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M.Sc. Thesis

Cognitive Radio in a Regulatory Environment

Adeola Adejuwon

Abstract

It has been widely recognized that the valuable, yet finite radio spectrum is being underutilized by licensed systems both spatially and temporally. To realize a more efficient use of this valuable resource, secondary spectrum usage by cognitive radios is being considered. Cognitive Radio is a paradigm for wireless communication in which either a network or a wireless node changes its transmission or reception parameters to communicate effectively while avoiding interference to licensed users. The cognitive radio in its operation may want to make opportunistic use of spectrum that is already allocated to primary users and adjust itself to certain conditions so that it does not impair the operation of these primary users. The purpose of this thesis is to investigate the feasibility of deploying cognitive radios within a Licensed User (LU) network without causing harmful interference. This thesis shows that this may be possible provided certain conditions are met by the cognitive radios, thereby achieving a more efficient use of the scarce frequency spectrum. The approach for this work is to model and analyze an interference scenario involving a cognitive radio interferer (secondary user) and a victim licensed receiver (primary user). The case scenario being considered involves secondary users which are being represented by public safety organizations (police, fire brigade and ambulance) who normally use the 380∼400MHz band for Emergency communications (in Europe). The primary users are considered to be commercial Private Mobile Radio systems operating in the 450∼470MHz band. Secondary access to the latter band could help to offload the 380∼400 MHz band in crisis situations.

Faculty of Electrical Engineering, Mathematics and Computer Science
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Cognitive Radio in a Regulatory Environment

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The undersigned hereby certify that they have read and recommend to the Faculty of Electrical Engineering, Mathematics and Computer Science for acceptance a thesis entitled **"Cognitive Radio in a Regulatory Environment"** by **Adeola Adejuwon** in partial fulfillment of the requirements for the degree of **Master of Science**.

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It has been widely recognized that the valuable, yet finite radio spectrum is being underutilized by licensed systems both spatially and temporally. To realize a more efficient use of this valuable resource, secondary spectrum usage by cognitive radios is being considered. Cognitive Radio is a paradigm for wireless communication in which either a network or a wireless node changes its transmission or reception parameters to communicate effectively while avoiding interference to licensed users. The cognitive radio in its operation may want to make opportunistic use of spectrum that is already allocated to primary users and adjust itself to certain conditions so that it does not impair the operation of these primary users. The purpose of this thesis is to investigate the feasibility of deploying cognitive radios within a Licensed User (LU) network without causing harmful interference. This thesis shows that this may be possible provided certain conditions are met by the cognitive radios, thereby achieving a more efficient use of the scarce frequency spectrum. The approach for this work is to model and analyze an interference scenario involving a cognitive radio interferer (secondary user) and a victim licensed receiver (primary user). The case scenario being considered involves secondary users which are being represented by public safety organizations (police, fire brigade and ambulance) who normally use the 380∼400MHz band for Emergency communications (in Europe). The primary users are considered to be commercial Private Mobile Radio systems operating in the 450∼470MHz band. Secondary access to the latter band could help to offload the 380∼400 MHz band in crisis situations.

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Adeola Adejuwon
Delft, The Netherlands
15th July 2009

Dedicated to Almighty God, my divine inspiration.

Contents

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List of Abbreviations

BER	Bit Error Rate
CDF	Cummulative Distribution Function
CEPT	European Conference of Postal and Telecommunications Administrations
CIR	Carrier-to-Interference Ratio
CR	Cognitive Radio
DL	Downlink
ECC	Electronic Communications Committee
ETSI	European Telecommunications Standards Institute
DMO	Direct Mode Operation
FEC	Forward Error Correction
PAMR	Public Access Mobile Radio
PBS	Private mobile radio Base Station
PDF	Probability Distribution Function
PMR	Private Mobile Radio
PMS	Private mobile radio Mobile Station
PU	Primary User
QoS	Quality of Service
SDR	Software Defined Ratio
SMS	Secondary user Mobile Station
SNR	Signal-to-Noise Ratio
SU	Secondary User
TDMA	Time Division Multiple Access
TETRA	Terrestrial TRunked Radio
TMO	Trunked Mode Operation
UWB	Ultra Wide Band
XG	NeXt Generation

List of Symbols

C	Carrier-to-interference Ratio
P_{min}	Minimum desired signal power at receiver.
$P_{T,W}$	PU transmit power
$P_{T,I}$	SU tranmsit power
L_W	Path loss along wanted link
L_I	Path loss along interfering link
$P_{R,W}$	Mean received wanted power
$P_{R,I}$	Mean received interfering power
R	PU cell radius
K	Cluster size of PU network
D	Frequency re-use distance in PU network
w	Wanted power at PU receiver
i	Interfering power at PU receiver
$f_W(w)$	PDF of wanted power at PU receiver
$f_I(i)$	PDF of interfering power at PU receiver
$f_C(c)$	PDF of CIR at PU receiver
σ	Standard deviation of variation caused by shadow fading
n	Path loss exponent
D_p	Distance betweeen PBS and PMS
D_s	Distance between SU and receiving PU
$E0$	Required SU exclusion distance

1 Introduction

This thesis involves a study of the feasibility of spectrum sharing between cognitive radios and primary spectrum users provided pre-defined regulatory constraints are obeyed. The purpose of this chapter is to describe the background motivation of this work, the main objectives and the general overview of the thesis.

1.1 Spectrum Scarcity and Utilization

The radio frequency (RF) electromagnetic spectrum has become very scarce in certain bands due to the dramatically increased demand in combination with rather strict regulations guiding its usage. In most countries, the government regulates the usage of the frequency spectrum by allocating frequency bands and issuing exclusive licenses to systems within a geographical area while prohibiting or at least regulating other systems with respect to these bands. Because of constantly increasing demand for spectrum in modern society, much of the frequency spectrum has been allocated in this way thereby making the spectrum scarce. For example, figure 1.1 shows the frequency allocation chart for the Netherlands, from where we can observe that a huge part of the spectrum has already been allocated. This chart is developed by Agentschap Telecom, under auspices of the Ministry of Economical Affairs (policy and regulations)[1].

Recent spectrum occupancy measurements and studies have shown, however that a vast number of these allocated spectrum bands are rarely or seldom operationally occupied by services assigned to them [23]. A band assigned to a primary user may be absolutely free or idle at a particular time or geographical area. This is expected because wireless signal levels attenuate over distance and a signal at a lower frequency will propagate farther than a signal at a higher frequency, for a given transmission power level. Figure 1.2 shows a typical utilization of spectrum resources in the UK. Studies carried out by the FCC's (Federal Communications Commission) Spectrum Policy Task Force reported the vast temporal and geographic variations in the usage of allocated spectrum with utilization ranging from 15% to 85% [11]. Figure 1.3 shows the measurements taken by Shared Spectrum Company (SSC) to determine the spectrum occupancy over multiple locations . It was observed that the average occupancy of the spectrum over all the six locations was only about 5.2% [23]. These measurements show that a significant part of the frequency spectrum is unused or underutilized most of the time leading to large chunks of 'whitespaces' or grey-spaces.

Since the demand for spectrum keeps growing, it is important to devise means by which these 'whitespaces' could be effectively utilized by wireless systems of any suitable type. Dynamic Spectrum Access (DSA) technology is a promising candidate technology for this purpose. Radios which employ DSA are supposed to make use of

[1]This work is co-sponsored by the Ministry of Economic Affairs, The Netherlands

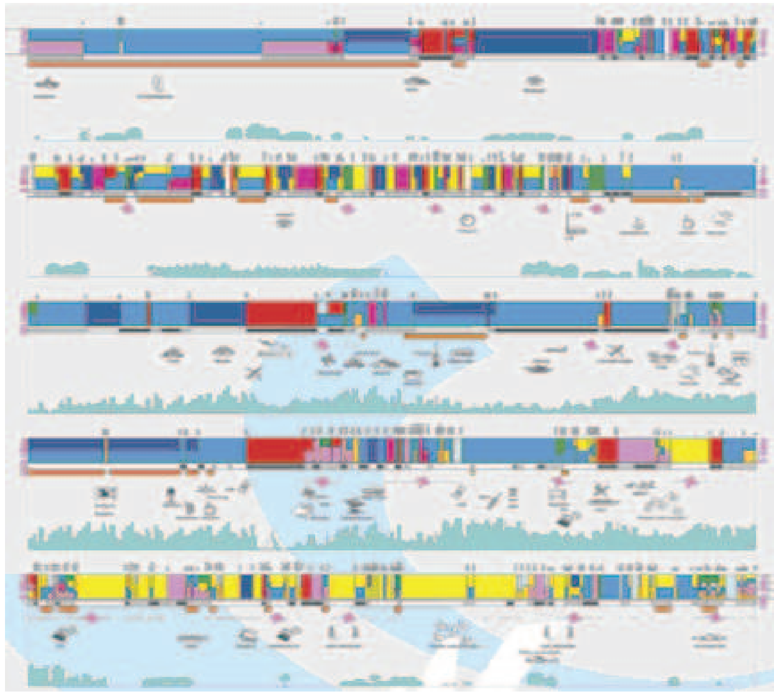


Figure 1.1: Frequency allocation chart in the Netherlands (Agentschap Telecom)

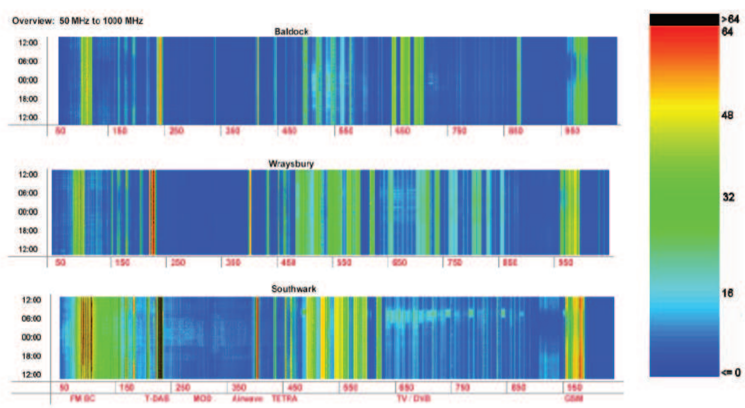


Figure 1.2: Measurement of spectrum utilization in the United Kingdom [28]

parts of the radio spectrum, for which they do not have proprietary or usage rights, only under conditions of not causing harmful interference to the users who do have such rights. In this way, the overall spectrum occupation could improve. Such radios must therefore only operate within specified regulatory constraints dictated by either a regulatory body or by the licensed user, whose spectrum band is being utilized. Wireless solutions that can accomplish effectively the use of spectrum whitespaces must be able to intelligently and autonomously adapt their transmission characteristics to suit the conditions under which they must operate at any time. Such solutions can be found

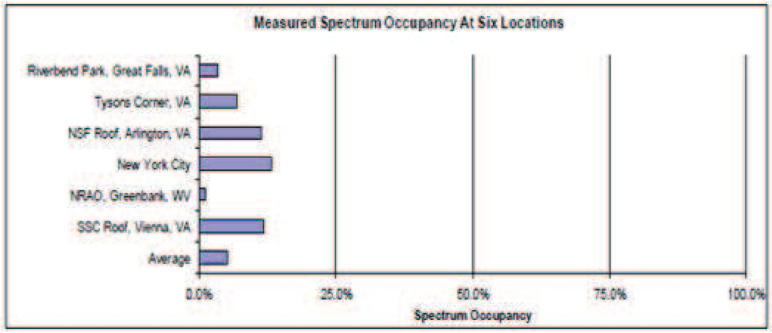


Figure 1.3: Measurement of spectrum occupancy over six locations in the United States [23]

in ***Cognitive Radios*** which can operate as secondary users of a licensed spectrum space.

