characterized by lognormal distribution and multipath is characterized by Raleigh distribution in the case of non line of sight or Ricean distribution in the case of a line of sight scenario.

2.13 Conclusion

In this chapter we presented an overview of CR and discussed various sensing techniques which can be employed by CR to identify white spaces. It had been found that energy detection is the simplest technique that does not require prior knowledge of the incumbent signal however they operate best at positive detection thresholds (SINR). Other techniques such as cyclostationary detection and matched filter are more complex and require prior primary signal information, however, they provide accurate sensing information even at detection thresholds below noise level. Cooperative sensing is another technique where multiple CR shares sensing information prior to decision. It provides a means of minimizing hidden terminal problem at the expense of utilizing radio resources for information exchange. A sensing technique where stringent operation conditions, e.g. transmit power, are imposed on cognitive user has also been presented. This technique is called interference temperature.

The possible applications of CR in white spaces including rural connectivity, Wi-Fi like applications, remote monitoring and public safety have been discussed and the comparison between the established TVWS and proposed GSM band has been made. The implementation of CR in TVWS could be challenging in developing countries owing to lack of supporting infrastructure to support real time incumbent database access and the need to use complex sensing mechanism to meet the required low detection thresholds which may add cost to cognitive devices. An alternative has been proposed for the use of CR in the GSM band in rural area where it is believed to be underutilized. The interference robustness of the GSM systems may be a key in using low power cognitive devices in this band without a need for real time database access to support incumbent protection. In the later chapters, we examine the coexistence performance and determine the impact of CR in this band.

The technical and regulatory challenges associated with the implementation of CR in white spaces have also been discussed and possible solutions outlined. The hidden terminal problem has been the course for concern and several solution including cooperative sensing and database access have been suggested. There has been a security concern on the use of online database access due to possible attacks by internet hackers which may interfere with the legitimate operations of these devices. Several authentication mechanisms such as PKI and reputation protocol have been suggested. On the regulatory aspects, the conventional command and control has been regarded as a rigid approach to dynamic spectrum access. More flexible market based approaches are being adopted by regulators to cater for current technical advancement.

To understand the interference behaviour of wireless systems, various channel models have been studied including their advantages and limitations. The COST-231 Hata model which has been extensively used in the UHF band will be adopted here to analyze the interference under coexistence between GSM and CR systems.

3 Simulation and Validation Methodologies

3.1 Introduction

In this chapter we present the simulation technique, programming tools and key performance indicators that have been used to investigate the coexistence of CR systems in the licensed bands. The focus of our analysis is on the GSM band where we determine the impact of CR on the existing GSM performance. Our analysis is based on the use of a Monte Carlo simulation technique and MATLAB programming tool to generate results. Each result represents certain key performance indicators including blocking probability, dropping probability, throughput, delay and power utilization measures such as mean power and power CDF. These indicators together with other parameters influencing performance such as SINR and INR will be highlighted. We will also present the propagation channel model and shadowing model parameters to be used for estimation of path loss between the transmitter and the receiver.

3.2 Monte Carlo Simulation Technique

The complexity of the systems under investigation renders it difficult to model their behaviours using analytical methods**,** so a Monte Carlo simulation technique has been used instead. Monte Carlo simulation is a statistical simulation method that utilizes random numbers assigned to key parameters to exercise a range of values to perform simulations. This method requires large number of statistical sampling experiments (trials) to get a sound approximation of the behaviour. However, it has become more widely used due to increase in computer technology and computational power.

Two simulation procedures will be used for analyzing coexistence performance. In the first procedure we will consider link by link, the activation process where GSM (primary systems) links will be activated first followed by the activation of CR (secondary systems) links. The impact of introducing secondary systems on the existing primary system will be studied. In the second procedure we will develop traffic models and coexistence performance will be investigated based on channel load conditions.

The simulation flowchart for these procedures will be presented in chapter 4 and 5. These chapters provide detailed coexistence analysis.

3.3 MATLAB Tool

In our simulation, the MATLAB (“MATrix LABoratory”) programming has been used as the numerical computation, data analysis and visualization tool. Although traditional programming languages such as FORTRAN and C may offer better execution speed, MATLAB has advantages that it is fast to write and reasonably fast run. This means simulations can be developed quickly and parallel computing capabilities allows us to run these simulations to completion without user intervention. This gives us more time to develop more simulation scenarios and have wider range of considerations, rather than concentrating on execution speed at the expense of a tedious simulation development period if C or FORTRAN is used.

3.4 Key performance Indicators

This section highlights the major performance indicators that have been utilized to assess the performance of the individual GSM and CR systems.

3.4.1 Blocking Probability

This parameter has been used to measure the probability that a call or data transmission cannot be established**.** This failure is due to insufficient network radio resources and poor link quality between the transmitter and receiver. When the available radio resources cannot support the existing users the network becomes congested resulting in call or data transmission blocking during initialization. Similarly, call/data blocking will occur when there is an excessive interference at the receiver due to other transmission on the same radio channel or excessive path loss due to propagation and fading. This will deteriorate the link quality to the extent that the SINR requirement is not met. SINR will be discussed later in this chapter.

The blocking probability of a system is statistically measured and is given by;

$$Prob\_Blocking = \frac{Number\ of\ blocked\ calls}{Total\ number\ of\ calls\ made} \qquad 3.1$$

Throughout this simulation it is assumed that the QoS requirement is met provided the call blocking probability does not exceed 5% of the total calls [58].

3.4.2 Dropping Probability

This parameter has been used to measure the probability that the call/data transmission in progress will be terminated before either involved party intentionally ends the call/data transmission. Call dropping occurs when the interference from newly activated transmissions is excessive to the extent of weakening the link quality of the call in progress. Dropping probability is one of the key performance indicators for measuring QoS particularly in circuit switched systems such as GSM voice calls. Users are generally more sensitive to call dropping than to call blocking at initialization. Proper network planning involves keeping this value as low as possible. The dropping probability of a system is expressed as

$$Dropping\_Probability = \frac{Number\ of\ drop\ calls}{Number\ of\ calls\ made - Number\ of\ blocked\ Calls} \qquad 3.2$$

Throughout this simulation it is assumed that the QoS requirement is met provided the call dropping probability does not exceed 0.5% of the total established calls [58].

3.4.3 Additional dropping probability

This parameter has the same meaning as the dropping probability but has been introduced to show the impact of coexistence. It is referred as the probability of dropping on the existing systems caused by the activation of new system under coexistence. In our scenario the impact of secondary systems (CR) on the existing systems (GSM) is measured by the additional dropping probability which is given by.

$$Additional\_Drop\_Probability(GSM) = \frac{Number\ of\ dropped\ calls\ caused\ by\ Cognitive\ radio\ activation}{Total\ GSM\ calls\ made - blocked\ GSM\ calls - dropped\ GSM\ calls} \qquad 3.3$$

3.4.4 Throughput

Throughput has been used to measure the number of data bits the system can transmit in a given time. The bits are usually grouped into packets or files. Throughput gives an indication of the capacity of the networks at a given channel load; it is particularly applied in packet switched networks such as GPRS and CR systems. Throughput is dependent on the quality of the link between transmitter and receiver, and the modulation schemes employed. Good link quality allows higher modulation schemes to be used, which support high data transmission rates, and hence increased throughput. On the other hand poor link quality will result in low transmission rates which will decrease the systems throughput. In our simulation the throughput is expressed as

$$Throughput = \frac{Total\ transmitted\ files\ (bits)}{Simulation\ time(seconds)} \qquad 3.4$$

3.4.5 Average transmission delay

Average transmission delay has been used to measure the average time it takes to transmit files from the source to destination including the retransmission waiting time. Retransmission occurs when the file (packets) fails to be transmitted at first attempt mainly due to radio resource unavailability or poor link quality.

The average file delay is expressed as follows

$$Average\ file\ delay = \frac{\sum File\ Size\ (bits) * Transmit\ time(seconds)}{Average\ file\ size(bits) * Total\ number\ of\ files} \qquad 3.5$$

3.4.6 Power utilization measures

We will measure the power utilization of the primary systems (GSM system) as a result of introduction of secondary systems in GSM band and compare with the GSM power utilization in absent of secondary systems. Two parameters namely mean transmit power and power commutative distribution will be used performance indicators.

Mean transmit power: describes the average power utilization in the GSM network and is given by

$$Mean\ transmit\ power = \frac{\sum BTS\ Transmit\ power\ to\ each\ user}{Total\ Number\ of\ users} \qquad 3.6$$

Transmit Power cumulative distribution: describe the probability that the random variable X (transmit power) falls in the given interval (-∞, X). In our simulation we use Normal Cumulative function which is inbuilt in MATLAB.

3.5 Propagation Channel models

In chapter 2 we discussed the different channel propagation models and adopted COST-231 Hata path loss model for interference analysis. In this section we present the radio channel parameters including shadowing. These parameters have been used to determine link budget between the transmitter and receiver for both GSM and CR. The SINR which determine the quality of the link will also be presented. Most of transmitter and receiver parameters for GSM are derived from GSM standards [46]. In case of CR the parameters are taken from typical broadband equipment specifications in the UHF band. The path loss simulation parameters are presented in the table 3-1 below.

GSM PARAMETERS	
Base station Maximum RF power	46 dBm
Base station receiver sensitivity	-104 dBm
Base station antenna gain	14 dBi
Base station antenna height	30 m
Base station antenna cable losses	3 dB
Mobile station Maximum power	33 dBm
Mobile station receiver sensitivity	-102 dBm
Mobile station antenna gain	0 dBi
Mobile station antenna Height	2 m
Mobile station Cable loss	0 dB
Mobile receiver SINR	Min=9 dB Max=18 dB
COGNITIVE RADIO PARAMETERS	
Maximum Access point transmit power	29 dBm
Access point receiver sensitivity	-110 dBm
Access point antenna gain	9 dB
Access point cable losses	1 dB

Table 3-1: Path Loss simulation Parameters

Access point antenna height	10 m
User terminal cable losses	0 dB
User terminal sensitivity	-104 dBm
User terminal antenna gain	8 dB
User terminal antenna height	1 m
User terminal SINR	Min=3.5 dB Max=18 dB

Table 3-1: Path loss simulation parameters

3.5.1 Shadowing parameters

The shadowing effect is characterized by the log-normal distribution (normal distribution in dB) with probability density given by

$$P(X_{SF}) = \frac{1}{\sqrt{2\pi}\,\sigma} e^{-\frac{X^{2}{}_{SF}}{2\sigma^{2}}} \tag{3.7}$$

Where X_{SF} is the zero mean Gaussian distributed random variable and σ is the standard deviation. The normal values for standard deviation reported in literature are between 5 to 12 dB [23]. The standard deviation (σ) value adopted for our simulation is 8.4 dB. The shadowing component is split into two parts; the first part reflects the contribution relative to location of the receiver and second part is the contribution relative to receiver – transmitter path. By splitting the shadowing effect between receiver and transmitter, increased correlation can be provided. This shadowing model provides a more realistic shadowing environment compared to non correlated shadowing model associated with the link only [22]. The distributed random variables and their corresponding standard deviation for each component are mathematically represented by;

$$X_{SF}(i) = X_L + X_P(i) \qquad 3.8$$

And $$\sigma^2 = {\sigma_L}^2 + {\sigma_P}^2 \qquad 3.9$$

Where subscript L and P represents the shadowing components relative to location and path respectively.

It is been assumed that the shadowing contribution from the two components are equal and therefore

$$\sigma_L = \sigma_L = \frac{8.4}{\sqrt{2}} \qquad 3.10$$

3.5.2 Signal to interference and Noise Ratio (SINR)

This is an important parameter which is derived from the link budget equation presented in chapter 2 and is used to determine the quality of the propagation path between the transmitter and receiver. A connection between transmitter and receiver can only be established if the SINR at the receiver is equal or above the specified SINR thresholds. SINR thresholds vary depending on the systems capabilities and user requirements. In our simulation the ranges of SINR threshold have been set between 3.5-18 dB.

SINR is expressed as follows

$$SINR(watts) = \frac{R_x}{N+\sum_{j=1}^{n} I} \qquad 3.11$$

Where R_x is the received signal power from wanted transmitter power, I is the received unwanted signal power from interfering transmitters and N thermal noise power expressed as

$$N(dB) = 10 * \log_{10}(KTB) \qquad 3.12$$

Where K is Boltzmann constant $1.381 * 10^{-23}\mathrm{J/K}$, T is the noise temperature 290 K and B is the channel bandwidth 200 kHz.

3.5.3 Interference to Noise Ratio (INR)

INR also referred to as detection threshold will be used to measure the availability of the channel for usage by secondary systems (CR). The sensing unit of the CR measures the received signal strength of a particular channel relative to noise level and if the detected signal is above the required threshold the channel is regarded as unsuitable for utilization. Due to interference robustness of GSM systems, different values ranging from 10 dB to 100 dB will be used to determine the impact of CR on the primary systems. From these values we will identify the appropriate threshold required to protect the primary systems from excessive CR. The INR of the i_{th} channel is given by

$$INR_i\ (dB) = \sum_{j=1}^{n} I_i(dB) - N(dB) \qquad 3.13$$

Where, I_i is the resultant detected signal strength from all transmitters transmitting on the i_{th} channel and N is the thermal noise power.

3.6 Conclusion

In this chapter, we have presented our approach for coexistence analysis between incumbent GSM systems and the secondary systems (CR). Owing to complexity of the systems a statistical simulation approach based on a Monte Carlo simulation technique will be used. Numerical computation and graphical representation of results will be performed using the MATLAB. The QoS parameters, including call blocking probability and call dropping probability will be used to measure the coexistence performance. The system capacity and average transmission time has will be measured in terms of throughput and delay. Interference has been analysed using the COST-231 Hata path loss model and shadowing which is derived from lognormal distribution. The SINR parameter will be used to determine the link quality and the CR channel detection mechanism have been based on the received channel signal strength relative to noise which is also referred to as INR.

4 Link Based Downlink Coexistence Performance Between GSM and Cognitive Radio System

4.1 Introduction

In this chapter we examine the coexistence constraints in the GSM band between incumbent (GSM systems) and secondary systems (CR). The aim of this analysis is to find out the interference protection criterion of the incumbent that may be required to support coexistence and our focus will be on the downlink GSM transmission (base station to mobile station). This analysis assumes a worst case scenario where at any time all GSM channels are fully utilized according to specific re-use pattern. A more detailed analysis based on a traffic models will be presented in chapter 5. The effect of introduction of CR in GSM band is assessed by measuring the performance of GSM systems without coexistence and compared it with the performance under coexistence**.** The key performance indicators that will be used to measure performance of GSM system includes additional call dropping probability and GSM power utilization in terms of mean power and CDF. These indicators have been highlighted in chapter 3 and will provide performance measures when GSM is subjected to various CR transmission power and detection thresholds. Based on the results of the analysis, we will determine different operation constraints that may be necessary to impose on CR to ensure the maximum protection of incumbent while facilitating secondary usage. A Monte Carlo simulation technique and MATLAB presented in chapter 3 will be important simulation tools.

4.2 Coexistence Scenarios

The coexistence scenario is shown in figure 4-1. It is assumed that the CRs coexist with the GSM network in the same geographical area. The total coverage area of under coexistence is approximately 1380 km^2 and it consists of 27 GSM Base Transceiver Stations (BTS) and 27 CR access points. We use a three hexagonal cell cluster GSM cellular network configuration where frequency is re-used after every three neighbouring cells. Each hexagonal cell represents one BTS coverage area which is 4.5 km radius and GSM cells which use the same frequency are shown with the same colour. This makes a GSM co-channel distance of 13.5 km. In the case of CR a point to multipoint architecture is used where each Access Point (AP) provide coverage of 1 km radius. In our coexistence scenario we have assumed that there is one randomly located AP within each GSM cell making the total number of AP equal to 27 within the entire GSM cellular coverage. The AP coverage is represented by small hexagonal cells in the figure 4-1. In our scenario both GSM and CR users are uniformly distributed within their cell coverage and total number of users in each cell is the same. A conventional three sector antenna configuration is employed in each base station, where a typical GSM antenna radiation pattern with a beam width of 90^0 has been used to provide 120^0 coverage in each sector. The CR systems employ omni-directional antennas for sensing and a directional antenna for transmitting and receiving. Each CR AP coverage is divided into three sectors, where a typical UHF broadband antenna radiation pattern with a beam width of 65^0 have been used to provide a coverage of 120^0 in each sector. With both GSM and CR using three directional antennas in their cells, 360^0 hexagonal cell coverage for both systems is obtained and is represented in the figure 4-1 below.

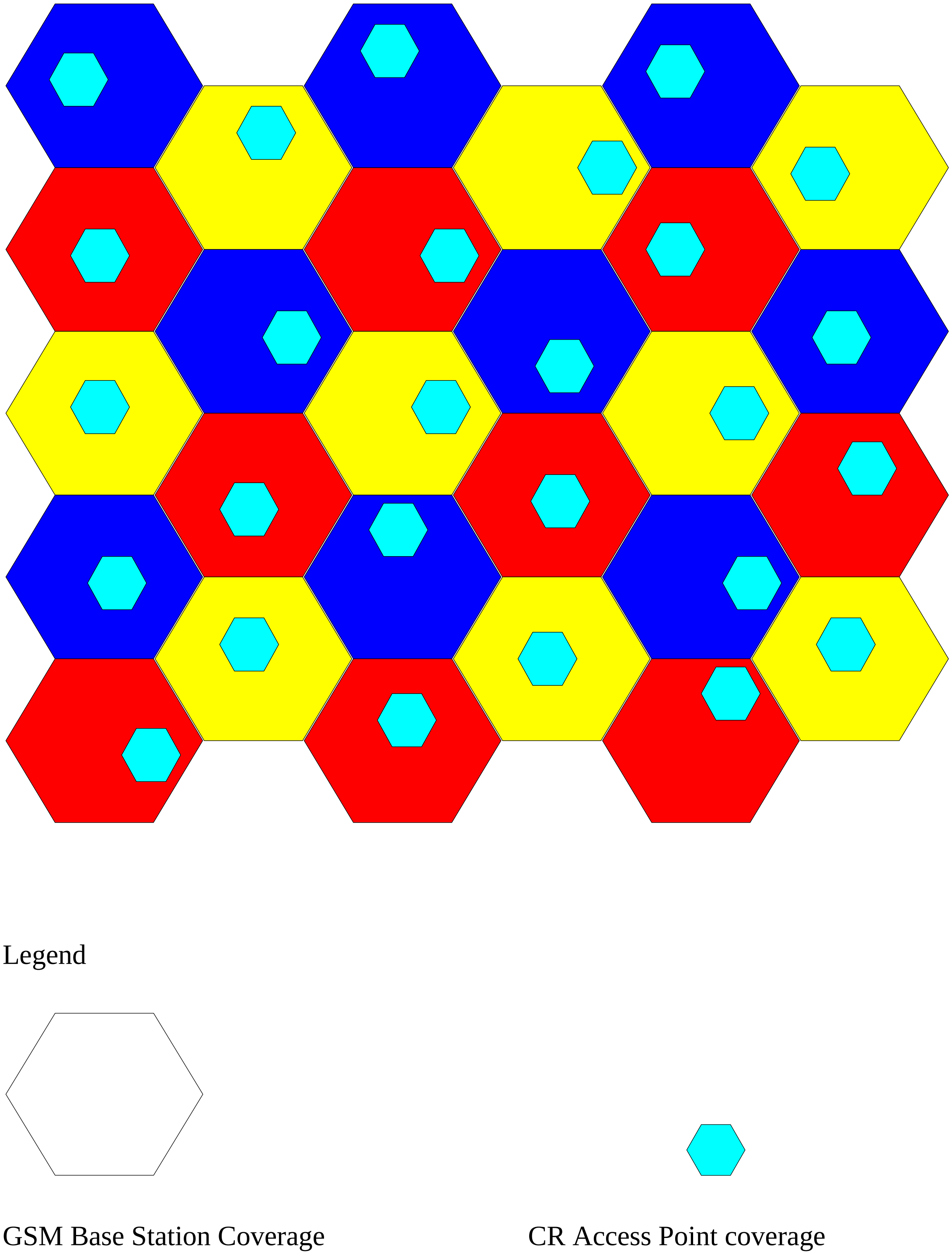


Figure 4-1: GSM and CR coexistence scenario showing coverage areas.

4.3 Link based performance analysis

This analysis is based on worst case scenario where it is assumed that a GSM network operates at full load. This implies that at any time all GSM channels are in use according to the frequency re-use pattern. The frequency re-use pattern corresponds to co-channel distance of 13.5 km as already discussed in section 4.2. We define a link as a propagation channel between a BTS and MS, and in case of a CR it is defined as a propagation channel between AP and user terminal. The propagation channel model used in our simulation is based on the COST-231 Hata model which has already been discussed in chapter 2. The effect of shadowing is incorporated in our channel model where we use a two component correlated shadowing based on a receiver position and receiver-transmitter link. This has been discussed in more detail in chapter 3 where shadowing and channel models parameters were also presented.

The activation of the link is related to call initialization process. The link will only be activated and call established when the SINR level is equal or greater than the required threshold. In GSM when the link quality is below the required SINR threshold the power control mechanism is used to try to achieve the required level. Under power control mechanism the BTS regulates the transmit power based on the received feedback information from the mobile receiver. The feedback information provides the channel quality at the receiver (SINR) which prompt the transmitter to either increase or decrease their power to ensure the required SINR level are met. More discussion on power control will be in chapter 5 when we discuss about radio resource management (RRM). If after power adjustment a link is still below the required threshold it will not be activated, or deactivated if it was already active. This will result in call blocking or call dropping. SINR, Call blocking probability and call dropping probability have been discussed in chapter 3.

The process of activating a CR link involves two stages. In the first stage the CR sense GSM channel and determine the INR threshold of which the details have been presented in chapter 3. In this stage if the link is above the required threshold, the channel is regarded as occupied and the link will not be established. The second stage is performed only when INR level is below the required threshold. This stage involves measuring of the SINR to determine if it is equal or above the required threshold. When the measured equal or above the required threshold the link will be activated. On the other hand if the measured value is below the required threshold the link will not be established and this will result in call blocking or dropping.

The flow chart illustrating the simulation algorithm for coexistence performance is presented in figure 4-2. It is assumed that the GSM already exists when the new CR system is introduced in the GSM band. Both GSM links and CR links are uniformly distributed and randomly selected from their associated cells. The activation process is performed on a link by link basis and number of links in each cell corresponds to total users in that particular cell. The GSM links are first activated one by one in all co-channel cells. At each activation the new link SINR is monitored and existing active links SINRs are also monitored. The new link will be blocked if it SINR falls below threshold and existing link will be dropped when its SINR falls below threshold. When link activation in all GSM co-channel cells is finished, the CR link activation starts one by one until a link in each cognitive cell has been activated. For every CR link activation, the quality of a new cognitive link and existing active GSM and CR links are monitored. Again when the link quality falls below SINR it will not be activated or it will be deactivated if it is an active link. When a link in each cognitive cell has been activated, all GSM and cognitive links are deactivated and the process repeats until the required number of runs is reached. At each run the link status such as blocking, dropping and transmitter power is recorded. The key performance indicators such as blocking probability, additional dropping probability and power utilization are statistically determined from these runs. In order to take into account different coexistence scenarios the whole simulation process is repeated for a number of iterations. Each iteration represents different arrangement of AP within the GSM coverage area. The final results are derived from combining the results of these iterations.

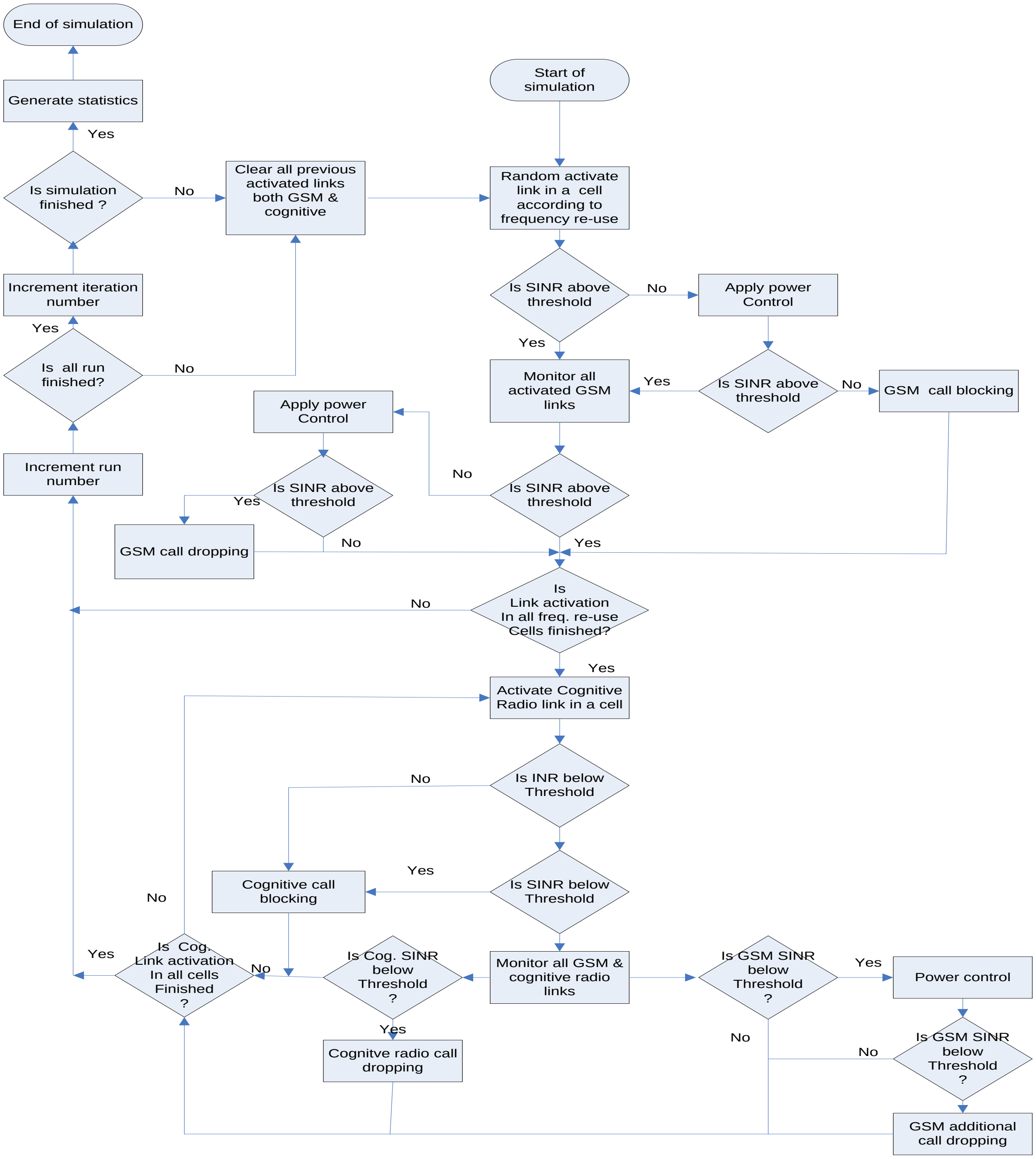


Figure 4-2: Flow chart illustrating the simulation algorithm for coexistence performance analysis

4.4 Simulation Results

This section presents the results of the simulation. All cells represented in figure 4-1 have been used in this simulation. However, in order to obtain the a better general representation results, the results have been obtained from the inner most GSM cluster and access points from which each cell has at least 6 co-channel interfering neighbour cells.