1.2 Thesis Objective

In this thesis, we explore the idea of increasing sharing opportunities between primary and secondary users in a non-predefined manner. Traditionally, sharing arrangements involving users with primary usage rights are often predefined and apriori regulated and typically do not take local opportunities for sharing into account[2]. In this work, we study the conditions under which cognitive radios can conveniently transmit within spectrum bands that are not licensed to them by exploiting the intelligence attributed to them, through location awareness and power adaptivity. The purpose is to investigate the feasibility of cognitive radios' co-existence with primary spectrum users within the same band without causing harmful interference, provided certain power and location-dependent regulatory constraints are obeyed. These constraints are being defined based on analysis that has been done using power and location based approaches.

1.3 Summary of Contributions

Conventionally, only licensed systems can make use of their assigned frequencies due to strict spectrum regulations but in this work, we explore the possibilities of making use of frequencies licensed to other systems on a ' harmful-interference-free' basis by exploiting the intelligence attributed to cognitive radios, through spectrum detection, location awareness and power adaptivity. Contrary to 'direct' cooperative or non-cooperative spectrum sharing addressed in previous work [9], we have focused on spectrum sharing involving '**indirect**' cooperation between a primary and secondary user where the secondary user requires no 'case-by-case permission' from the Primary User but only requires a frequency look-up database for the primary user network. Therefore, no control channels or no pilot channels are required, thereby overcoming the issue of handling large communication overhead or complexity of system design.

[2]This is typically the case in Industrial, Scientific and Medical (ISM) bands

The outcome of this study gives conditions under which a secondary user can co-exist with a primary user without causing a performance degradation in the primary user beyond an assumed acceptable level of about 5%. In other words, the primary user is assured of acceptable performance 95% of the time provided the secondary users obey the regulatory constraints which are defined in this work.

1.4 Overview

In this work, we investigate the feasibility of 'indirect' cooperative spectrum sharing between primary and secondary users. We consider a future crisis scenario where a public safety network has insufficient spectrum space to handle all communication requirements. Extra capacity will be needed to support all communication traffic, which in such a scenario will specifically be broadband data. This may be due to large transfer of voice, video, audio and data files that will be required. In order to cater for this additional but ad-hoc spectrum need, we have considered the possibility of using spectrum which is licensed to commercial Private Mobile Radios (PMR) without causing harmful interference to these primary users.

In Chapter 2, we give a general overview of the cognitive radio technology. We discuss the motivation for using cognitive radios in terms of the current state of spectrum utilization. We further discuss software defined radios as platform for cognitive radios. The functionalities involved in cognitive radio technology are also discussed with emphasis on spectrum sensing and spectrum sharing.

In Chapter 3, we discuss the general design of the work, stating the main problem that is being solved. We then move to discussing the set up of the primary and secondary user networks. Some sections have also been dedicated to discussing the technologies involved in the study. The scenarios considered in this work are discussed in this chapter as well.

In Chapter 4, the models that have been used in each scenario were discussed. Following this, the analysis performed for each scenario are presented. The results from each analysis including the interpretation and deductions from the results are presented in this chapter.

Lastly, Chapter 5 presents the conclusions that have been drawn from all results obtained in the course of this work. Recommendations for future research are also given in this chapter

Dynamic Sharing with Cognitive Radio Technology 2

In this chapter, we discuss spectrum sharing and cognitive radio as its key enabling technology. We further give a general overview of the cognitive radio technology. The motivation for using cognitive radios in terms of the current state of spectrum utilization is also presented here. We describe the important spectrum management capabilities of cognitive radio technology based on findings from past literature.

2.1 Spectrum Sharing

Spectrum Sharing is a way in which better spectrum utilization can be achieved. Through spectrum sharing techniques, radios which need additional capacity to accommodate their increased demands can make use of spectrum assigned to other users. Akyildiz et al [4] have grouped spectrum sharing, as shown in figure 2.1 into three categories based on *architecture*, *spectrum access technique* and *spectrum allocation behaviour*.

2.1.1 Arcitecture: centralized vs distributed Spectrum Sharing

In **centralized spectrum sharing**, a central entity exists which collects the spectrum measurements from all the secondary user systems involved and based on the results, builds a spectrum allocation map for itself from which it then allocates spectrum to each secondary user involved. In other words, the central entity (or server) collects information from nodes which may be primary or secondary users; this information may include power, spectrum, location or interference measurements. It is based on

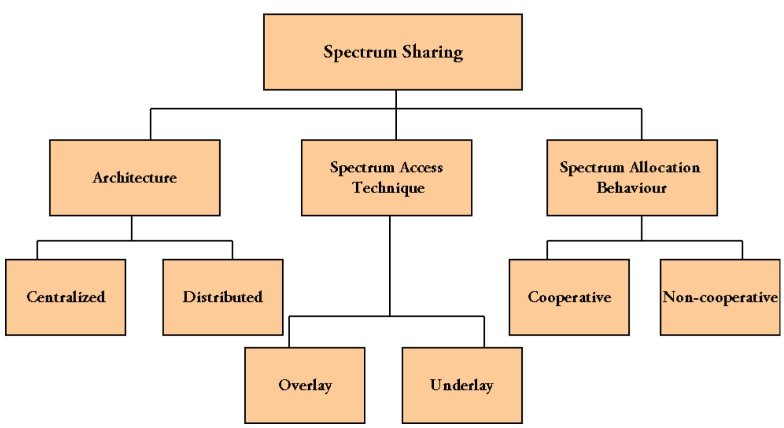


Figure 2.1: Spectrum sharing classification

this information that the central server then assigns channels to the nodes over a pre-assigned control channel. The primary goal of the centralized entity is to increase performance of wireless networks by intelligently distributing segments of available radio frequency spectrum to wireless nodes to avoid congestion, to minimize interference as well as to adjust the clients' wireless channel usage to fit the needs of the network.

Quite a number of papers have been addressing the use of a centralized methodology in spectrum allocation. In Buddhikot et al. [8] , a dynamic alternative to fixed and rigid frequency spectrum allocation was proposed - a technique called the DIMSUMnet makes use of a centralized spectrum broker that manages large portions of the spectrum and assigns these portions to individual users. Similarly, in Marias et al. [22], another spectrum brokering approach was proposed with emphasis on its use in heavily-used, densely populated localized areas in contrast to DIMSUMnet which is best suited for serving relatively large geographical areas.

When there's no infrastructure or central controller present, **distributed spectrum sharing** amongst the communicating radios is used such that the radios organize themselves in making efficient use of available spectrum bands without causing any interference to each other or to primary users that may be present. In this method, each node makes use of available spectrum based on its local observation of the spectrum. In order to avoid collisions or interference, control channels are introduced alongside the data communication channels. These control channels are then used to transmit control information amongst all radios such that some kind of coordination can be achieved amongst them.

Unlike the centralized approach, no central controller or manager of spectrum is present. The nodes will have to coordinate amongst themselves. Two approaches of control were studied - (1) The use of Common Spectrum Coordination Channel and (2) The use of Q-frames in a scheme called the Distributed QoS based Dynamic Channel Reservation (D-QDCR) was presented in [18].

2.1.2 Spectrum Access Technique: overlay vs underlay spectrum sharing

This technique of spectrum sharing is based on the manner of accessing spectrum, used by a secondary user. In the **overlay** method, the secondary users access the spectrum by finding spectrum holes, where no licensed user is operational. This results in minimum interference to the primary spectrum users if it is done in the proper way.

In order to prevent harmful interference to existing licensed users, the channels in which these primary users are active are avoided, of course by performing efficient spectrum sensing and making sure that the available channels still remain free at the time of transmission. Dynamic Spectrum Access (DSA) networks and Dynamic Frequency Selection[3](DFS) systems (e.g in 802.11a) are examples of systems making use of overlay spectrum sharing.

OFDM based Cognitive Radios as described in [5] are examples of radios which make use of the overlay technique. This is because OFDM provides the capability to transmit only in subcarriers where primary user signals are not present. The inherent

[3]Dynamic Frequency Selection (DFS) is the process of detecting radar signals that must be protected against 802.11a interference, and upon detection switching the 802.11a operating frequency to one that is not interfering with the radar systems

FFT operation of OFDM will ease the spectrum sensing capability in the frequency domain. After spectrum sensing, the primary users are detected and the subcarriers covering frequencies where primary users exist can be disabled such that the transmitted signal spectrum of the OFDM-CR transmitter only uses the free parts of the spectrum for signal transmission, hence the spectrum is shaped to avoid harmful interference with the primary user signals. Therefore, in overlay spectrum sharing approach, secondary users transmit power within the unused part of the frequency spectrum.

In **underlay spectrum sharing**, secondary users are allowed to coexist and share spectrum with licensed users while using the same spectrum bands but reducing the transmission power to an extent where the primary users do not encounter any harmful interference. Spread spectrum techniques can be employed in this approach such that the power being transmitted by the cognitive radios is spread over a wide bandwidth. In the portions of the spectrum where primary users are present, signals from the secondary users are observed as noise.