4.4.1 Effect of Cognitive Radio transmit power and INR on GSM additional dropping probability

The additional dropping probability as a result of GSM network being subjected to CR interference is shown in figure 4-3. Different CRs AP transmit power ranging from -1 dBW to 10 dBW have been used. It can be seen from this figure that as we increase the CR transmit power the GSM additional dropping probability also increases. This is due to interference increase at the GSM link caused by increased CR transmit power. However the level of interference caused by CR can be controlled by introducing the INR threshold (detection threshold) which will prevent activation close to GSM receivers. Three INR thresholds 30, 60,100 have been used and it is shown that as we increase these thresholds the GSM additional dropping probability increases. When we limit the INR level to 30 dB, we find that there is insignificant additional dropping probability. From this we note that the GSM performance is unaffected by the presence of CR when the detection threshold is set at 30 dB and below. This is because the CR is blocked from co-channel sharing when separation distance from GSM links is not adequate to make the channel available to cognitive user.

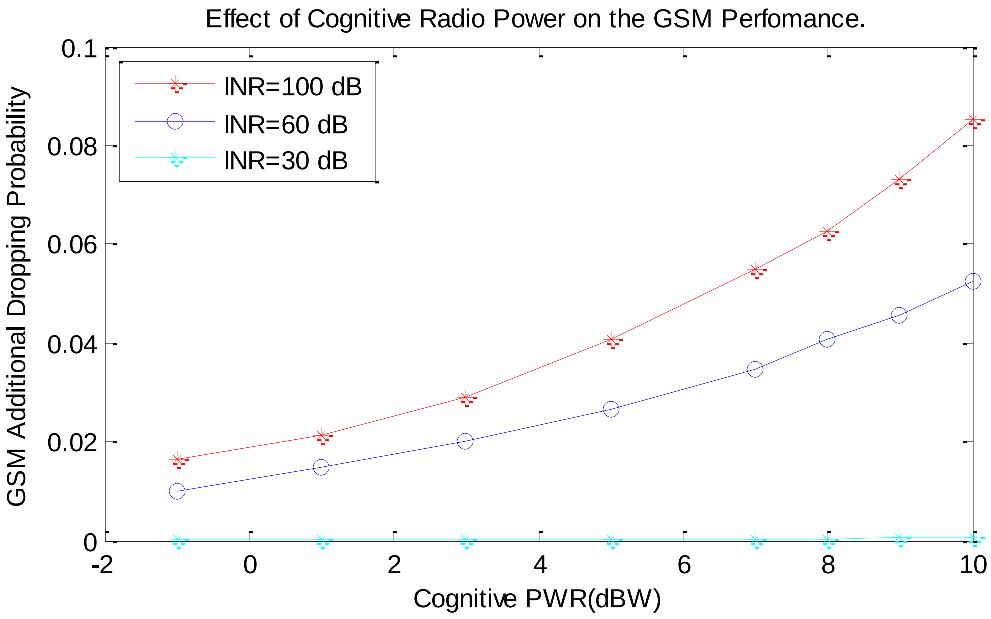


Figure 4-3: Effect of Cognitive Radio transmit power on GSM additional dropping probability.

4.4.2 Effect of Cognitive Radio transmit power and INR on GSM power utilization

Figure 4-4 shows the effect of INR on the performance of GSM systems based on power utilization. In this scenario the GSM system is subject to a transmit power of -1dBW from the CR systems under different INR thresholds. The GSM power utilization in terms of CDF (Cumulative Distribution Function) is measured at different cognitive INR thresholds and compared with the power utilization when GSM operates without coexistence. It can be seen from the graph that as we increase the INR threshold the GSM power utilization increases, e.g. at 100 dB INR threshold there are about 77% of the links utilizing power below 8 watts, but when GSM operates in absent of the CR systems there are about 86% of links utilizing power below 8 watts. This happens as the results of experiencing more interference from CR which forces the GSM BTSs to increase their power in order to maintain the required SINR at the mobile station receiver. However, when we limit the INR thresholds to 30 dB we find out that GSM power utilization remains the same with or without the presence of CR. It is clear that at this INR level the CR is blocked from utilizing channels which are already occupied by GSM systems when the separation distance is not adequate to make the channel available to cognitive users.

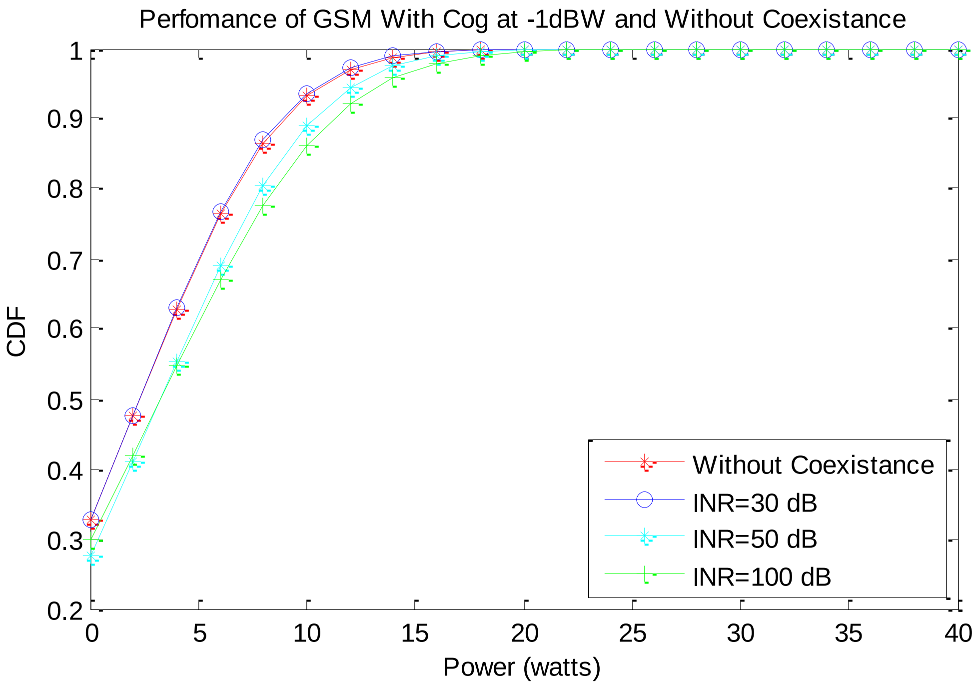


Figure 4-4: Effect of Interference to Noise Ratio threshold on the GSM Power utilization based on CDF.

The effects of CR transmit power and channel INR on the performance of GSM based on mean power utilization is shown in figure 4-5. In this scenario GSM systems are subjected to different CR transmit power and the INR levels. We note from this graph that the mean GSM transmit power increases with the increase in CR transmit power. This is due to excessive interference which forces the GSM to increase power to maintain the link quality. We already stated that the interference can be controlled by limiting the detection thresholds. Again we note that at the INR level of 30 dB, the presence of CR does not influence the performance of the GSM.

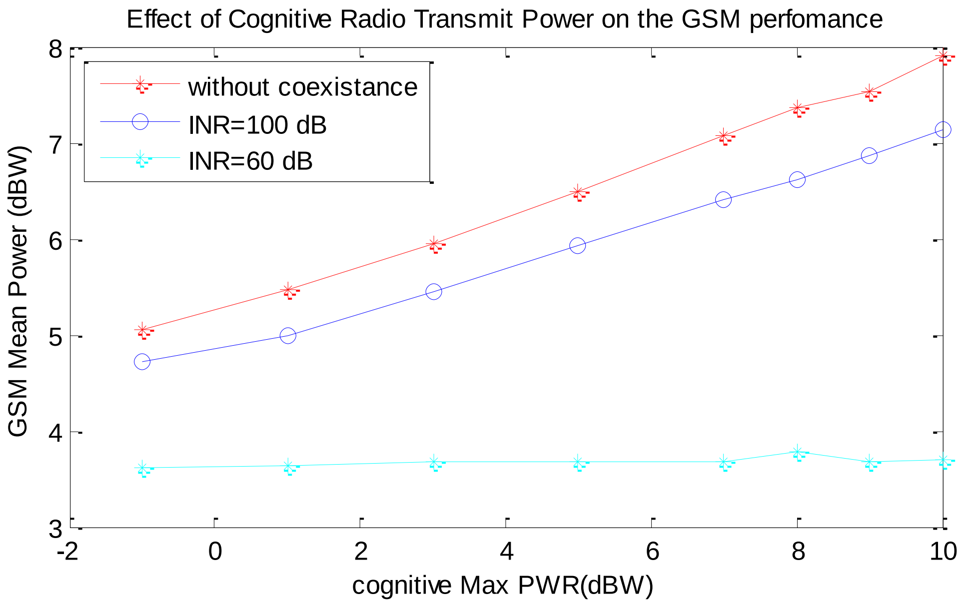


Figure 4-5: Effect of Cognitive Radio power on the GSM mean transmit power

4.4.3 Cognitive Radio Blocking Probability under Coexistence

The performance of CR based on blocking probability is shown in figure 4-6. In this analysis the blocking probability is determined from different cognitive transmit powers and detection thresholds (INR). It is shown that the blocking probability is dependent on the channel detection threshold. The more we increase the INR the more channel availability opportunity the CR system will have. The reduction in blocking probability as we increase the INR arises from the fact that in downlink transmission the sensing (INR detection) is preformed at the CR transmitter and the SINR is measured at the user terminal. Although the interference at the cognitive AP may be higher it may not be the case for the user terminal receiver because in this scenario the GSM utilizes directional antenna. We can also note from figure 4-6 that when the INR threshold is 30 dB the channel availability opportunity is limited and as expected the CR is blocked from using the GSM channels that are being utilized.

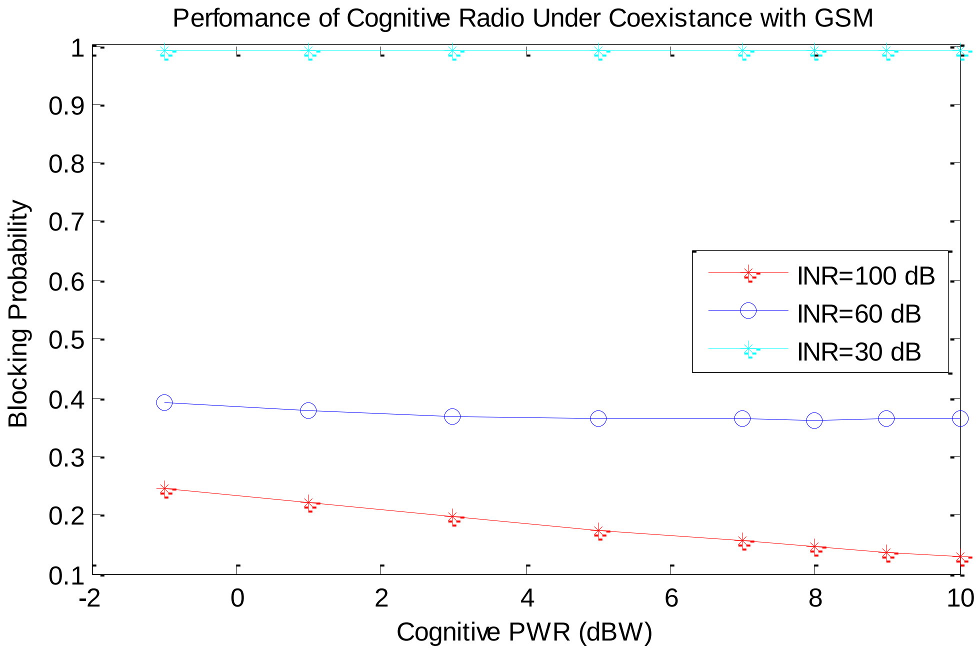


Figure 4-6: The effect of Interference to Noise Ratio on the Cognitive Radio blocking probability.

4.5 Discussions

This performance analysis has given us an insight into the coexistence constraints between the two systems. By taking into account the worst case interference scenario where we assume the primary user (GSM) systems utilizes all channels at all time, we ensure a guaranteed protection of primary user under all conditions. The maximum acceptable level of INR threshold required to fully protect the incumbent against secondary user interference has been found to be 30 dB. At this value the effect of CR on the performance of GSM is insignificant. Since CR opportunistically utilizes GSM channels depending on the detection threshold set up, it means that under 30 dB INR threshold the CR systems have no access to utilized GSM channels. This has been shown to be the case even when CR operates at high power of up to 10 dBW. From this we can establish that the GSM channel can only be made available to cognitive system in two ways, first is when the channel is not in use by GSM systems. Second is when the separation distance between the GSM link and cognitive link sharing the channel is large enough to achieve the required detection threshold. In the context of our analysis the channels that are opportunistically utilized by CR systems in GSM band are referred to as GSM white spaces.