Ultra Wide Band (UWB) based Cognitive Radios, as described in [5] make use of this technique. The UWB technology is mostly suited for this type of spectrum sharing because signals are spread over large bands of spectrum and the signal strength is around the RF noise level (which allows a UWB signal to operate in occupied spectrum with a very low power output, and not cause any interference). The ambient noise and interference caused within the operating range of the primary users is measured and maintained under a predefined threshold (the interference temperature threshold). With this system, much attention is not required to be focused on the detection of the primary users, but rather on controlling the transmission power of the secondary users and ensuring that the interference temperature is not exceeded. Therefore, interference measurement and constant transmission power control is of much importance.

2.1.3 Spectrum Allocation Behaviour: cooperative vs non-cooperative spectrum sharing

In **cooperative spectrum sharing**, the effect of a node's communication on other nodes is considered such that harmful interference amongst nodes can be avoided as effectively as possible. This technique is otherwise called coordinated sharing as it ensures coordination between nodes to reduce the possibility of interference.

Centralized spectrum sharing techniques described above are also methods of cooperative sharing because they bring about a sense of coordination amongst the nodes - when the nodes are allocated spectrum bands based on the measurements received by the central entity from all the nodes. Distributed spectrum sharing techniques which are cooperative also exist. Examples include the interference pricing mechanism [32] and the distributed coordination mechanism [21] as described in previous sections. Communication overhead as well as complexity of designs are drawbacks in this type of spectrum sharing.

Unlike the cooperative spectrum sharing, **non-cooperative spectrum sharing** describes a 'selfish' behaviour of nodes where nodes do not coordinate with other nodes but rather allocate available channels to themselves based on their local observation of the spectrum. In non-cooperative spectrum sharing, the secondary user typically shares the spectrum with the primary user while obeying pre-defined constraints. Such constraints may involve reduction of its transmission power to a level which is not harmful to primary user receivers. An example of systems which exhibit non-cooperative spectrum sharing are Low power ultra wideband (UWB) devices [16]. We must note however, that even though the communication overhead in non-cooperative sharing technique is much lower than the other techniques (as there is no coordination amongst nodes), the network performance or reliability might not measure up since each node only bases allocations on its local observations.

In this work, we have defined a new type of spectrum sharing which involves **'indirect'** cooperation between the secondary and the primary users. The secodary users (the public safety communication systems) do not require any 'case-by-case' permission from the primary users (the commercial PMR systems) to make use of their spectrum bands. In other words, every attempt of transmission from the secondary users does not require interaction with the primary users. This concept, however requires access to the frequency database of the primary user network by the secondary user. This look-up database is assumed to be available to the secondary users from which they can identify if the spectrum holes they have detected are being used for downlink or uplink within the primary user network. For this spectrum sharing technique to be implemented in the case being studied, ***cognitive radios*** have been chosen as the most appropriate candidates. The following sections therefore introduce cognitive radios and their capabilities.

2.2 Aware, Adaptive and Cognitive Radios

Spectrum awareness in a radio is the capacity of a radio to capture spectrum activity within its local environment. A radio is said to be **aware** when it can sense all or part of its environment and interprete information that it receives of its environment. Such information may include channel estimates, interference or signals of interest. One example of an aware radio is the code division multiple access(CDMA) based cellular system proposed by Chen et al [10] a system which is aware of QoS metrics and makes reservations of bandwidth to improve overall QoS.

A radio is **adaptive** when it can autonomously modify its operating parameters in response to the characteristics of the environment in which it finds itself. For instance, a radio that modifies intermediate frequency (IF) filter characteristics in response to the characteristics of the channel it is using may be considered adaptive. In other words, an adaptive radio must be able to make changes to its operating parameters such as power level, modulation, frequency, etc. An 802.11a radio exhibits a level of adaptivity as it is able to sense the bit error rate (BER) of its link and adapts the modulation to a data rate and a corresponding forward error correction (FEC) that sets the BER to an acceptable level for data applications.[14]

A radio may have the capabilities of awareness, adaptivity as well as learning. Awareness of its environment can be created by sensors, interaction with its environment created by actuators, a model of the environment which includes state or memory of observed events may also be included. The learning capability which helps to select specific actions or adaptations to reach a performance goal when combined with awareness and adaptivity capabilities makes a radio **cognitive**. The first examples of cognitive radios were modeled in the Defense Advanced Research Projects Agency (DARPA) Next Generation (XG) radio development program.[12]

In addition to the awareness and adaptivity capabilities of cognitive radios, they must also be spectrum and policy agile as stated in [16]. Spectrum agility refers to their ability to operate over a wide range of frequencies while policy agility refers to their ability to understand the constraints under which they must operate: which frequencies are available and the rules for opportunistically using those frequencies.

Furthermore, technology agility may also be considered a requirement in cognitive radios because they should be able to adapt their modulation type, coding schemes and infact technology to the operating environment. According to [20] these attributes will be found in a full Cognitive Radio, referred to as the '**Mitola**' radio.

2.3 Cognitive Radio Definitions

In the past and till present, a lot of definitions have been given to the cognitive radio (CR). Each author defined this radio based on various perspectives. In the perspective of the awareness, adaptivity and learning capability, the Centre for Wireless telecommunications (CWT) defined a Cognitive radio as follows:

"*A transceiver that is aware of its environment and can combine this awareness with knowledge of its users priorities, needs, operational procedures, and governing regulatory rules. It adapts to its environment and configures itself in an appropriate fashion. The radio learns through experience and is capable of generating solutions for communications problems unforeseen by its designer*"

Haykin [17] defined a CR as:

"*Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming radio frequency stimuli by making corresponding changes in certain operating parameters (e.g., transmit power; carrier frequency, and modulation strategy) in real-time, with two primary objectives in mind: (i.) highly reliable communication whenever and wherever needed and (ii.) efficient utilization of the radio spectrum.*"

Joseph Mitola III, who first presented the cognitive radio technology defined CR in his dissertation [24] as:

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

In the study performed by Qinetiq for Ofcom - a body which regulates UKs broadcasting, telecommunications and wireless communications sectors, cognitive radio was defined as:

"*A radio which uses intelligent signal processing (ISP) at the physical layer of a wireless system.*" [20]

The Federal Communications Commission (FCC) defined the CR simply as:

"*A radio that can change its transmitter parameters based on interaction with the environment in which it operates.*"[11]

The FCC definition of the Cognitive Radio is adopted in most related literature, reasons which may be attributed to its simplicity and clarity.

2.4 Why Cognitive Radios?

Today's wireless networks are regulated by a fixed spectrum assignment policy; in other words, the spectrum is regulated by governmental agencies and is assigned to license holders or services on a long term basis for large geographical regions. In addition, a large portion of the assigned spectrum is used sporadically as illustrated in figure 2.2, where the signal strength distribution over a large portion of the wireless spectrum is represented both spatially and temporally. The green regions show where the spectrum is being utilized while the blue portions show when the spectrum is not being used at all. From this figure, we can observe that a large portion of the frequency spectrum is being underutilized, hence the need to establish a means by which these spectrum bands can be effectively utilized.

Cognitive radio offers a novel way of solving spectrum underutilization problems. It does so by sensing the radio environment with a two-fold objective: (1) Identifying those sub-bands of the radio spectrum that are underutilized by the primary (i.e legacy) users and (2) Providing the means for making those bands available for employment by unserviced secondary users. However, we must note that in order to achieve these goals in an autonomous manner, multiuser cognitive radio networks will have to be self-organizing.

When several devices are operating in the same frequency band, for example in the unlicensed bands known as the industrial, scientific and medical (ISM) bands, interference may occur as a result of combined noise from different transmitters thereby increasing the noise floor at the receiving systems. Cognitive radios will be a solution to spectral noise and spectral crowding and can help mitigate the problems associated with many personal devices all attempting to communicate in close proximity to eachother[6].

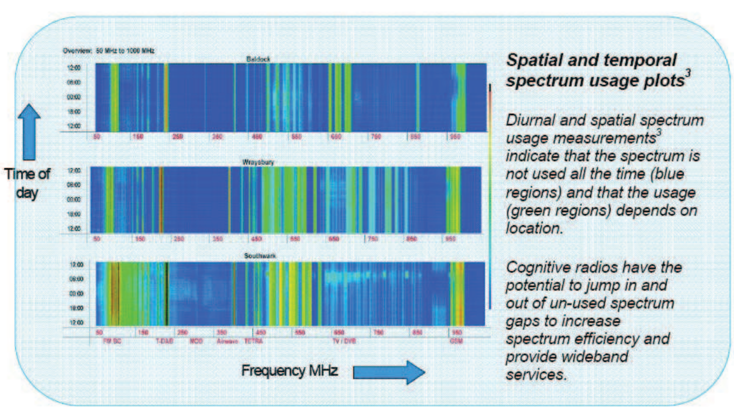


Figure 2.2: Spectrum Utilization [20]

This is because it will smartly find and use available spectrum spaces rather than bands already filled up by other systems.

There is a fast increasing demand for spectrum use by new technologies and new wireless applications and infrastructures. It therefore cannot be over-emphasized that the development of cognitive radio technology promises a means by which spectrum bands can be used more efficiently, thereby making room for new services and applications.

2.5 Software Defined Radio: a platform for Cognitive Radios?

FCC defines a Software Defined Radio (SDR) as "*a transmitter in which the operating parameters can be altered by making a change in software that controls the operation of the device without changes in the hardware components that affect the radio frequency emissions*". The term 'transmitter' may be replaced with 'transceiver' as an SDR can be viewed both from a transmitter and a receiver perspective. Software Defined Radio architecture allows for software programmability of radio parameters like bandwidth, centre frequency, modulation and demodulation schemes, coding and decoding schemes, etc.

One of the main characteristics of a cognitive radio is the adaptivity where the radio parameters (which includes frequency, power, modulation, bandwidth, etc) can be changed depending on the radio environment, user situation, network condition, geolocation, and so on[5]. The SDR therefore has the capability to provide a very flexible radio functionality by avoiding the use of application specific fixed analog circuits and components. However, it results in replacement of fixed application specific hardware with flexible and reconfigurable hardware that may be programmed to provide the desired functionality. Therefore, changing an operating mode will simply mean changing the underlying software, with the hardware remaining the same. SDR can then in principle be said to be a core enabling technology for cognitive radios. The flexibility and ease provided by SDRs makes it a general belief that majority of Cognitive radios will have SDRs as their basis.

In some systems however, some level of smartness can be found in their behaviour even though they have not been realized from a software defined radio. For instance, a cordless phone in the 43.71-44.49 MHz band is a simple form of cognitive radio since it incorporates an automatic channel selection mechanism that prevents establishment of a communication link on any occupied frequency in this band to prevent interference to private land mobile radio service operations. None of the present models of these cordless phones have been found to be based on a modifiable software, yet they exhibit smart radio attributes.

A relationship between SDR and CR can be represented using several models. However, according to [5], one of the conceptual models describes their relation, incorporating the cognitive engine, SDR capabilities, internal and external sensing as well as upper layer functionalities. In figure 2.3, this model is represented. The cognitive engine is responsible for optimizing or controlling the SDR based on some input parameters such as those which are sensed or learned from the radio environment, users context and network condition. Since the cognitive engine is aware of the radios hardware resources,

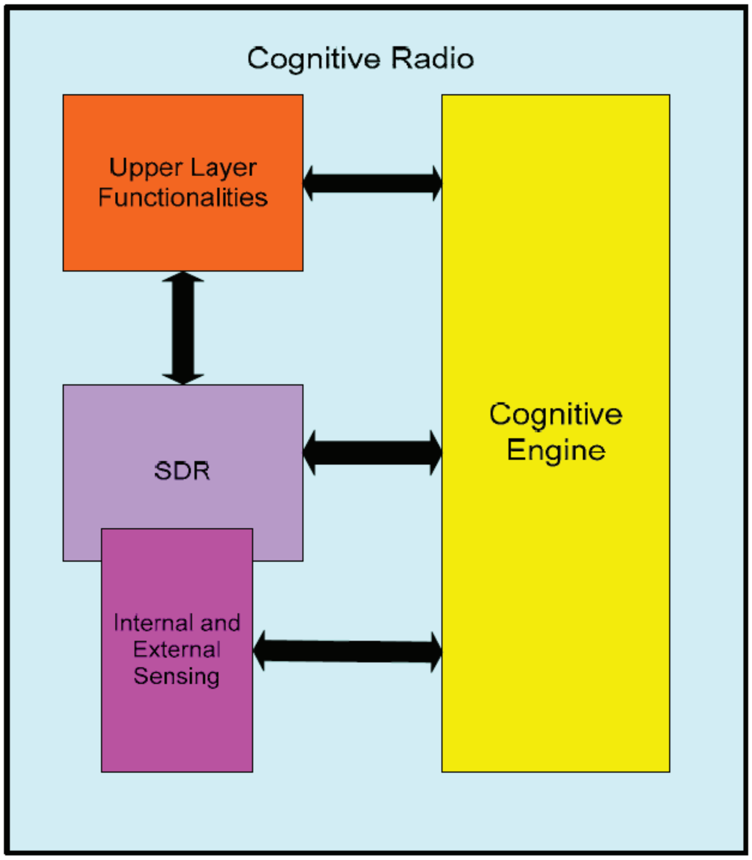


Figure 2.3: Illustration of relationship between SDR and Cognitive Radio [5]

parameters and capabilities, it tries to satisfy the radio link requirements of a higher layer application. The SDR is built around software based digital signal processing along with software tunable RF components. Hence, the SDR can be said to represent a very flexible and generic radio platform which can support a wide range of parameters that may be controlled by the cognitive engine.

SDR is a promising technology to facilitate flexibility in cognitive radios; for instance, a crucial cognition capability of cognitive radios is the dynamic spectrum management system which involves spectrum sensing, optimization mechanism to utilize a specific spectrum band, and spectrum shaping.

2.6 The Cognition Cycle

The cognitive cycle for cognitive radios was first described by Mitola et al [?] but this concept has been further described and represented differently by several authors depending on the perspective with which they are viewing the cognitive radio. We shall discuss three of these representations in this section.

First, the cognition cycle can be viewed as a state machine that resides in the

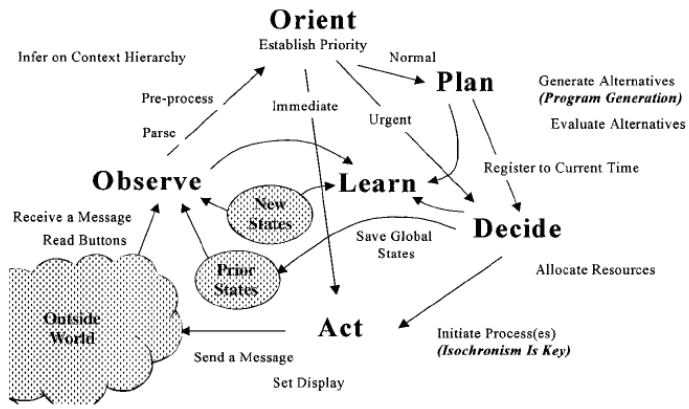


Figure 2.4: Cognition cycle (Mitolas representation) [24]

cognitive radio and defines how the radio learns about as well as reacts to its operating environment. In the cognition cycle, the radio will receive information about its operating environment (illustrated in fig 2.4 as the *outside world*) by performing direct observation or through signaling. The information received is then evaluated (*Orient stage*) to determine its importance. Based on this evaluation, the radio will determine its alternatives (*Plan*) and choose (*Decide*) an alternative in a way that presumably would improve the evaluation that has been previously carried out. Assuming a waveform change was deemed necessary, the radio then implements the alternative (*Act* stage) by adjusting its resources and performing the appropriate signaling. These changes are then reflected in the interference profile presented by the cognitive radio in the Outside world. Throughout the process, the radio uses these observations and decisions to improve its own operation (*Learn* stage), perhaps by creating new modeling states, generating new alternatives, or making new evaluations.

Second, the cognitive cycle of a CR was viewed by Akyildiz et al [4] based on its cognitive capability to enable real time interaction with its environment to determine appropriate communication parameters and adapt to the dynamic radio environment. The tasks required for this adaptive operation in open spectrum are shown in the cognitive cycle represented in fig 2.5. The steps involved are **spectrum sensing** - when a cognitive radio monitors the spectrum bands and captures the information in the bands then searches and identifies spectrum holes, **spectrum analysis** - characteristics of these spectrum holes are estimated/analysed, **spectrum decision** - the transmission mode, data rate and bandwidth of transmission are determined by the cognitive radio after which the appropriate spectrum band is chosen according to spectrum characteristics and user requirements.

From the study carried out by Qinetiq for Ofcom, UK [20], they viewed a cognitive radio as being a result of the combination of the RF flexibility provided by an SDR and intelligence provided by intelligent signal processing (ISP). As a result of their study, they came up with the cognitive cycle shown in fig 2.6. This figure illustrates that the cognitive cycle involves first, measuring the physical radio environment (RF stimuli), analysing these measurements, estimating predicting and learning from these

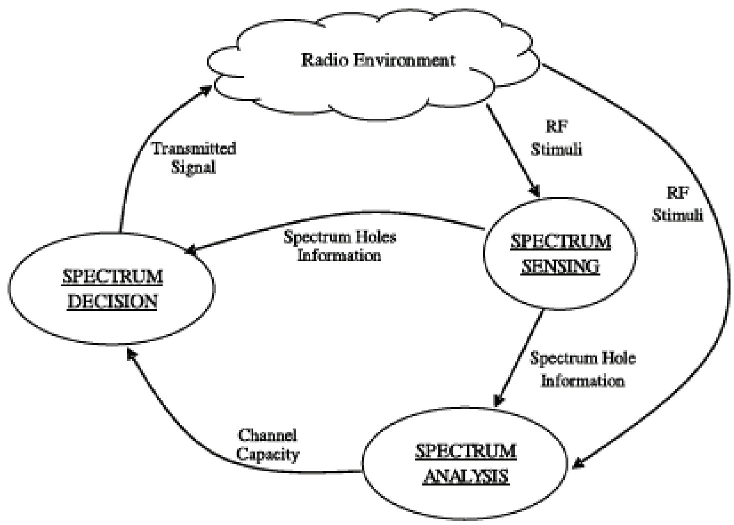


Figure 2.5: Cognitive cycle (Akyildiz representation) [4]

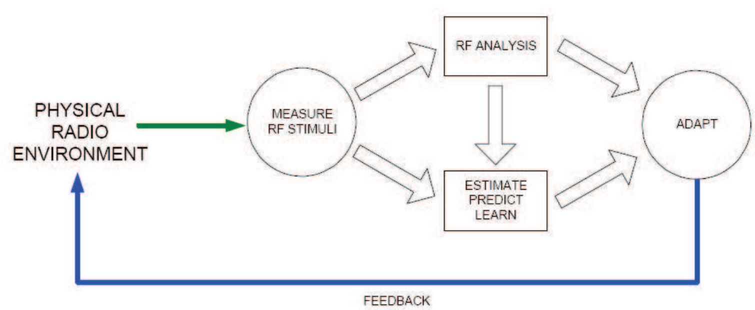


Figure 2.6: Cognitive cycle (Ofcom representation) [20]

and previous measurements and analysis (experience), implementing change as appropriate (adapting) and monitoring the results by looking once more at the physical radio environment (thus providing feedback).

2.7 Important Spectrum Management Capabilities

Spectrum management in cognitive radios in general relates to their ability to rationalize and optimize the use of the radio spectrum. In other words, through spectrum management capabilities, they can choose the best possible spectrum band that will meet required QoS amongst all detected available spectrum 'whitespaces' found. The spectrum management functions of a cognitive radio include **spectrum sensing**, **spectrum analysis** and **spectrum decision**. Spectrum sensing is mainly a physical layer issue while spectrum analysis and decision are more of upper layer issues. In the following sections we present a description of each of these functions.

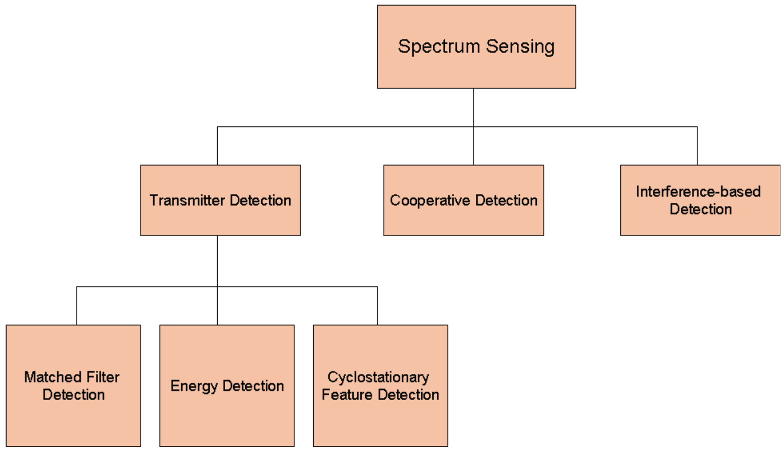


Figure 2.7: Classification of spectrum sensing techniques.