Compared to the already established TVWS (Television White Spaces) in the UHF band, the detection threshold for CR devices in the GSM band is significantly higher than in TV band. In chapter 2 we presented technical requirements for the CR devices operating in TV band and typical value for detection threshold is -114 dBm for both high power and low power applications. In our GSM band analysis it has been shown the detection threshold of 30 dB relative to noise level or (-91 dBm) signal power is sufficient for protection of GSM systems. Since in GSM band the detection threshold requirement is above noise level we can employ simple energy detection techniques to determine GSM white spaces. In the case of TVWS, energy detection technique may not provide accurate sensing information because this technique is less reliable if the detection threshold is below noise level. This means a more complex detection mechanism such as feature detection may be necessary for CR devices operating in TVWS. The device complexity may add cost and make it difficult to implement in countries with limited financial resources. On the hand the GSM white space may provide a cost effect means of deploying CR devices.

4.6 Conclusion

In this chapter we have examined the coexistence performance between GSM and CR systems under the worst case scenario where the GSM systems operate at full load (utilizing all the channels). It has been shown that the performance of GSM is heavily influenced by CR transmission power and the INR threshold (channel detection threshold). The GSM power utilization and additional dropping probability has been shown to increase when either cognitive power or INR is increased. However there is no significant impact on the performance of GSM system when CR detection threshold (INR) is set to 30 dB and below. At this level the CR is blocked from utilizing channel already occupied by GSM systems. This ensures the guaranteed protection against excessive interference from the CR system.

5 Downlink Coexistence Performance Analysis Between GSM and Cognitive Radio Systems Based on Traffic Model.

5.1 Introduction

In this chapter we examine the coexistence performance between GSM systems and CR systems in the GSM band based on their traffic behaviours. The focus of this analysis will be downlink performance for both GSM and CR. The traffic models will be developed for both systems and the performance of these systems when they operate on their own will be compared with the performance under a coexistence scenario. The main objectives of this chapter are to assess the impact of the introduction of secondary usage into the GSM band on the performance of primary GSM users and also to analyze the impact of primary GSM systems on the operation of secondary users employing CR devices. Under the coexistence scenario the CR senses the GSM spectrum and opportunistically utilizes the spectrum holes. From this we will estimates the level of interference caused by CR on the incumbent and determine whether this interference can be tolerated or not. We will also look at measures that may help to minimize interference to acceptable levels. The effect of GSM interference on CR performance will also be investigated and appropriate mechanisms to improve coexistence will be discussed. The key performance indicators discussed in chapter 3 will be used as a measure of coexistence analysis.

5.2 Coexistence scenario

The same propagation channel models and coexistence architecture as in chapter 4 is adopted where both the GSM and cognitive systems employ directional antennas with beamwidths of 90^0 and 65^0 respectively. The GSM will incorporate both circuit switching for voice services and packet switching GPRS for data services while CR is assumed to be a completely packet switching. Frequency division duplexing (FDD) is employed for GSM and time division duplexing (TDD) is adopted for CR systems. In the case of channel access methods, the GSM uses Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA) whereas CR uses Orthogonal Frequency Division Multiple Access (OFDMA). For both GPRS and CR systems adaptive modulation will be employed where different data rates will be achieved depending on coding scheme and the SINR levels as indicated in Tables 5-1 and 5-2. In this analysis the GSM systems parameters are derived from the specifications provided in the GSM standards [46] and the CR parameters are derived from the WiMAX specifications as provided in 802.16 IEEE standards [47] from which other CR standards such as IEEE802.22[2] for the TV band have been developed.

Channel coding scheme	CS-1	CS-2	CS-3	CS-4
Code rate	1/2	2/3	3/4	1
Data rate (kbps)	9.05	13.4	15.6	21.4
SINR threshold(dB)	9	13	15	24

Table 5-1: GPRS data rates and required SINR threshold at 200 KHz Channel bandwidth

Modulation	QPSK	QPSK	16QAM	16QAM	16QAM	16QAM
Code Rate	1/2	3/4	1/2	3/4	2/3	3/4
Data Rate (Mbps)	2.016	3.024	4.032	6.048	8.064	9.072
SINR threshold	3.5	6.5	9	12.5	16.5	18.5

Table 5-2: Cognitive Radio data rates (OFDMA symbol rate) and required SINR thresholds at 5 MHz bandwidth and 512 FFT

5.3 Radio Resource Management (RRM)

The aim of Radio Resource Management (RRM) is to optimize the radio resource usage based on a specific resources sharing algorithm. The tasks performed by RRM include admission control, channel assignment, power control and handoff [44]. In the following we present a mechanism that will be used to carry out radio resource management tasks for GSM (both for voice and data) and CR systems.

5.3.1 GSM/GPRS RRM

GSM/GPRS channel sharing strategy: GSM employs a fixed channel allocation scheme (FCA) where each base station is allocated a set of channel through a frequency planning process. In GSM networks supporting GPRS, both systems use the same radio interface implying the radio resources is shared between GSM voice calls traffic and GPRS data traffic for each base station. There are three widely used schemes for sharing radio resource between GSM and GPRS [48]. In the first scheme called complete sharing (CS), all radio resources are shared between voice and data with the priority given to voice. In the second scheme, complete partitioning (CP) channel/time slots are divided and dedicated to each of the traffic type. In the last scheme called Partial Partitioning (PP), some of the channels are dedicated to each of the traffic types and remaining channels are shared by both, with the highest priority given to voice. The choice of the allocation scheme is dependent on the deployment scenario, e.g. when dealing with high varying demands a PP scheme may offer better options, as each type is guaranteed minimum QOS and in addition it offers flexibility and hence maximizes radio utilization. Our analysis is based on a rural deployment scenario where traffic demand is expected to be low and therefore we will adopt the CP scheme.

Best effort strategy for voice and data traffic channel allocation: For voice GSM users, the RRM strategy called “best effort’’ is widely used [49]. This strategy does not take into account the QoS or propagation conditions for choosing radio resources to allocate to the user, instead all users are considered having equal probability. In GSM, one RF channel contains 8 time slots and each voice call can only occupy one time slot. When resources are insufficient, the GSM call is blocked and it is regarded as unsuccessful. In some schemes such as CS and PP where a pool of radio channels is shared by both GPRS and GSM systems, a voice call has highest priority over GPRS data. In case a resource is not available for a voice call it can be taken from existing GPRS transmission this process is called preemption. In GPRS the “best effort’’ is also widely used, but unlike voice calls, multiple time slots can be allocated to the same GPRS user, and a time slot can be used by more than one GPRS user. This allocation process is called Temporary Block Flow assignment (TBF). When the resource is unavailable, the data to be transmitted is placed in queue, which uses First in First out (FIFO) for retransmission. The best effort for both GSM voice traffic and GPRS data traffic are represented in the figure 5-1 below.

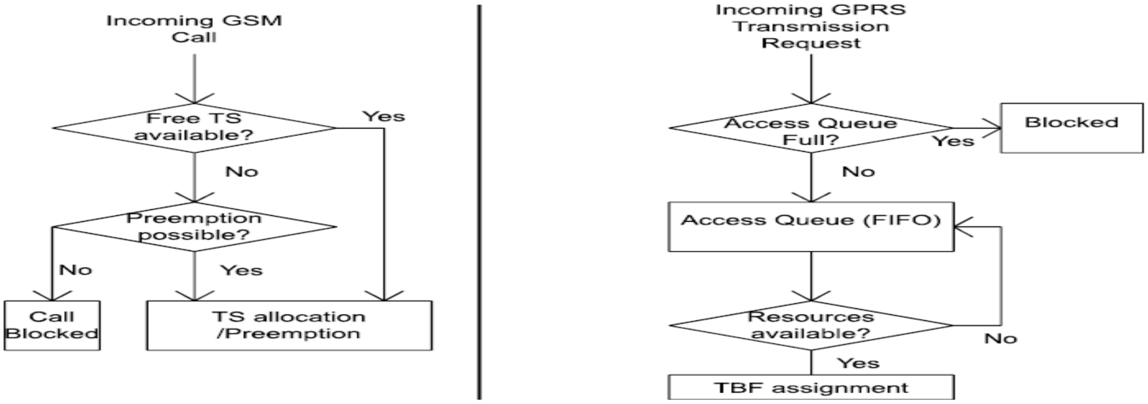


Figure 5-1: GSM and GPRS Time slot selection in best effort strategy

In the literature, other RRM strategies that take into account propagation conditions and QoS have been suggested for GPRS data, e.g. a credit based strategies which incorporate the carrier to interference ratio (C/I) of the propagation link have been proposed [49]. Based on the C/I level a credit value is assigned to each TBF set up request when it is stored to access the queue. The more credit implies the higher C/I values. The priority for time-slot allocation is given to TBF with more credit. Compared to the best effort strategy, a credit based mechanism provides improved throughput and delay because priority is given to users capable of transmitting at higher data rates [49]. However in best effort strategy, the resources are fairly allocated to all users in the network. In our coexistence analysis we will employ best effort strategy for both GSM and GPRS.

GSM/GPRS Dynamic Power Control: In order to minimize the cochanel interference and reduce BTS/mobile station power consumption, GSM systems usually employ a dynamic power control mechanism. Instead of transmitting at full power the BTS/mobile stations regulates it power until the required quality threshold conditions are met. Usually two variables, the received signal strength (RxLevel), and Received Quality (RxQuality) are used to determine the BTS/mobile station transmit power requirements. Rxlevel and RxQuality values are a function of the received signal to interference ratio (SINR). Two power control mechanism are usually employed for transmit power estimation. The first one is called closed loop power control where the base stations adjust their transmit power based on the SIR information of the target receiver obtained from the reverse link. In the second mechanism, the base stations adjust their transmit power based on the path loss condition. Studies indicate that closed loop power control has better performance than open loop power control in a terrestrial environment where round-trip delay is small. However, it is more complex in terms of implementation. On the other hand open loop provides a fast, inexpensive channel power estimation mechanism. In practice though, the closed loop power control mechanism is widely used. Our simulation will be based on the closed loop power control mechanism, and SINR thresholds as specified in standards [46], will be used as a reference for transmit power adjustment. For any of the power control schemes, in case of the GSM voice call when the transmit power is increased to maximum and the required SIR level is not met, the call is blocked or handover is performed if an alternative radio resource is available. However for simplicity call handover will not be taken into account in our analysis. For a GPRS user when the power is adjusted to a maximum level, depending on the SIR level, data transmission rate will be adjusted to higher or low values as specified in the standards. However, if the SIR level is too low to be able to support the specified transmission rates then the GPRS user will be dropped for retransmission at a random time.

5.3.2 Sensing and Cognitive Radio RRM

Sensing: In chapter 2, we pointed out that in GSM/GPRS the radio resource is made available to the network operator on primary use basis whereas CR systems operate on the secondary use basis, with the availability of radio resources being dependent on the sensed white spaces/spectrum holes. Different sensing mechanisms were also discussed and for the purpose of our coexistence analysis, an energy detection sensing technique is employed on a non-cooperative approach, where each CR access point individually senses the spectrum for GSM white spaces. These white spaces are determined by the level of the interference to INR. In our simulation a channel selection method based on Least Interfered Channel will be used. In this method the CR sensing unit scans all channels and selects the one with minimum interference level. The LIC scheme tries to maximize the geographical separation for the radios using the same frequency and hence minimize the interference on primary users and other CR users. A channel selection scheme based on a least interfered channel has been shown to perform better compared to other schemes [15]. Two different scenarios based on LIC scheme will be used for channel selection. In the first scenario channel are selected based on only LIC. In the second scenario, the LIC channel is selected if it is equal or below the predetermined INR threshold.

Cognitive Radio systems RRM: Unlike in GSM systems where each base station has a fixed channel allocation, CR Systems (CRS) employ dynamic channel allocation schemes (DCA) where the channel is eligible for use in any cognitive access point provided interference constraints are satisfied. Depending on the type of control employed, DCA can be classified into centralized DCA and distributed DCA. In centralized DCA the central controller is responsible for coordination of all access points and allocation of channels whereas in distributed DCA, each access point keeps the channel information within its vicinity and allocate channel to its associated users. Compared to centralized DCA, distributed DCA offers better system capacity, efficiency, radio coverage, adaptation to traffic changes and fast real time processing [51]. In our analysis we will adopt the distributed DCA where the radio resource allocation is based on the SNIR level of the user. Since the CR systems employs the orthogonal frequency division multiple access (OFDMA) technique, the available wideband channel is divided in the frequency domain into multiple sub-channels. Each sub-channel is further divided into a group of subcarriers. Each user in OFDMA is assigned a number of subcarriers for use, and each subcarrier is exclusively allocated to one user. Various subcarrier allocation algorithms have been developed to improve the performance of the OFDMA based systems. Papers [52] and [53] describe algorithms that are designed to be computationally non-intensive important for real-time application. Paper [55] presents an algorithm focused on satisfying the QoS requirement of users and [56] describes an approach using non-convex optimizations. In our simulation however for simplicity of coexistence analysis, each user will be allocated a fixed number of consecutive subcarriers subject to satisfying the minimum SINR requirement of the channel. In order to maximize the utilization of the channel, an adaptive modulation scheme is also employed [4]. Based on the RF quality of the channel, different modulation schemes are selected per user. In case where channel conditions permit, a more complex modulation scheme can be utilized to maximize throughput while still allowing reliable data transfer. On the other hand if the channel condition is poor a less complex modulation scheme is used to allow more reliable data transfer at the expense of reduced throughput. The modulation schemes supported by OFDMA use include QPSK, 16-QAM and 64 –QAM and corresponding channel quality requirements (SINR) are as indicated in table 2.