2.7.1 Spectrum Sensing

A cognitive radio is designed to be aware of its surrounding and be able to make changes to its own parameters in response to the information it is able to gather from its surroundings. The cognitive radio therefore needs to find spaces within the spectrum band that are not occupied by licensed users (otherwise called *spectrum holes* or *whitespaces*.) This process is known as spectrum sensing. It involves searching for spectrum holes with no activity of primary users that are operating within the communication range of the CR. In reality, it may be difficult for a cognitive radio to have a direct measurement of a channel between a primary receiver and a transmitter. Thus, most studies have focused on on primary transmitter detection based on local observations of secondary users. Spectrum sensing techniques can be classified as transmitter detection, cooperative detection and interference-based detection, as shown in figure 2.7.

2.7.1.1 Transmitter detection

The CR should have the capability to distinguish a used spectrum from an unused spectrum by detecting if the signal from a primary transmitter is locally present in a certain frequency channel. The basic hypothesis model for transmitter detection can be defined as follows:

$$\text{x(t)} = \begin{cases} n(t), & H_0 \\ hs(t) + n(t), & H_1 \end{cases}$$

Where:
$x(t)$ is the signal that is received by the cognitive radio user,
h is the amplitude gain of the channel,
$s(t)$ is the signal transmitted by the primary user,
$n(t)$ is AWGN,
H_0 is a null hypothesis stating that there is no licensed user signal in a certain spectrum band,
H_1 is the hypothesis which states that there is some licensed user signal active within

the spectrum band considered.

Transmitter detection in cognitive radios consists of three categories: matched filter detection, energy detection and cyclostationary feature detection.

In **matched filter detection**, information of the primary user transmitted signal (such as modulation type and order, the pulse shape, and the packet format) are known to the CR user. The optimum detector in the presence of stationary Gaussian noise is a matched filter which detects the presence of the primary user when the transmitted signal is known. It requires that the received signals are demodulated. The main advantage of this technique is that it requires less time to achieve detection, however, it is prone to false detection especially if wrong information about the transmitted signal is available at the CR. Another shortcoming of this technique is that large power consumption may result as various receiver algorithms need to be executed for detection.

Energy detection may be employed if the receiver cannot gather sufficient information about the primary user signal. In this case, the received signal power level is measured instead. If the power measured is more than the specified threshold, it decides that a primary user is present. The shortcomings of the energy detector are that the performance of energy detection is susceptible to uncertainty in noise power - its accuracy can however be improved by detection of a pilot tone from the primary transmitter. Also, the energy detector cannot differentiate signal types but can only determine the presence of the signal - the energy detector is therefore prone to false detection triggered by unintended signals.

In **cyclostationary feature detection**, modulated signals are in general coupled with sine wave carriers, pulse trains, repeated spreading, hopping sequences, or cyclic prefixes, which result in built-in periodicity. Because the mean and autocorrelation of these modulated signals exhibit periodicity, they are characterized as cyclostationary. This feature can be detected by analyzing a spectral correlation function. The main advantage of the spectral correlation function is that it differentiates the noise energy from modulated signal energy, which is a result of the fact that the noise is a wide-sense stationary signal with no correlation, while modulated signals are cyclostationary with spectral correlation due to the embedded redundancy of signal periodicity. Therefore, in the area of discrimination against noise, the feature detector performs better than the energy detector although it is computationally complex and requires significantly longer observation time.

2.7.1.2 Cooperative Detection

Cognitive radios in general cannot interact with primary user receivers; they do not have any information about these receivers therefore there might be a problem when the primary user transmitters cannot also be detected as shown in figure 2.8. Also, there may be instances where the CR users are hidden from the primary transmitters which may be due to an obstruction. In this scenario, collection of sensing information of all CR users within vicinity will reduce the possibility of falsely detecting a primary user absent. [31] describes cooperative detection between cognitive radios which individually make use of energy detectors; this can be seen as a synergy between energy detection and cooperative detection.

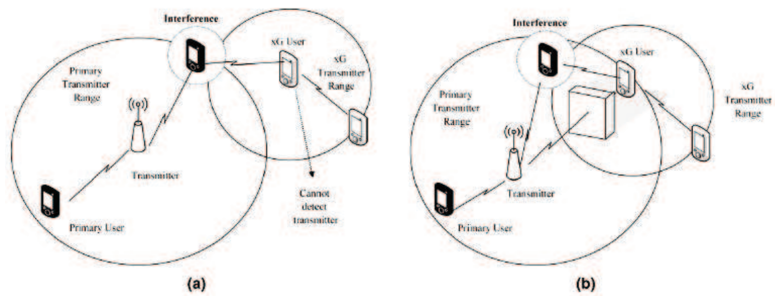


Figure 2.8: Transmitter detection problem: (a) Receiver uncertainty (b) Shadowing uncertainty

The cooperative detection method requires that sensing information from multiple CR users are combined to achieve primary user detection. Cooperative detection can either be centralized- where a CR base station gathers all sensing information from all CRs and detects the spectrum holes; or distributed wherein sensing information is exchanged amongst CR users. Cooperative detection schemes allow to mitigate the multi-path fading and shadowing effects, which improves the detection probability in a heavily shadowed environment. In this cooperative mechanism, there can exist a sensor network (comprising of sensor nodes located within the target area) and the operational network (comprising all participating network nodes). The sensor nodes collect sensing information and dump it in a central controller. This central controller processes the spectrum information collected from sensors and makes the spectrum occupancy map for the operational network. The operational network uses this information to determine the available spectrum. An advantage of this technique is that more accurate sensing performance is achieved. Its shortcoming is that it causes adverse effects on resource-constrained networks due to the additional operations and overhead traffic. Furthermore, the primary receiver uncertainty problem caused by the lack of the primary receiver location knowledge is still unsolved in the cooperative sensing.

2.7.1.3 Interference based detection

This technique uses a model known as the interference temperature[4]. Unlike the traditional transmitter-centric approach, the interference temperature model manages interference at the receiver through the interference temperature limit, which is represented by the amount of new interference that the receiver can tolerate. In other words, the interference temperature model accounts for the cumulative RF energy from multiple transmissions and sets a maximum cap on their aggregate level. As long as CR users do not exceed this limit by their transmissions, they can use this spectrum band. An illustration of the interference temperature model is shown in figure 2.9

Now, we must realize that there are some limitations involved in measuring interference temperature. According to [33], the interference is defined as the expected

[4]Interference temperature is a measure of how well a radio operating with a particular protocol and modulation scheme can tolerate interference in its spectrum space

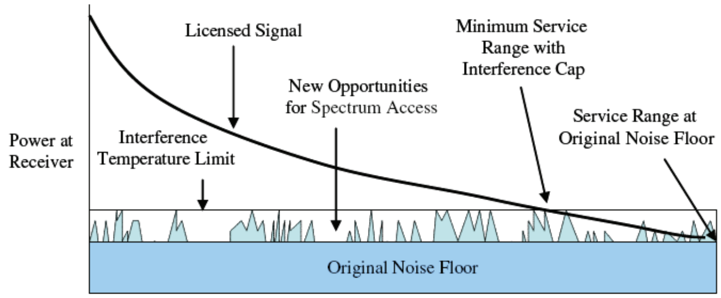


Figure 2.9: Interference temperature model[11]

fraction of primary users with service disrupted by the CR operations. This method considers factors such as the type of unlicensed signal modulation, antennas, ability to detect active licensed channels, power control, and activity levels of the licensed and unlicensed users. However, what should be noted here is that this model describes the interference disrupted by a single CR user and does not consider the effect of multiple CR users.

2.7.2 Spectrum Analysis

This involves the characterization of the spectrum bands. It addresses the characteristics of the spectrum band that will make it suitable for use based on users requirements. The interference level, path loss, link layer error, wireless link error and holding time are some of the characteristics of a channel which may be realizable by a cognitive radio through spectrum analysis [4]. The capacity of the channel can be estimated by characterizing the interference level at the primary receiver. Spectrum characterization is focused on the capacity estimation based on the interference at the licensed receivers. The interference temperature limit indicates an upper bound or cap on the potential RF energy that could be introduced into the band. Consequently, using the amount of permissible interference, the maximum permissible transmission power of a CR user can be determined. Most recent work on spectrum analysis is focused on capacity estimation which can be expressed as:

$$C = Blog_2(1 + \frac{S}{N+I}) \qquad Bits/s \tag{2.1}$$

Where B is the bandwidth, S is the received signal power from the CR user, N is the CR receiver noise power, and I is the interference power received at the CR receiver due to the primary transmitter.

2.7.3 Spectrum Decision

This is carried out when all available spectrum bands have been characterized. Based on the QoS requirements and spectrum characteristics, the appropriate operating spectrum band should be selected for the ongoing transmission. Based on the user requirements, the data rate, acceptable error rate, delay bound, the transmission mode, and the bandwidth of the transmission can be determined. According to the decision rule, the set of appropriate spectrum bands can then be chosen. When channel decision is based on SNR detection,an opportunistic frequency channel skipping protocol may be used for the search of a better quality channel. In order to consider the primary user activity, the number of spectrum handoffs, which happens in a certain spectrum band, is used for spectrum decision. The process of spectrum handoffs, where a secondary user '**dynamically**' changes its frequency to a more suitable one is sometimes refered to as **Spectrum Mobility**. Spectrum mobility arises when current channel conditions become worse or a primary user appears.

Having discussed the cognitive radio technology as an enabling technology to achieve dynamic spectrum sharing, the next chapter presents the design of the case being addressed and a background of the analysis work done.

3 Case Design

In this chapter, we describe the main problem that is being studied, our approach towards the solution of this problem and the general design of the case we are considering. We then discuss the set up of the primary and secodary user networks that are involved in the spectrum sharing scenario we have analyzed. In our case, these networks are based on the TETRA technology and the general concepts involved in this technology as found in [2, 3] relevant to our study are also discussed in this chapter. Furthermore, we discuss the scenarios involved in our subsequent analysis.

3.1 The Problem Statement

We are currently still in a rather strict spectrum licensing regime where the majority of the radio spectrum is licensed. This licensing scheme specifically prescribes who can use which part of the spectrum as well as when, where and how it can be used. A license holder with exclusive rights prefers not to have any other user in his spectrum space. Existing sharing arrangements with primary and secondary usage rights are often too conservative. Now, the classical assignment schemes introduce the situation of under-utilization of scarce spectrum, especially in cases where incumbent users apply very moderate duty cycles or with great imbalance in geographical usage. This will inherently tie down very precious spectrum bands! If systems were allowed to transmit within these spectrum holes each time they appear, without having to obtain a license but with the condition to leave as soon as a primary user re-occupies its space, a far more efficient utilization of the spectrum could be achieved.

This thesis work investigates the feasibility of deploying cognitive radios within a Primary User (PU) network, while obeying specific regulatory conditions which ensure that the primary users are not harmfully interfered - hence preserving the Quality of Service of these 'superior' primary users. In the past, as we pointed out in chapter 2, schemes which require control channels between the primary users and the secondary users have been considered. Since this will surely lead to a high communication overhead and great complexity in the design of such systems, this thesis work analyzes conditions under which such cognitive radio secondary users can co-exist in the same band with primary (or licensed) users without requiring such control channels while still ensuring that harmful interference is adequately prevented.

As a case scenario, we consider a crisis situation (e.g occurence of a disaster such as an earthquake) where the allocated spectrum to a user system such as the public safety communication system becomes insufficient to handle the large communication overhead. Extra capacity will be needed to support all communication traffic, which in such a scenario will specifically be broadband data that may typically occur as a result of the need to exchange large chunks of voice, video and audio files - hence the need for more spectrum space to handle broadband communication. This case has been supplied by TNO, due to the future spectrum needs the public safety sector is currently addressing as we further describe in the next section.

3.2 Case Description

Public safety organizations have over the years experienced increasing pressure on their activities due to growing natural and man-made catastrophes [26]. They have therefore recognized that in order to support full service capability and to improve operational efficiency during mission critical operations, they will need to increasingly depend on broadband data via advanced ICT solutions [25].

Unfortunately, the current spectrum will not be able to handle such communication demands. Therefore ETSI, ECC and the EU council have recognized the need for new dedicated radio spectrum for mission critical applications due to the future mobile data services that will be required by Public Safety organizations [25]. They concluded that about 2 x 16 MHz of additional spectrum will be needed and are therefore currently considering dedicating a portion of the Digital Dividend[5] for this purpose.

In this work, we are considering an alternative to the currently deliberated 'new dedicated spectrum' solution. Our study considers the option of employing cognitive radio technology to aid access to new spectrum by the public safety communication systems. This option will not require a dedicated 'fixed' spectrum but rather, allow for dynamic use of underutilized spectrum space. We are considering the case where the underutilized portions of spectrum allocated to commercial PMR systems can be exploited by these Public Safety organizations in order to cater for the increasing broadband data communication demands. We investigate the constraints under which the public safety organizations must operate in order to protect the primary spectrum users (the commercial PMR systems) from harmful interference.

3.3 TETRA Based PMR System

TErrestrial TRunked RAdio (TETRA) is a European digital standard (developed by ETSI) for PMR and PAMR systems which provide integrated digital trunked and direct modes of operation with a standardized way of inter-working between these two modes [13]. This standard was developed to meet the needs of traditional Professional Mobile Radio (PMR) user organizations such as:

- Public Safety
- Transportation
- Utilities
- Government

[5]Digital Dividend: The release of significant spectrum in the UHF bands due to switchover from analogue to digital TV broadcasting in Europe. It offers a unique opportunity to meet new demands for services and to support the European agenda for innovation [15].

- Military
- PAMR
- Commercial & Industry
- Oil & Gas

A typical TETRA system consists of one or more switches, one or more dispatch centers, base stations and user terminals which may be handheld or mobile radio stations. Similar to other modern digital PMR systems, TETRA supports virtual networks and enables a number of independent users to share a common communication infrastructure while maintaining their communications virtually separated from eachother. Figure 3.1 shows an example of a simple TETRA system and its constituents.

The TETRA system was designed to allow migration from analogue PMR systems hence the radio parameters related to this technology are as shown in table A.1 in appendix A.3. The spacing between TETRA carriers is 25 kHz thereby allowing for direct replacement of two 12.5 kHz analogue FM channels or a single 25 kHz analogue FM channel. TETRA operates within 150MHz to 900MHz frequency range and the uplink and downlink frequencies are separated by 10MHz (in the VHF band) or 45MHz (in the UHF band). Since TDMA is used by this technology, each carrier provides four physical channels which each occupy slots of 14.167ms duration.

In general, TETRA provides features which are not typically catered for by most public digital cellular systems such as fast call set-up, broader range of services, scalable architecture and a high level of user control [13]. Also, the capability of TETRA to provide direct mode operation between user terminals makes it very unique. The two types of TETRA modes of operation are the Trunked Mode and Direct Mode Operations, each with its own distinct features and capabilities.

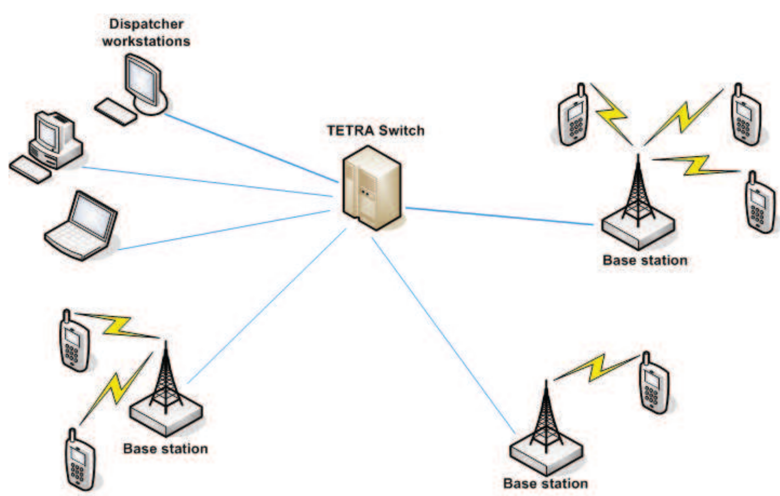


Figure 3.1: A Simple TETRA System

3.3.1 TETRA Trunked Mode Operation (TMO)

This mode of operation is also referred to as the Circuit mode or the Voice plus Data mode whereby simultaneous transmission of voice and data is allowed using a circuit switched mechanism. TETRA TMO requires the use of a network infrastructure such as the base station which is sometimes called the Switching and Management Infrastructure (SwMI) . In this mode, the base station has no power control capability while mobile stations employ this capability by stepping up power level in 5dB steps [2]. Tables 3.1 and 3.2 show the BS and MS power classes and MS power control levels respectively.

Table 3.1: BS and MS transmitter power classes (TMO)[2]

Power Class	BS Nominal Power (dBm)	MS Nominal Power (dBm)
1	46	45
2	44	40
3	42	35
4	40	30
5	38	
6	36	
7	34	
8	32	
9	30	
10	28	

3.3.2 TETRA Direct Mode Operation (DMO)

TETRA DMO is the mode of operation which does not require the use of network infrastructure (or SwMI). DMO involves direct mobile-to-mobile communications and is usually very useful when the mobile station is outside the coverage area of the network [3]. It is also very useful in cases of emergency for instance when the network infras-

Table 3.2: MS Power control levels (TMO)[2]

Step level	Nominal Power (dBm)
1	45
2	40
3	35
4	30
5	25
6	20
7	15

Table 3.3: MS transmitter power classes (DMO) [3]

Power class	Nominal Power (dBm)
2	40.0
2L	37.5
3	35.0
3L	32.5
4	30.0
4L	27.5
5	25.0
5L	22.5

tructure is broken down and communication is highly required. TETRA DMO can also be used as a more secure communication channel even within the coverage of a trunked Network. In general, there are four basic operational modes of TETRA DMO which includes the Back-to-Back mode - which involves direct terminal-to-terminal communication between mobiles over the radio interface; Repeater mode - used in cases where repeater stations are used to retransmit signals that would have been blocked off due to shadowing; Gateway mode - where a gateway mobile station is used to relay signals from DM terminals, either to the mobiles in the trunked mode or to other mobiles using the Direct Mode; Dual-Watch mode - where a special radio terminal connects both DMO and TMO networks simultaneously such that while it operates in one mode (say DMO), it monitors the other mode (TMO) for incoming communications. In this work, the back-to-back mode has been assumed for the secondary user links in order to eliminate the complexity that may be involved in having to deal with gateway or repeater stations. As a major disparity from MS transmitters in trunked mode, TETRA DMO mobile transmitters do not have power control capability but exist in different power classes as shown in table 3.3 where the power classes start from level 2. Levels 1 and 1L are not available to MS transmitters with DMO configuration (see [3]).

3.4 Primary and Secondary User Characteristics

In this section, we describe the primary and secondary user networks stating the characteristics and assumptions that have been made as a background to the analysis of our case scenario.

3.4.1 The Primary User Network

The Primary User (PU) network is supposed to be a commercial Private Mobile Radio (PMR) network operating within the 450∼470MHz band. Private Mobile Radios (sometimes also referred to as Professional Mobile radios) are radio communication systems that make use of handheld mobiles, base stations or dispatch console terminals. Most PMR applications are commercial in nature [19], examples of which include large organizations such as utilities for electricity, gas, water supply, public transport including buses, trams, trains, etc. Such large organizations constitute a large network with regional coverage and a huge number of mobile stations. However, smaller organizations such as manufacturing, construction, mining companies and private transportation such as taxi companies also make use of PMR systems but with a smaller coverage since smaller network sizes are required to be served. There exists a number of standards for PMR systems amongst which are EDACS, APCO25, Geotek-FHMA, TETRAPOL and TETRA. In this work, the focus is on TETRA based PMR systems.