CR power control: In this simulation the downlink transmission power from CR access point is fixed. This means that power allocated to all sub-channels is the same, and depending on the user position, the received SINR will determine the appropriate modulation schemes and data rate to be used.

5.4 Traffic Models

Traffic models are defined to represent the behavior of the users in the network. In this section we study the time variations of traffic and use it to predict the performance of both GSM and CR systems. Two traffic types will be analyzed. The GSM voice traffic based on circuit switching and GPRS, and CR data traffic is based on the packet switching. The term session will be referred to both types of traffic and is defined as the moment when an event arrives to the base station until the transmission is completed, such as for voice, where the end time is reached and for GPRS or CR a file have been sent to a specific user or in worst case when it has been dropped or blocked. A file is referred to as a group of data packets to be transmitted in a session. The session length depends on the file size.

The arrival and duration of sessions as well as file sizes are statistically distributed depending on specific parameters for each type of traffic. In addition, each generated session is associated with one user using a uniform distribution. The distribution of arrival time and holding time for each traffic type is presented in the next section. The flowchart illustrating the simulation algorithm is shown in figure 5-2.

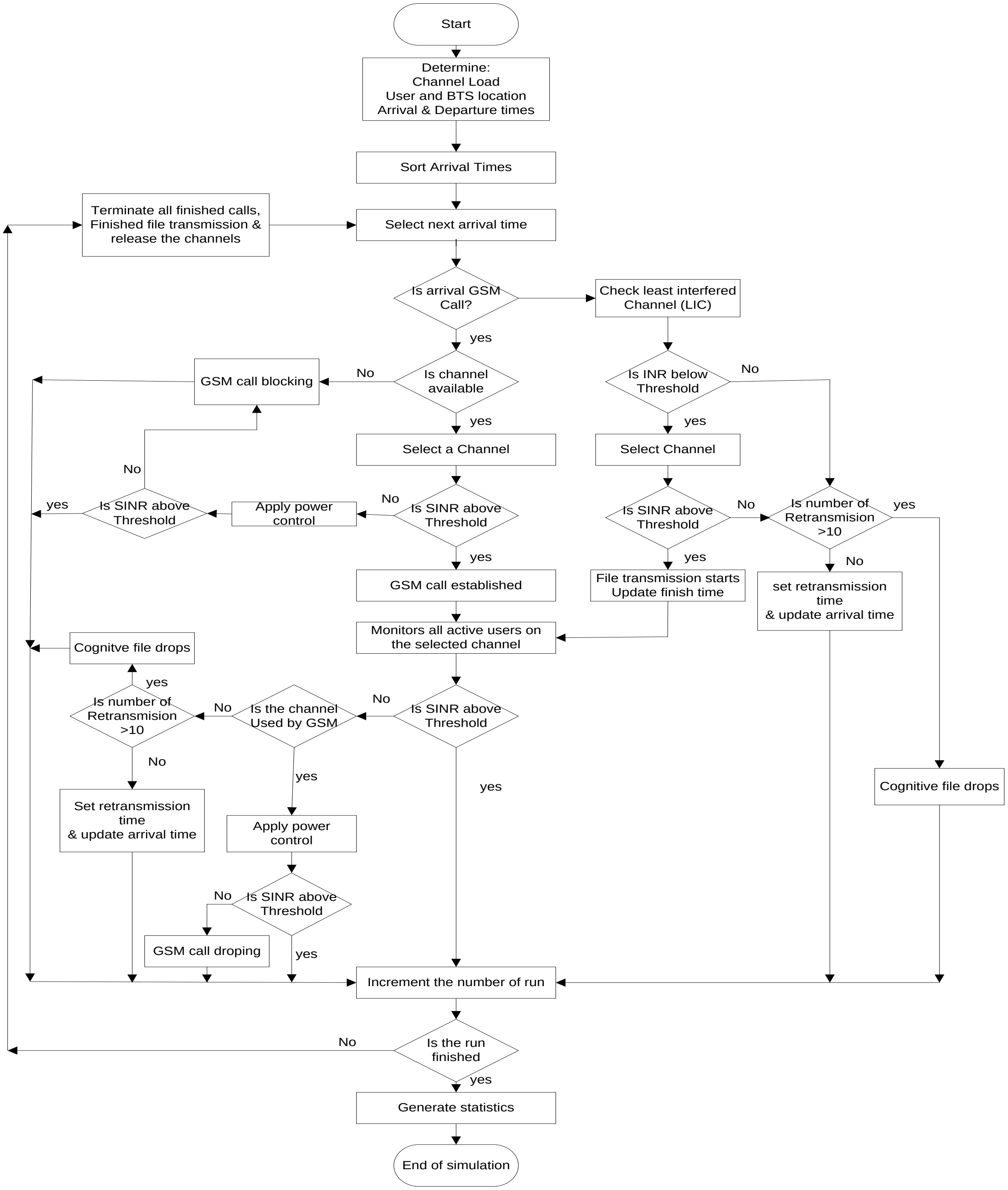


Figure 5-2: Flowchart illustrating the simulation flowchart for coexistence analysis based on a traffic model

5.4.1 GSM voice calls traffic parameter

Arrival time: The number of calls arriving in one radio cell is assumed to form a Poisson process with the mean arrival rate denoted by λ_{GSM}. This process represents the number of random occurrences of voice calls N (t) in a specified unit of time. The probability that the value reaches a value n is given by the formula:

$$F(N(t) = n) = \frac{(\lambda_{GSM}t)^n e^{-\lambda_{GSM}t}}{n!} \qquad (5.1)$$

It is assumed that the inter-arrival times are independent and identically distributed according to an exponential distribution.

Holding time: Is represented by exponential distribution with the mean holding time denoted by $1/\mu_{GSM}$

The probability density function (pdf) of exponential distribution (parameter μ_{GSM}>0) is

$$F(t) = \mu_{GSM}\mathrm{t}\, e^{-(\mu_{GSM}\mathrm{t})},\ \mathrm{t} >= 0 \qquad (5.2)$$

5.4.2 GPRS and CR Data Session

Unlike a GSM voice call, the data traffic is more complex to model due to applications and bursty nature. Depending on the application the traffic data can mainly be web browsing (www), e-mail, FTP, WAP and other applications. However, this application specific approach is not binding since a session is assumed to contain a number of bits whose size can be estimated according to certain process and activity phase. Just like GSM voice traffic, data traffic also consists of two parts namely the arrival process and activity as described below.

Arrival times: It is assumed that the arrival process is characterized by the Poisson distribution which counts the number of events coming within a certain time period with a mean arrival rate per session denoted by 8_{GPRS} or 8_{COG} for CR. In the same way we described in GSM, data traffic inter-arrival times are independent and are determined by exponential distribution. We use inter-arrival process to determine exact time when GPRS event arrives within simulation time.

Activity phase: The duration of the session is characterized with the number of bits transmitted (file size) and estimated by means of the Pareto distribution. Then according to file size and the coding scheme specified, file transmission time is determined.

The probability density function (pdf) of the Pareto distribution is given by [57]

$$F_{(\varepsilon,\mu,\sigma)}(x) = 1/\sigma(1+\varepsilon\frac{x-\mu}{\sigma})^{-(\frac{1}{\varepsilon}+1)} \tag{5.3}$$

$$\text{And the mean } = \mu + \frac{\sigma}{1-\varepsilon} \quad (\varepsilon < 1) \tag{5.4}$$

Where $\mu \in /$ is location parameter, $\sigma > 0$ is the scale parameter and $\varepsilon \in /$ is a shape parameter.

5.4.3 GSM/GPRS/CR Traffic load

The two traffic parameters described above, mean arrival time and session duration are useful in determining the traffic load and hence measurement of the capacity of the network. For GSM voice call, the traffic load is defined as the measurement of channel time utilization, i.e. the channel time occupancy. It is expressed by means of average holding time $1/\mu_{GSM}$ and average arrival rate as shown below.

Offered traffic load for voice,

$$G_{GSM} = \lambda_{GSM} \times 1/\mu_{GSM} \tag{5.5}$$

For GPRS and CR, the offered traffic is also estimated with the average arrival rate and mean holding time, which is determined by means of average session size and data rate in coding scheme employed.

Offered traffic for data,

$$G_{GPRS} = \lambda_{GPRS} \times 1/\mu_{GPRS} \qquad (5.6)$$

$$G_{COG} = \lambda_{COG} \times 1/\mu_{COG} \qquad (5.7)$$

The relationship between mean holding time and mean file size is given by

$1/\mu_{GPRS} = Mean\ GPRS\ file\ size/Mean\ GPRS\ data\ rate$ and

$1/\mu_{COG}$ = mean COG file size/mean COG data rate

5.5 Simulation parameters and assumptions

Table 5-3 provides the simulation parameters for GSM voice calls, GPRS and CR systems.

Parameter	**Value**
GSM:	
Average call duration	180 seconds
Channel load	(0.1-1) Erlang
Channel Width	200 kHz
Number of channel per BTS	9
Total BTS	27
Re-use pattern	3 BTS per cluster
GPRS:	
Average file size	187.6 KB
Number of channel	9
Channel load	(0.1-1) Erlang
CR:	
OFDMA width	5 MHz
Average file size	5.4 MB
Total number of subchannels	25
Total subcarrier per subchannel	18

Table 5-3: GSM/GPRS/CR Simulation parameters

In this simulation, we assume that both GSM and GPRS have dedicated channels allocated to them. This means that there is no co-channel interference between the two systems. For simplicity, and since GSM and GPRS do not share the same RF channels, simulation of coexistence performance between CR systems and GSM will be treated separately from the simulation of coexistence performance between CR and GPRS.

While it is possible for GPRS session to utilize up to four channel time slots depending on the availability, we assume that each GPRS session can only occupy one timeslot so as to reduce the complexity of simulating coexistence performance.

When the GPRS user data is blocked from transmission due to poor channel conditions or unavailability of channel, the data is placed in a queue for retransmission at later time. In our simulation, re-transmission time is randomly chosen based on the exponential distribution that is used in inter-arrival time generation. The same principle is applied to cognitive user data.

OFDMA users can be allocated a number of subcarrier from different sub-channels, however for simplicity we assume that the number of subcarriers allocated to cognitive users is fixed and each CR user can only occupy one sub-channel. The width of the subcarrier is 10.94 kHz as specified in the standards [4] and the total number of subcarrier per width is assumed to be 18. This implies the subchannel width of OFDMA symbol is 200 kHz. The user data rate is dependent on the channel quality (SINR) and is calculated as follows

$$User\ data\ rate = \frac{OFDMA\ symbol\ rate}{subcarrier\ width \times total\ subcarrier\ per\ subchannel} \tag{5.8}$$

The different OFDMA symbol rates and required channel SINR threshold values have been shown in table 5-2

The numbers of users for each base station/access point are fixed and the total channel loading (offered traffic) is determined by the rate of arrival of events (voice /data) and average session time. Each event is associated with one user, depending on the length of simulation the number of users may be increased or decreased to ensure that both the system under coexistence finishes at the same time.

5.6 Performance Evaluation

We examine the effect of interference on GSM/GPRS caused by the introduction of CR on the GSM band. Subject to different traffic loading, the performance of GSM/GPRS without the influence of CR is compared to the performance under coexistence with CR. The performance of CR under coexistence is evaluated. The key performance indicators to be assessed includes throughput, average delay, blocking probability and dropping probability. These indicators have been discussed in detail in chapter 3. Here we present how these indicators are derived from our simulation

$$Throughput\ per\ cell = \frac{\sum transmitted\ files(bits)}{simulation\ duration} \tag{5.9}$$

$$Average\ delay\ per\ file = \frac{\sum transmitted\ file(bits)}{\sum file\ trasmission\ time} \tag{5.10}$$

$$blocking\ probabiltiy = \frac{\sum unsuccesful\ calls}{\sum calls\ attempt} \tag{5.11}$$

$$Dropping\ probabily = \frac{\sum dropped\ calls}{\sum calls\ attempt - \sum unsuccessful\ calls} \tag{5.12}$$

5.7 Simulation Results

5.7.1 Effects of CR Loads on GSM Voice Blocking and Dropping Probability

The performance of GSM circuit switched based network when subjected to different CR channel loads are shown in figures 5-2 (a) and (b). The CR channel selection is based on a least interfered channel. Three CR channel loads 0.1 Erlang, 0.5 Erlang and 0.8 Erlang have been selected to show the impact of low, average and high CR channel loads respectively on the performance of GSM system.

We measure the performance of GSM based on the blocking and dropping probabilities of voice calls under the influence of CRs and compare with the performance in the absence of CR. In our simulation, a CR operates at -1dBW transmit power and within 1km coverage radius. From graph 5-3 (a), we note that GSM operates within the required QoS thresholds of 5% blocking probability at channel load below 0.8 Erlang. We also note that the GSM calls blocking when operating at a channel load of 0.5 Erlang and below is less affected than at higher loads even at high cognitive channel loads of up to 0.8 Erlang. We can also see that at low cognitive loads there is little impact on call blocking when the GSM channel load is below 0.8. However, when cognitive channel load is beyond 0.5 Erlang, the GSM performance at higher loads deteriorates as indicated by increase in voice call blocking probabilities. From this result we note that the impact of CR is insignificant when GSM operates at a channel load 0.5 Erlang and below.

In Figure 5-3 (b) we note that the GSM operates within the required QoS thresholds of 0.5% dropping probability, even in the presence of high cognitive channel load. This implies that CR has minimum effect in the GSM call dropping. The small variations we see in the graph are the effect of random shadowing.

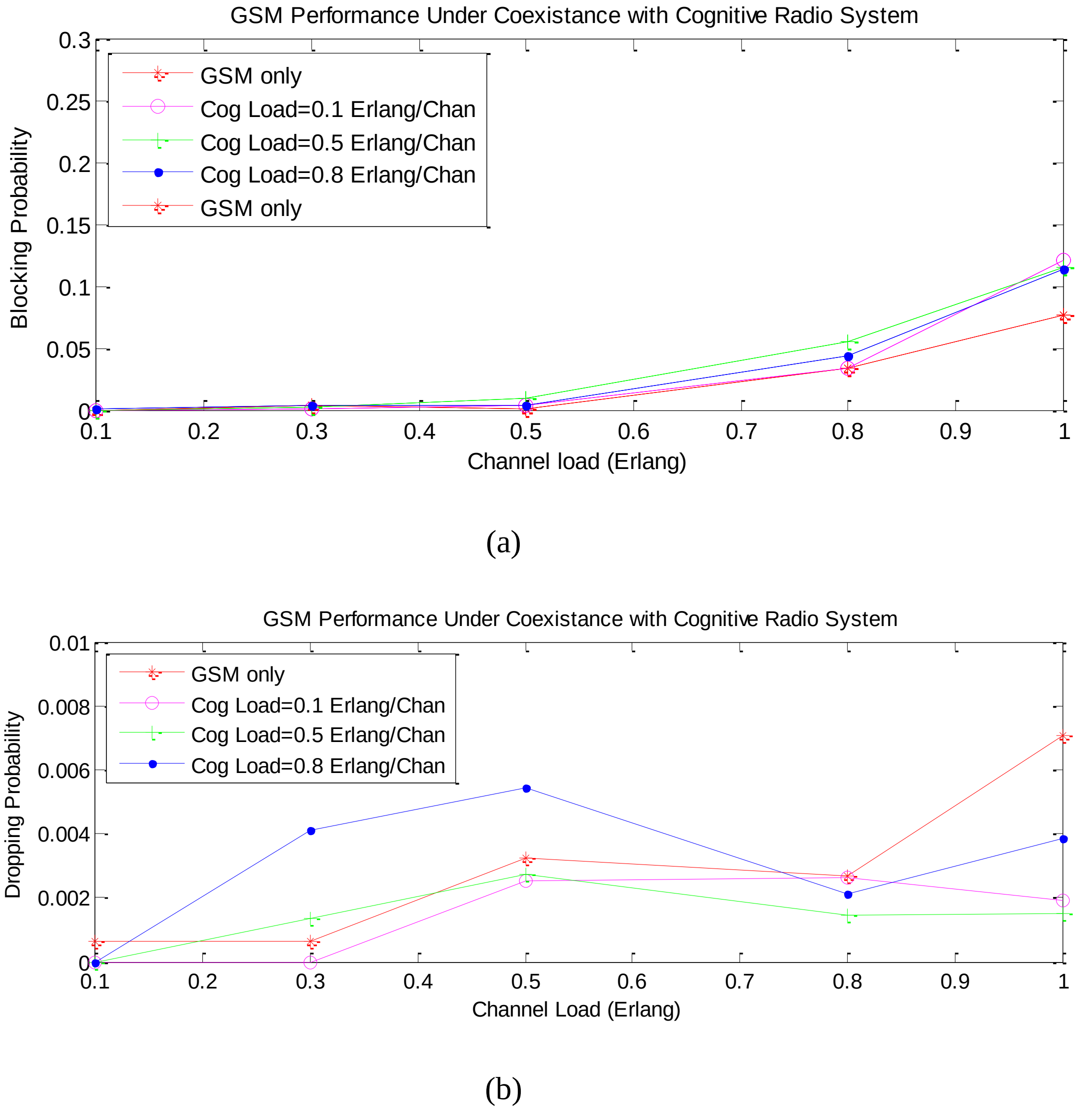


Figure 5-3: Effect of CR channel loads on the GSM calls blocking and dropping probability at cognitive transmit power of -1 dBW and AP Coverage 1 km radius.

5.7.2 Effect of Cognitive INR Threshold on the GSM Call Blocking Probability

Figure 5-4 shows the performance of GSM subject to different CR INR thresholds (also referred to as detection thresholds). Instead of only employing LIC channel selection scheme as in the previous approach, the CRs select the LIC if the channel is within the predetermined INR thresholds**.** In this simulation the measurements are taken at cognitive load of 0.5 Erlang. We note that by limiting the INR levels the amount of interference caused by CR on GSM systems is controlled. As we increase INR thresholds we allow CR to have more channel selection options at the expense of increasing interference to GSM systems. When INR thresholds are set below 40 dB the performance of GSM remains stable within channel load range of 0.1-0.8 Erlang/channel and indicates almost same blocking probabilities level. On the other hand at a higher INR threshold of 50 dB and above, we see a little increase in call blocking probabilities in the GSM channel load range of 0.5 Erlang and beyond. For GSM loading of more than 0.8 Erlang/channel the performance is generally unstable regardless of the INR levels. From these results we note that the impact of INR on GSM system is noticeable at the thresholds values above 50 dB. This means that we can control the amount of interference on GSM by limiting detection thresholds depending on the QoS requirements of the user.

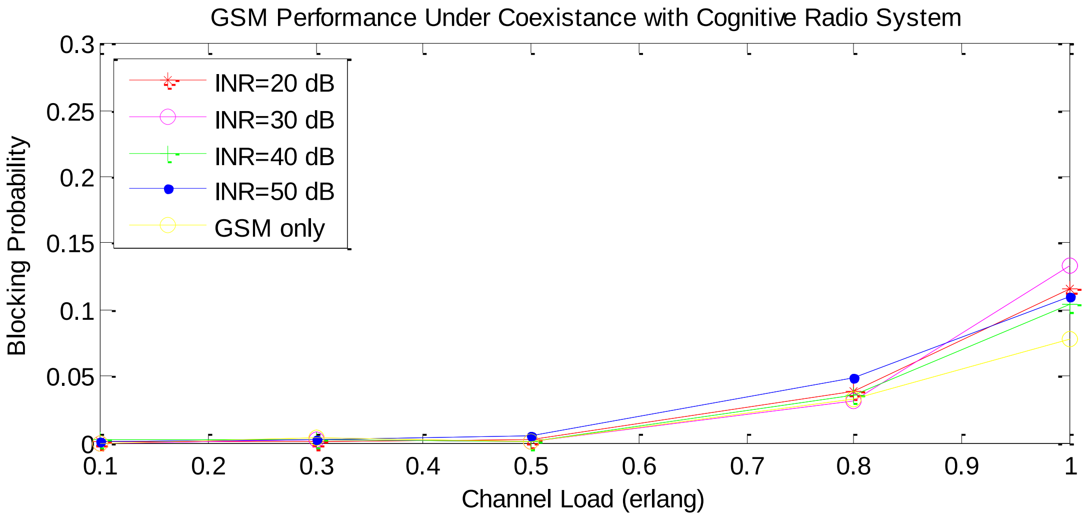
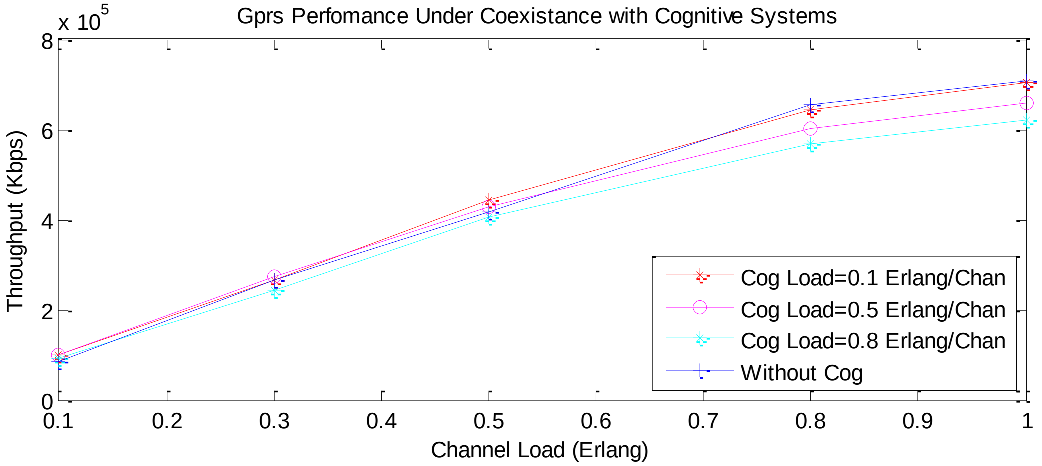


Fig 5-4: Effect on Interference to Noise Ratio (INR) threshold on the GSM call blocking probability at CR transmit power -1 dBW and AP coverage 1 km radius

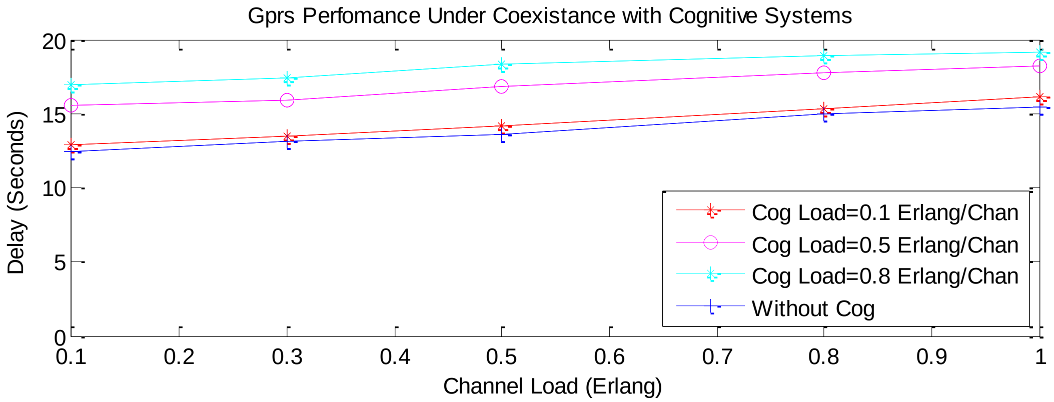
5.7.3 Effect of Cognitive Radio Loading on GPRS Throughput and GPRS Delay

The performance of GPRS when subjected to different Cognitive Channel load is as shown in figures 5-5 (a) and (b). The CR employs the LIC scheme to determine the channel availability. GPRS performance is measured in terms of throughput and delay at different channel loads. From figure 5-5 (a), we note that there is insignificant impact on GPRS at low cognitive channel loads of 0.1 Erlang. We also note that the impact of CR at low GPRS channel loads of 0.5 Erlang and below is insignificant. However, at high GPRS channel loads above 0.5 Erlang there is noticeable impact at cognitive channel loads above 0.5 Erlang. This is shown by the reduced throughput which is caused by increased interference as a result of CR channel load increase. As interference increases the channel SINR level decreases. Since the data rates are dependent on the channel SINR, a low SINR level causes a data rates reduction and hence a reduced GPRS throughput.

From figure 5-5 (b), we note that there is minimum impact on the GPRS delay at low CR channel loads. However, there is a significant impact GPRS performance at cognitive channel load above 0.5 Erlang. This is indicated by delay increase, and is caused by excessive interference due to high cognitive channel loading. The increased interference causes the SINR level to drop as a result of which transmission data rates become lower. Due to low data rates a file transmission takes longer, leading to increased delay.



(a)



(b)

Figure 5-5: Effect of Cognitive Radio channel load on GPRS throughput and delay at Cognitive Radio transmit power -1 dBW and AP coverage 1 km

5.7.4 Effect of Cognitive Radio INR Threshold Control on the Performance of GPRS

The performance of GPRS subject to different CR detection thresholds (INR) is shown in figure 5-6 (a) and (b). We note that at INR of 40 dB and below there is noticeable improvement in the GPRS throughput figure 5-6 (a). Limiting the INR level controls the level of interference caused by the CR systems. A low INR level means that the CR picks the channel that is widely separated from the GPRS user. This minimizes the effect of interference on the primary GPRS user and ensure the channel SINR is at good level to support high data rate.

The performance of GPRS in terms of delay when subjected to different cognitive detection thresholds (INR) is shown in figure 5-6 (b). We find that there is little or no delay variation when GPRS is subjected to CR interference at detection threshold of 40 dB and below. However, at INR levels above 50 dB there is a noticeable increase in delay due to increased interference from the CR systems. The more the INR is increased, the more CR is allowed to use channels that are closer to the GPRS users. The increased interference deteriorates the quality of the channel (reduces SINR level). When the condition of the channel is poor, the GPRS system uses low data rate modulation schemes which are more tolerant to interference.