In general, PMR systems can be deployed in a variety of configurations depending on the conditions governing the application or the environmental limitations. To mention a few, such configurations include **Direct mode configuration** - when there is no network infrastructure in place, **Dispatch mode configuration** - where a dispatcher relays information between mobile terminals via a central base station, **Talkthrough repeater configuration** - where signals are retransmitted via repeaters especially when extended coverage is required and lastly, **Cellular configuration** - the PMR configuration being assumed in this work, is that configuration which involves the use of multiple cellular sites with a frequency re-use scheme in place as it is mostly deployed in applications where large capacity is used and a large area is required to be served. The assumptions made for this user network are listed as follows:

1. The network is deployed in an urban environment
2. The cluster size of the network is 7
3. Each cell is at a frequency re-use distance, D away from its co-channel cell.
4. Each cell has a cell radius, R that is derived based on 95% area coverage.
5. Log-normal shadowing effects with zero mean and standard deviation, σ=6dB
6. Path loss exponent, n=3.5 (valid for an urban area cellular radio, see table 3.2 in [27])
7. Minimum wanted signal level at a receiving terminal = -85dBm

3.4.1.1 Cell Radius

The typical cell radius of each PU cell was estimated using the Hata path loss model (Appendix A.4) and assuming that the required coverage probability is at least 95%. Using equation(3.1),a path loss exponent, n=3.5 and σ=6dB due to log-normal shadowing, the required 95% area coverage, C requires that the probability that the power received at the boundary exceeds a minimum threshold, P_{min} of 85dBm is about 75%. Figure A.1 in [27] (Appendix A.2) was also used to verify this result. Having obtained the required minimum boundary coverage to satisfy a coverage area of 95% to be 75%, the required cell radius for this condition to be met for all possible BS transmit power range of the TETRA based primary user system were estimated using equation 3.2. These required cell radii are represented in table 3.4.

$$C = \frac{1}{2}(1 - erf(a) + exp(\frac{1-2ab}{b^2})(1 - erf(\frac{1-ab}{b}))) \quad (3.1)$$

$$\text{where } a = (\frac{P_{min} - (P_t - PL(R))}{\sigma\sqrt{2}});\ b = \frac{10nlog_{10}(e)}{\sigma\sqrt{2}}$$

$$p(Pr{>}P_{min}) = Q(\frac{P_{min} - (P_t - PL(R))}{\sigma}) \tag{3.2}$$

Where P_t represents transmit power, PL is the path loss between the base station and mobile station and $Q(.)$ denotes Q-Function.

3.4.1.2 Frequency Re-use Distance

We consider the PU cellular system with hexagonal cells of radius R as shown in Figure 3.2. In this figure, we represent a cluster of seven cells to be composed of a central base station 0 in addition to its six direct neighbors 1-6. We can assume that the same cluster is repeated in all directions to cover the entire service area of the PU network. The distance between any two co-channel cells is denoted as D - this we refer to as the *frequency re-use distance*. Equation (3.3) has been used to obtain the frequency re-use distance with respect to each power class. The frequency re-use distances for all possible BS transmit power range of the TETRA based primary user system are represented in table 3.4.

$$D = R\sqrt{3K} \tag{3.3}$$

Table 3.4: Primary User Cell Parameters

BS Transmit Power (dBm)	Cell Radius (km)	Re-use Distance (km)
46	1.73	7.928
44	1.52	6.966
42	1.33	6.095
40	1.17	5.362
38	1.03	4.720
36	0.90	4.124
34	0.79	3.620
32	0.69	3.162
30	0.61	2.795
28	0.53	2.429

3.4.2 The Secondary User Network

The secondary user (SU) is considered to be a communication network that is exclusively used for public safety purposes. This system is assumed to be making use of the TETRA technology as well and operating normally within the 380∼400MHz band which is a harmonized band for public safety services in Europe. The current generation of Public Safety Systems is usually only limited to voice calls and some

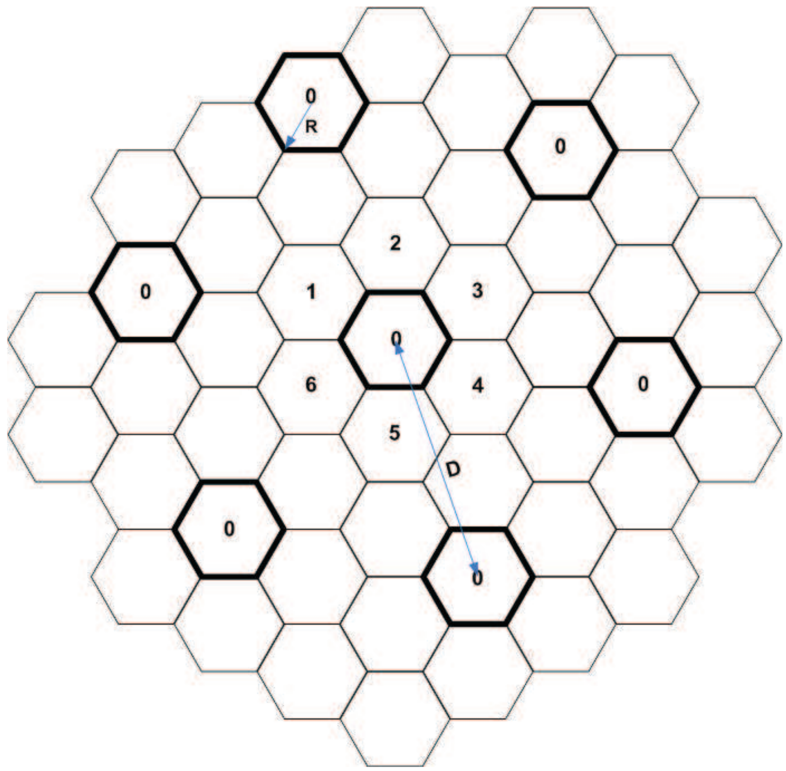


Figure 3.2: Frequency re-use in the PU cellular network

low data rate applications. However, requirements for broadband communications will emerge rapidly and the current harmonized band may not provide sufficient bandwidth to accommodate this requirement. This may however make communication difficult especially in large crisis incidents when the exchange of a large information overhead will be required. For instance, in a situation where a disaster, such as an earthquake or a plane crash has occurred, large communication overhead may include exchange of large data files such as scene pictures and video, victim pictures, medical history of victims, large audio files, etc. Since SU base stations cannot be deployed within the PU network, we consider a direct mobile-to-mobile communication mechanism amongst the secondary users. This mechanism, known as Direct Mode Operation (DMO) is adequately supported by the TETRA technology. The possibility to offload DMO traffic to another frequency band on an ad-hoc basis is the proposition we are considering in this thesis. We assume that the user terminals can be configured in this way.

3.5 Case Scenarios

As previously mentioned in section 3.4.1, the Primary User network considered in this work has a cellular configuration where separate frequencies are used for uplink and downlink communication. Separation between the uplink and downlink frequencies in a typical TETRA system is 10MHz such that 450∼460MHz is allocated to the uplink while 460∼470MHz is allocated to the downlink communications. Each channel within the TETRA system is separated by 25kHz[19]. This implies that ideally, the secondary user should be able to make use of either the uplink or downlink frequency, depending on which is available at a particular time or within a particular geographic region. The outcome of the analysis performed in this work will provide information on which is more feasible for use.

In the course of this work, the interference analysis performed is basically based on the block diagram shown in figure 3.3 where the victim receiver may either be a PMR mobile station or base station. The two case scenarios considered are therefore the following:

- **Scenario 1**: SU making use of downlink frequency; If the SU makes use of a DOWNLINK frequency, the victim of such transmission will be a mobile station belonging to the PU network, actively receiving from a transmitting base station within the same downlink frequency band.
- **Scenario 2**: SU making use of uplink frequency; If the SU makes use of an UPLINK frequency, the victim of such transmission will be a a Primary User base station that is actively receiving from a mobile station making use of the same uplink frequency band.

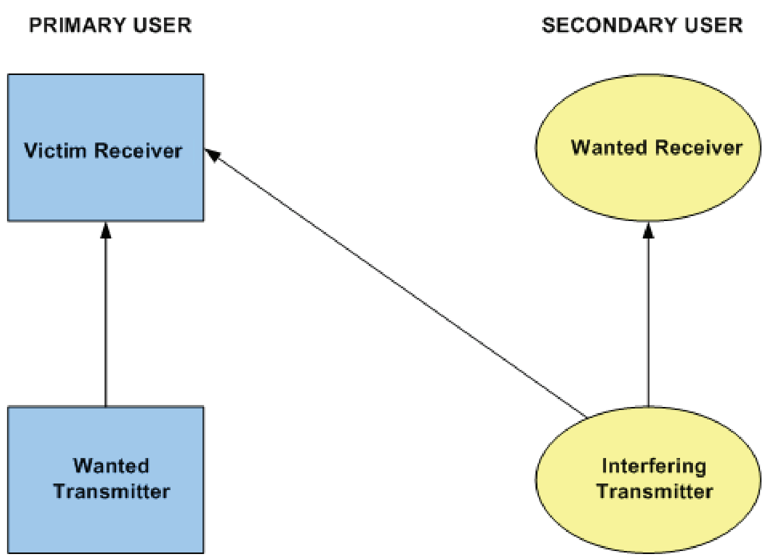


Figure 3.3: Block diagram showing main scenario

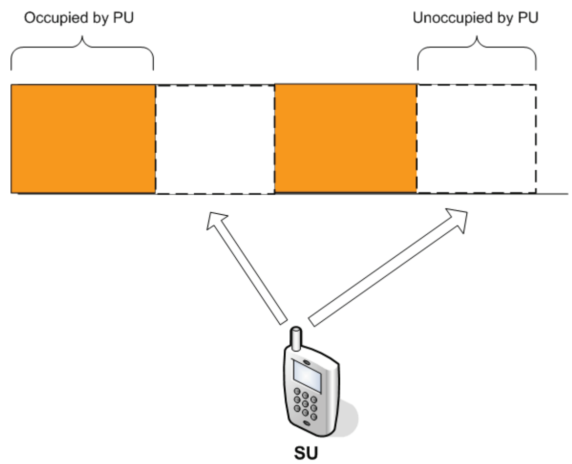
3.6 Approach Towards Solution

As pointed out in the previous sections, we identified the need for additional spectrum to handle the large demand for broadband communication by public safety systems in our case sceanrio. We further established that the spectrum licensed to commercial Professional Mobile Radio (PMR) systems may serve this purpose as PMR systems generally exhibit the limitation of channel underutilization, as stated in [30]. This is because these PMR systems are generally allocated to channels based on their respective user groups and since all user groups may not be active at the same time, it is expected that some channels may be idle and therefore candidates for usage by secondary users (the public safety communications systems).