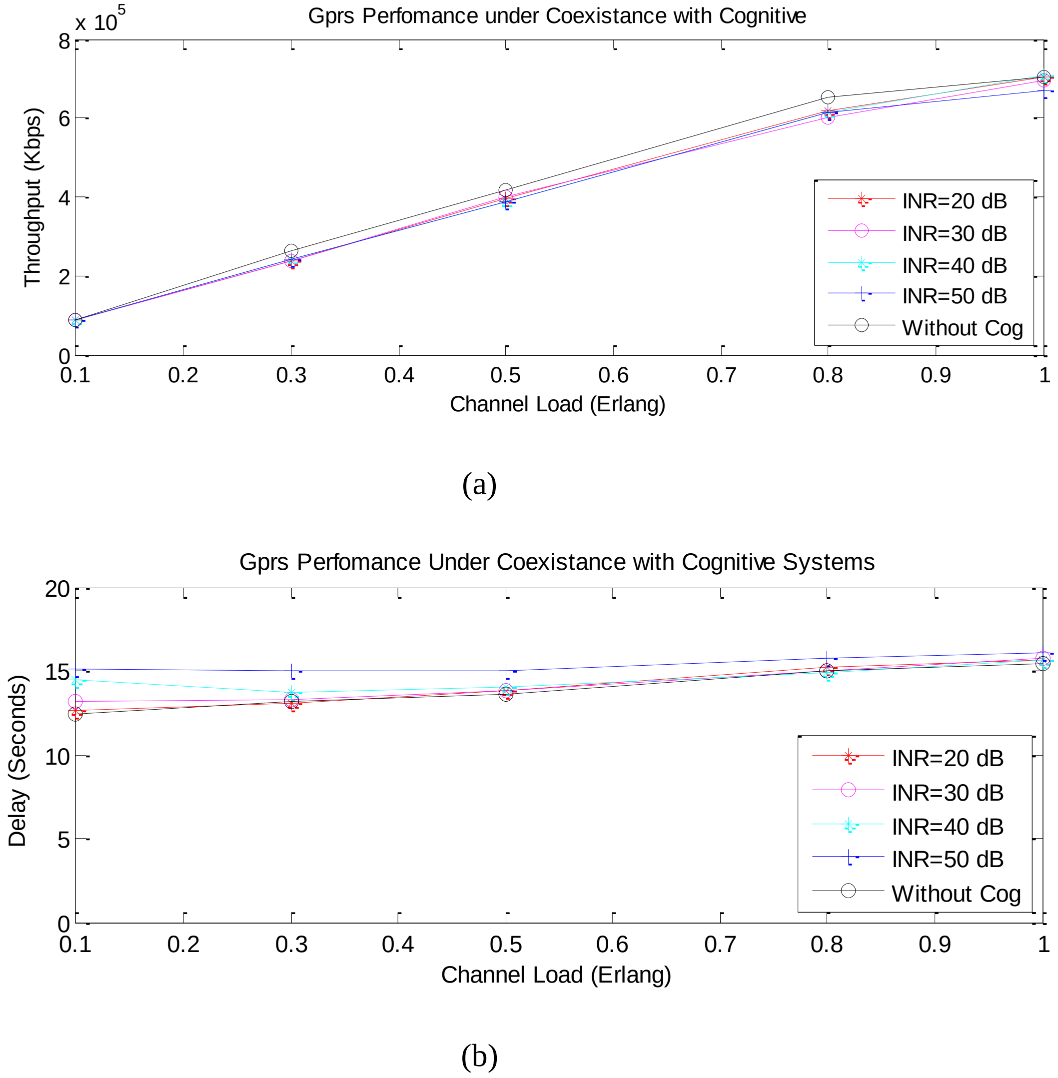
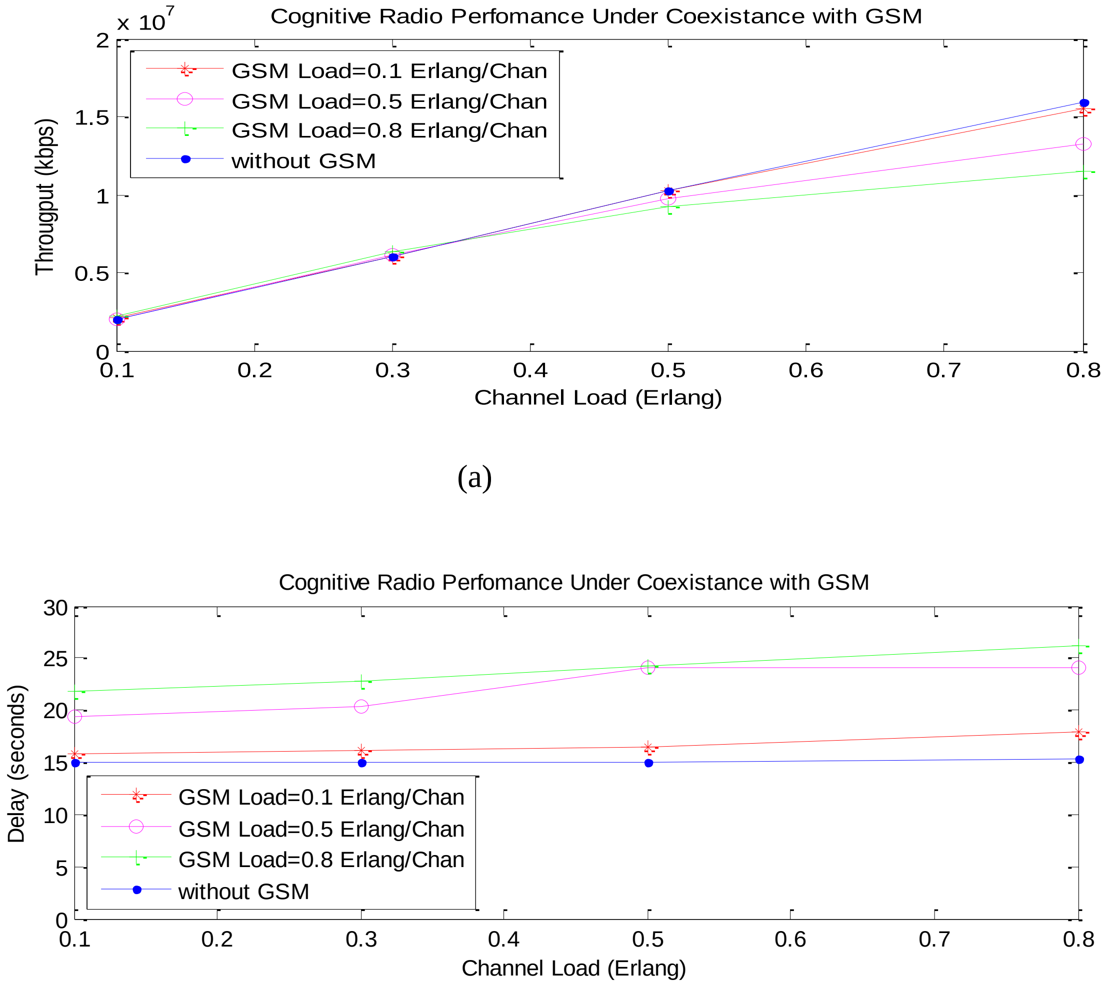


Figure 5-6: Effect of Interference to Noise Ration on the GPRS throughput and delay at Cognitive Radio channel load of 0.5 Erlang

5.7.5 Effect of GSM Channel Load on Cognitive Radio Throughput and Delay

The performance of CR at different GSM loads is measured and compared with the performance of CR assumed to operate without the presence of primary user (GSM system). The performance analysis of CR is based on the measured throughput and delay as indicated in figures 5-7 (a) and (b) respectively. We note from figure 5-7 (a) that there is minimal GSM influence on throughput when CR operates at channel load of about 0.4 Erlang and below. There is also insignificant impact on cognitive throughput when GSM operates at channel loads below 0.1 Erlang. However, at GSM channel loads above 0.5 Erlang there is a noticeable decrease in throughput particularly at cognitive channel load above 0.4 Erlang. This is because as GSM channel load increases the interference on CR system also increases which in turn lowers the cognitive SINR. We mentioned earlier that the data transmission rate (throughput) depends on SINR level, at low SINR levels the data throughput is low. The same phenomenon is applied in case of CR delay where we note from figure 5-7 (b) that the delay increases as GSM load increases due to SINR reduction caused by excessive interference.

From these results we can deduce that the performance of CR at Channel load above 0.4 Erlang rely heavily on the GSM channel load conditions. When the GSM load increases above 0.5 Erlang the performance of cognitive deteriorates. This is shown by decreased throughput and increased delay.



(a)

(b)

Figure 5-7: Effect of GSM channel loads on the Cognitive Radio throughput and delay

5.7.6 Effect of Interference to Noise Ratio (INR) threshold on the performance of Cognitive Radio

Figure 5-8 present the CR performance results in terms of throughput. We note that as the INR threshold is increased the CR throughput increases. This is because when we increase INR levels we allow more channel to be selected for cognitive use. On the other hand if we decrease the INR levels we inhibit channel availability because the interference from GSM system is high due to frequency re-use. If INR thresholds are kept at low values it means that only few channels qualify for use by CR. This is shown by the decreased throughput on our results.

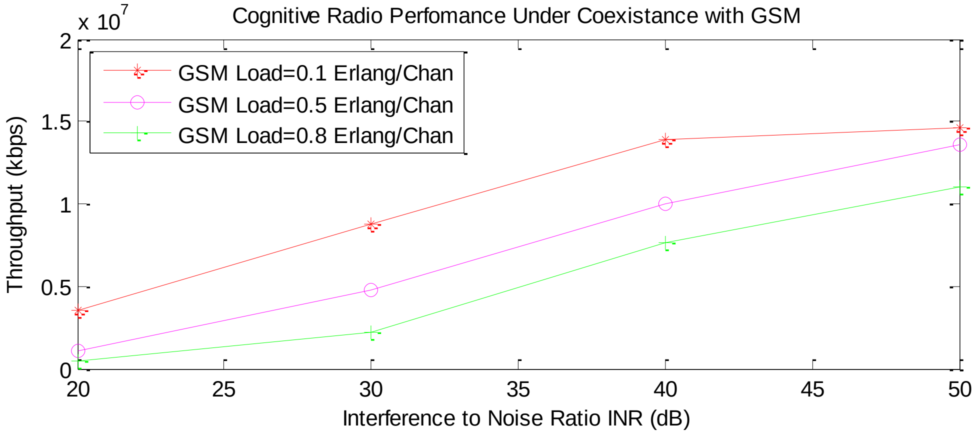
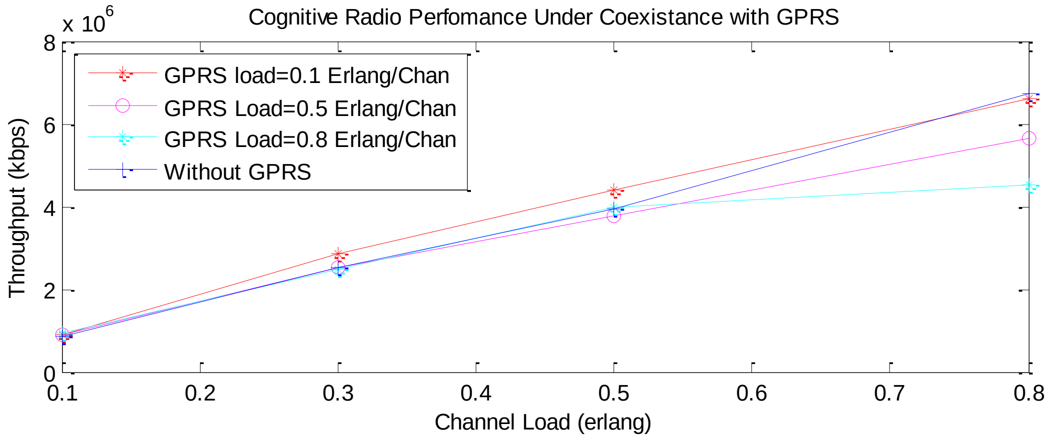


Figure 5-8: Effect of Interference to Noise Ratio (INR) threshold on Cognitive Radio throughput

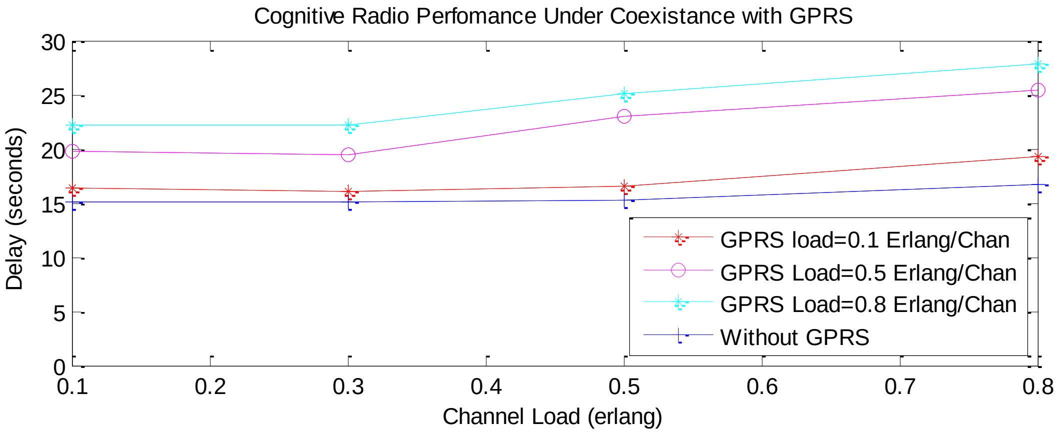
5.7.7 Effect of GPRS channel loads on Cognitive Radio throughput and delay

The performance of CR at different GPRS loads is measured and compared with the performance of CR assumed to operate without the presence of primary users (GPRS). The performance analysis of CR is based on the measured throughput and delay as indicated in figures 5-9 (a) and (b) respectively. We note from figure 5-9 (a) that there is minimum GPRS influence on throughput when CR operates at channel load below 0.4 Erlang. There is also limited impact on cognitive throughput when GPRS operate at channel load below 0.1 Erlang. However, at GSM channel load above 0.5 Erlang there is noticeable decrease in throughput particularly at cognitive channel load above 0.4 Erlang. This is because the increase in GPRS channel load increases the interference on CR system leading to a reduction in cognitive SINR. We mentioned earlier that data transmission rate (throughput) depends on SINR levels, and at low SINR level the data throughput is low and vice-versa. The same phenomenon is seen in case of CR delay where we note from figure 5-9 (b) that the delay increases as GPRS load increases due to SINR reduction caused by excessive interference.

From these results we can deduce that the performance of CR at channel loads above 0.4 Erlang rely heavily on the GPRS channel load conditions. When the GPRS load increases performance of CR systems deteriorates. This is shown by decreased throughput and increased delay.



(a)



(b)

Figure 5-9: Effect of GPRS channel loads on the performance of Cognitive Radio throughput and delay.

5.8 Discussions

Based on the simulations results presented in this chapter, it is evident that the coexistence of CR in GSM band is best applicable in rural area where GSM traffic load is often low. The protection of primary GSM users is achieved by means of predefined signal detection thresholds (INR) at the CR transmitter. Depending on the regulatory OoS requirements, appropriate detection threshold can be selected to meet these requirements while at the same time optimizing the CR throughput.

In chapter 4 it was shown that a 30 dB threshold can provide maximum protection to GSM systems under worst case scenario, i.e. at full channel load. In this chapter we have shown that when GSM operates at channel loads below 0.8 Erlang the INR threshold requirement for incumbent protection is less than 40 dB corresponding to -81 dBm signal detection threshold. From this we find out that signal detection in GSM band is relative simple compared TVWS where the INR threshold is below noise level (-114dBm). The TVWS sensing requirement was discussed in chapter 2. The low INR threshold requirement in TVWS may require complex sensing mechanisms to be able to detect incumbent. This complexity may add cost to CR devices operating in TVWS. On the other hand CR devices may only require the use of simple detection mechanism such as energy detection when operating in GSM band. This may reduce the complexity of CR devices and make them affordable to end users. In countries facing financial constraints, the underutilized GSM band particularly in rural areas may provide a cost-effective means of deploying CR systems.

5.9 Conclusions

In this chapter the coexistence performance of primary GSM/GPRS users with secondary CR users has been examined. To assess the impact of coexistence, the performance of this system under coexistence were compared with their performance without coexistence under the same operating parameters. The coexistence performance of GSM voice which is a circuit switch based system has been measured based on the blocking and dropping probabilities while for packet based systems GPRS and CR the performance has been measured based on the throughput and delay.

It has been found that the CR can operate at maximum transmitter power of -1 dBW and coverage radius of up to 1km without causing significant impact on GSM/GPRS performance. This is achieved when both Least Interfered Channel and signal detection (INR) thresholds are employed as channel selection mechanism at the CR transmitter. It is been shown that at INR threshold below 40 dB the interference caused by CR does not compromise the GSM/GPRS performance. It has been found that when LIC scheme is used without predefining the INR thresholds, there is slight but not significant performance degradation at high channel loads caused by increased CR interference. It was further found that the introduction of detection thresholds limit the amount of interference caused by CR. However, predefining detection thresholds affects the CR throughput and delay as it was observed that at low INR levels there is significant reduction in throughput and increased delay.

The effect of GSM/GPRS channel load on the performance of CR has also been examined and it has been found that CR performances rely heavily on the GSM channel load condition. The impact is less noticeable at GSM/GPRS channel load below 0.5 Erlang. However, at GSM/GPRS load above 0.5 Erlang we found significant performance degradation in the CR system as indicated by decreased throughput and increase delay.

6 Further Work

This chapter presents suggestion for further work of this research as highlighted below

6.1 Reinforcement Learning

Our work has relied on the use of CR spectrum sensing capability to determine the white spaces. This work could further be improved by incorporating other cognitive capabilities particularly reinforcement learning. Reinforcement Learning (RL) is a machine learning technique whereby an agent interacts with an environment in the hope of achieving a goal in an optimal fashion [42]. In the context of CR, RL process involves the learning from experience by the CR about the environment in which it operates with the aim of optimizing channel allocation process. For example CR can learn things like network coverage, the preference of the user of the systems and the behavioural pattern of primary users. Once the CRs have finished learning, it can then make decision on what it has learned. The ability for a CR to be able to preempt whether the channel is going to be in use before accessing it enables channel usage optimization for itself and any other radio that may be accessing the same channel [42]. Different reinforcement learning algorithms have been proposed in literature and it has been shown that there is significant performance improvement of CR when both sensing and reinforcement learning is employed [14][43]

6.2 Co-operative sensing

In this thesis an individual sensing approach has been employed, where each CR node makes decision on channel occupancy based on its own sensed information. Cooperative sensing has also been suggested in literature as discussed in chapter 2. In this approach the channel occupancy decision is based on the collaboration among the CR nodes in the area of interest. The coordination among the CR nodes improves sensing reliability and minimizes the hidden terminal problem. We suggest further investigation of our work with the introduction of cooperative sensing.

6.3 Coexistence performance in GSM uplink transmission

Due to time constraints, the focus of our analysis has been on downlink coexistence performance for both GSM and CR system. In order to explore full GSM band coexistence performance, there is a need also to look at the coexistence performance in GSM uplink transmission.

6.4 Extension of GSM Band to Long Range Cognitive Radio Systems

In this thesis, the cluster size of 3 has been used as GSM network configuration with the cell radius of 4.5 km. This architecture provides a closer GSM co-channel separation distance as a result of which the achievable cognitive operation range was limited to 1 km radius. However, in some scenarios, especially in rural areas, the GSM cell can have large cell radius and cluster size of more cells than the one used in our study. In such cases the much longer cognitive operation range can be achieved and with appropriate detection threshold and power, the incumbent can be protected from CR excessive interference. Further work of our research that will take into account the long distance (beyond 1 km) CR coverage in the underutilized GSM band is suggested.

7 Conclusion

This thesis investigates on how CR can be developed for Africa and other developing countries to support rural broadband access. The GSM band which is being underutilized in rural areas is proposed as a possible white space for use by CR in Africa deployment scenario. The coexistence performance analysis, with the shadowing effect taken into account, has indicated that the CR can coexist with primary users in GSM band without compromising the performance of the incumbent. For maximum protection of primary users, the maximum required INR at the CR sensing unit has been shown to be below 30 dB corresponding to 91 dBm signal detection threshold**.** It has also been shown that there is little impact on the performance of CR systems when the GSM channel load is below 0.5 Erlang. At this GSM channel load, the simulation results indicates that each CR access point within the GSM coverage can achieve coverage of up to 1 km radius at -1 dBW maximum transmit power.

Studies show that a simple sensing mechanism such as energy detection could be employed at the CR devices which operate with a positive INR threshold. The studies further show that the use of simple detection technique minimizes the complexity of the CR devices leading to low development cost. It is evident that simple and low cost CR systems can be developed for use in GSM white space, as it has been shown a positive INR threshold of up to 30 dB can be used. Unlike the GSM white space requirements proposed in this thesis, the requirements in established TVWS are different. Low TVWS detection threshold requirement such as -114 dBm imposed by FCC and proposed by Ofcom make it less practical to use a simple detection mechanism. As a result the use of real time database access mechanism to determine channel occupancy is seen as a better approach. If sensing is to be used it may require a complex detection mechanism such as feature detection, which is capable of detecting signal below noise level. The requirement of real time database access infrastructure or use of complex sensing mechanism in TVWS could add device complexity and deployment cost making them less affordable. The TVWS requirements are considered to be more challenging for countries with limited financial resources and supporting infrastructure. The CR device simplicity and cost-effectiveness achieved in the GSM white space underlined the importance of this band in Africa deployment scenario.

The CR background information is provided in chapter 2. It has been found that until now the focus on CR research and standardization activities has been on the TVWS. The notable achievement to date is establishment of IEEE 802.22 standards for wireless regional networks, designed for last mile services in low populated areas particularly rural areas. Some of the communications regulators around the global have already made rules to support the use of CR devices in the TV band, for example the FCC has made the TVWS license exempt and requires the CR to have both online database access capabilities and detection threshold of -114 dBm for both low and high power applications. Ofcom has taken the same step, but at the moment is considering only rules for low power applications such as the rules for Wi-Fi, like the IEEE 802.11af standard for TVWS which is current under development. The technical and regulatory challenges associated with CR applications in white spaces have also been explored. The hidden terminal problem is regarded as the major problem and several solutions have been suggested including the co-operative sensing where all cognitive nodes share information and real time database access where the cognitive gets all information related to frequencies in use and required transmit power prior to their operation. The widely used command and control approach e.g. exclusive allocation is seen as too rigid to support spectrum sharing, this has prompted regulators across the global to review their regulation to accommodate new technologies such as CR systems to facilitate dynamic spectrum sharing. The market based approach is seen as the ideal model for supporting the current trend in technological advancement. In chapter 2, we also looked at different propagation model with the aim of finding an appropriate model for use in a study of coexistence performance analysis between CR systems and GSM systems. We adopted COST-231 Hata model due to it’s widely acceptance in UHF band and simplicity.

Chapter 3 presents the simulation and validation methodologies employed for investigation of coexistence of the CR system in the GSM band. Owing to complexity of the systems under investigation, a statistical approach based on Monte Carlo simulation techniques has been used in our simulation. MATLAB programming has been used as numerical computational, data analysis and visualization tool. The performance of both GSM systems and CR has been measured based on the key performance indicators including blocking probability, dropping probability, throughput, and delay. The power utilization has also been measured in terms of mean transmit power and transmit power CDF. The link quality has been measured based on the SINR level. The SINR has also been used to determine the data rates the system can support. The COST-231 Hata model has been employed as the path loss model. A two component shadowing model based on the log normal distribution has been included in the path loss to account for the effects of shadowing in the propagation path. The parameter INR threshold has been used by CR systems as a measure of channel occupancy.

The coexistence performance between the GSM and CR system under a worst scenario where the incumbent fully utilizes all the available channels is investigated in chapter 4. The impact of the introduction of CR systems on the performance of the GSM system is measured and compared to the performance of GSM without the coexistence. The results of the simulation have shown that the required detection threshold (INR) for the maximum protection of the primary user is below 30 dB. At this level the CR system is completely blocked from the utilization of the channel occupied by the incumbent.

A detailed coexistence performance based on the behaviour of users is examined in chapter 5. The appropriate traffic models have been used for both the GSM and CR systems and performance measured subject to different channel loading conditions. The simulation results show that at a low GSM channel load (below 0.5 Erlang), a CR detection threshold below 40 dB and transmit power of -1 dBW, the two systems can coexist without compromising their performances.

Chapter 6 provides suggestions for further work. Reinforcement learning which was not considered in our work has been suggested as a way of improving CR channel optimization. The work carried out by this research has been based on the individual sensing, where each cognitive node makes decision based on their own sensing information. Suggestions have been made to incorporate co-operative sensing, where the CR make channel utilization decisions based on the shared sensing information among the cognitive nodes. It has already been mentioned that, the collaborative sensing will minimize the hidden terminal problem. Due to time constraints our work was only limited to GSM downlink transmission coexistence performance analysis, so further coexistence analysis in the GSM uplink transmission is also proposed.

Glossary

AP	Access Point
ATSC	Advanced Television Systems Committee
BER	Bit Error Rate
BTS	Base Transceiver Station
C/I	Carrier to Interference ratio
CA-SIG	Cognitive Applications Special Interest Group CA-SIG
CDF	Cumulative Distribution Function
CEPT	European Conference of Postal and Telecommunications Administrations
CP	Complete partitioning
CR	Cognitive Radio
CS	Complete Sharing
CWRG	CR Working Group
DySPAN	Dynamic Spectrum Access Networks
EC	European Commission
EIRP	Effective Isotropic Radiated Power
ERMES	European Radio Messaging System
ETSI	European Telecommunications Standards Institute
FCC	Federal Communication Commission
FDD	Frequency Division Duplexing
FDMA	Frequency Division Multiple Access
FFT	Fast Fourier Transform
FIFO	First In First Out
FORTRAN	Formula Translation
FPL	Free Space Loss
GPRS	General Packet Radio Services
GSM	Global Systems for Mobile Communications
HD	High Definition

ICT	Information and Communication Technology
IEEE	Institute of Electrical and Electronic Engineers
INR	Interference to Noise Ratio
ITU	International Telecommunication Union
LAN	Local Area Network
LIC	Least Interfered Channel
MAC	Medium Access Control
MATLAB	Matrix Laboratory
MS	Mobile Station
NTSC	National Television System Committee
OFCOM	Office of Communications
OFDMA	Orthogonal Frequency Division Multiple Access
PEL	Planet Earth Loss
PKI	Public Key Infrastructure)
PP	Partial Partitioning
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RA	Radio Assembly
RF	Radio Frequency
RL	Reinforcement Learning
RRM	Radio Resource Management
RRS	Reconfigurable Radio Systems
SCC-41	Standards Coordinating Committee 41
SDR	Software Defined Radio
SINR	Signal to Interference and Noise Ration
SIR	Signal to Interference Ratio
SM	Spectrum Manager
SNR	Signal to Noise Ratio
SS	Spectrum Sensing

SUI	Stanford University Interim
TBF	Temporary Block Flow
TDD	Time Division Duplexing
TDMA	Time Division Multiple Access
TFTS	Terrestrial Flight Telecommunications System
TV	Television
TVWS	Television White Space
UHF	Ultra High Frequency
WAPECS	Wireless Access Policy for Electronic Communication Services
WCDMA	Wideband Code Division Multiple Access
WFI	Wireless Innovation Forum
Wi-Fi.	Wireless Fidelity (IEEE 802.11b wireless networking)
WiMAX	Worldwide Interoperability for Microwave Access
WRAN	Wireless Regional Access Network
WRC	World Radiocommunication Conference

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