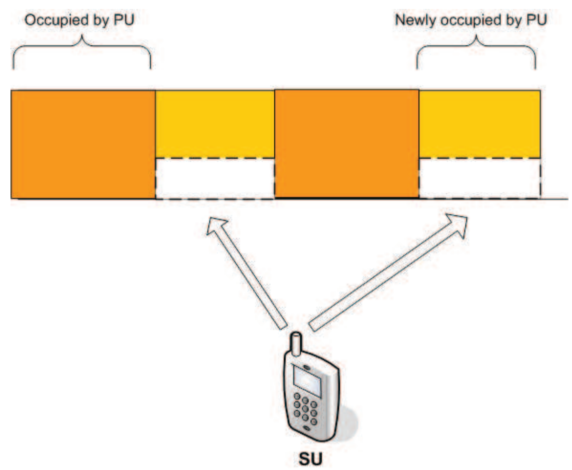
For the purpose of reducing the complexity of this work, we have assumed ideal spectrum sensing capabilities of the cognitive radios - which implies that the secondary users can accurately detect the presence or absence of the primary users at any point in time. Missed or false detection probabilities are therefore assumed to be zero, perhaps due to cooperative detection techniques. In essence, we only deal with conditions that govern the spectrum occupancy by secondary users having correctly identified usable spectrum bands.

Two possibilities of spectrum occupancy were considered during the course of this work as shown in figure 3.4 where the orange colour indicates an occupied band and the white bands indicates that the region is unoccupied. The first possibility involves the secondary user scanning the frequency band licensed to the primary users and identifying the available “white spaces” which may then be used for its own transmission. However, the primary users may re-occupy the bands that had been previously determined as available by the secondary users. Normally, the secondary users are expected to vacate such bands and look for other available bands to occupy. Logically, we know that if this happens repeatedly the service of the secondary users will be greatly degraded. To avoid such a scenario, we consider a second sharing possibility where the secondary user does not vacate the band but instead, co-exists within the same band as the primary user while it adapts its transmit power to a level that will not harmfully affect the performance of the primary user. This power adaptation will be based on the proximity of the secondary user to the primary user.

The next chapter presents the analysis of the case scenarios as well as interpretation of results obtained from the analysis, which was based on the approach we have hitherto described.



(a)



(b)

Figure 3.4: SU spectrum occupancy(a)with PU absent (b) with PU present

4 Analysis and Results

In the previous chapter, we introduced the case design where we described the cases involved and general properties of the network and technologies being considered. In this chapter, we therefore discuss the analysis that was performed for the case interference scenarios. The results of the analysis performed are presented here, where interpretations and deductions are also discussed.

4.1 Interference Scenario

The case scenario as described in the previous chapter involves a public safety communication system (Secondary Users) making opportunistic use of the spectrum licensed to commercial PMR/PAMR systems (Primary Users). A secondary user co-existing with these primary users has the potential of interfering with the signals being received by the primary system. In our model, the link between the primary user base station and its counterpart mobile station is called the **Wanted Link** while the signal path between an interfering secondary user station and a receiving primary user is called the **Interfering Link** as shown in figure 4.1. The receiving primary user is the called the Victim Receiver while its transmitting counterpart is called the Wanted Transmitter; the transmitting SU is the Interfering Transmitter while the receiving SU is called the Wanted Receiver as indicated schematically in figure 3.3. In this analysis, the victim receiver may either be the Primary User Base Station while the Wanted Transmitter is the PU mobile station or vice versa depending on which frequency is being used by a co-existing secondary user. By this, we imply that the PU mobile station is the victim receiver if downlink frequencies are being used by the secondary user while the PU base station will be the victim receiver if uplink frequencies are being used by the secondary user.

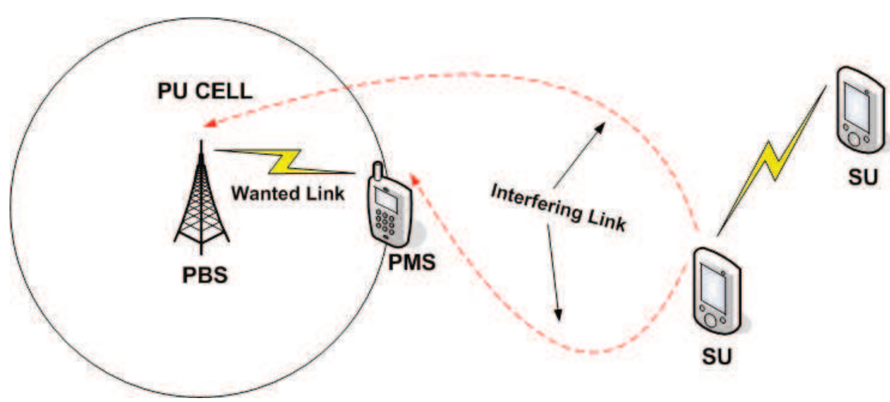


Figure 4.1: Interference Scenario

4.1.1 Wanted Link

The wanted link is the communication link between a base station and a mobile station that have the licence to operate within a specific portion of the frequency spectrum. By this, we refer to the primary users of the spectrum hence they have priority to make use of the spectrum over any 'spectrum seeking' secondary user. Typical transmitter power levels used in a real-life practical scenario for PMR networks have been used for this study in order to obtain results that simulate a real life situation. For example, a base station with a power class of 2, corresponding to transmit power of 44dBm (see table 3.1was used. Further assumptions made will be discussed in following sections.

At the PU receiver, the power received from the ***wanted transmitter*** was estimated considering large scale path loss effects and effects due to lognormal shadowing with zero mean and 6dB standard deviation. This wanted power is therefore a stochastic variable with probability density function (pdf) estimated as follows:

$$f_W(w) = \frac{1}{\sigma_w\sqrt{2\pi}} exp(\frac{-(w-\bar{w})^2}{2\sigma_w^2}) \tag{4.1}$$

$$\bar{w} = P_{R,W}$$

$$P_{R,W} = P_{T,W} - L_W \ \ \text{(dB)} \tag{4.2}$$

$P_{R,W}$ represents the mean received wanted power, P_T represents the transmit power, σ_w represents the standard deviation of wanted signal variation due to shadow fading and L_W represents large scale path loss effects.

4.1.2 Interfering Link

At the PU ***victim receiver***, transmission from an interfering SU transmitter may also be received. This 'unwanted' received power from the interferer also encounters attenuation due to large scale path loss effects as well as lognormal shadowing of zero mean and 6dB standard deviation. As a result, this link from a secondary user interferer to a receiving primary user is also a stochastic variable with probability density function represented by the following equation:

$$f_I(i) = \frac{1}{\sigma_i\sqrt{2\pi}} exp(\frac{-(i-\bar{i})^2}{2\sigma_i^2}) \tag{4.3}$$

$$\bar{i} = P_{R,I}$$

$$P_{R,I} = P_{T,I} - L_I \ \ \text{(dB)} \tag{4.4}$$

Where $P_{R,I}$ represents the mean received interfering power, P_T represents the transmit power, σ_i represents the standard deviation of interfering signal variation due to shadow fading and L_I represents large scale path loss effects.

4.1.3 Carrier-to-Interference Ratio at the PU Receiver

The PU ***victim receiver*** receives signals from both its wanted transmitter and an interfering secondary user. The ratio of the received power over the wanted link and the received power over the interfering link gives rise to the Carrier-to-Interference Ratio (**CIR**) at the PU receiver. On dB scale, this parameter becomes the difference between the wanted power and the interfering power. Since the wanted (or carrier) power and the interfering power are both stochastic and independent, the CIR is therefore also a stochastic variable with pdf resulting from the convolution of $f_W(w)$ and $f_I(i)$. By performing a step by step convolution of these pdfs similar to method given in [7](see derivation in appendix A.1), we obtain the following closed form expression for the pdf of CIR, $f_C(c)$ at the PU victim receiver:

$$f_C(c) = \frac{1}{\sqrt{2\pi(\sigma_w^2 + \sigma_i^2)}} exp(\frac{-(c-(\bar{w}-\bar{i}))^2}{2(\sigma_w^2 + \sigma_i^2)}) \tag{4.5}$$

4.1.4 Harmful Interference

In order to define what harmful interference means to the primary user receivers in our case scenario, the specified CIR for receiver systems based on TETRA technology became of importance. TETRA standards [3] specify that the required CIR at the MS or BS must be at least 19dB for acceptable performance, hence this value was used for the analysis to specify the target CIR required at the PU victim receiver. This, we translated to mean that **Harmful Interference** occurs when the interference caused by a secondary user results in the CIR at the PU falling below the 19dB target value. In this work, conditions under which harmful interference occur have been based on a 95% confidence level. Now, this means that we assume an allowed maximum intereefernce probability of about 5%. In order words, any interference that occurs with probability greater than 5% is considered as '**harmful**'.

4.1.5 Exclusion Distance

This work is aimed towards defining conditions under which a transmitting secondary user must operate in order to prevent harmful interference at the PU (BS or MS) receiver. One of such conditions is based on the proximity of the interferer to the victim receiver. Depending on the transmit power of a co-existing secondary user, it has to keep a minimum distance, D_s away from the PU victim receiver in order not to cause harmful interference to the PU. This minimum distance required for the SU is what we refer to as the **Exclusion Distance**. The exclusion distance was estimated as the distance between the SU and PU receiver such that the probability of interference (CIR <19dB) is 5%. The result gives the closest distance that the SU can be to the PU receiver. This analysis was performed based on pre-defined system models for both case scenarios 1 and 2.

4.2 Case Scenario 1

This represents the scenario where the Uplink (**UL**) frequency of the primary user is used by a secondary user, such that the primary user base station (PBS) is the victim receiver which receives wanted signals from the primary user mobile station (PMS) as well as interfering signals from a transmitting secondary user. In this scenario, we assume a typical BS power class 2 which is normally deployed in a practical PMR network was used for the analysis - this corresponds to a cell radius of 1.52km and a frequency re-use distance of about 6.97km (see table 3.4). Since in this scenario, the PMS being the transmitting PU station has power control capabilities, it can therefore control its power level from 15dBm to 45dBm in 5dB steps although typically, a PMR mobile station operates at 23dBm. The analysis was therefore based on the following three cases:

- PMS transmits at 45dBm
- PMS transmits at 15dBm
- PMS transmits at 23dBm (typical transmit power of a TETRA PMS)

4.2.1 System Model I

Consider a PU network with a cluster size of 7 and having a frequency re-use distance, Dkm and each cell having a radius, Rkm. The exclusion distance of a transmitting secondary user located at X within the network can be represented by E0 as illustrated in figure 4.2. E1, E2, E3, E4, E5 and E6 represent the distance of the SU away from the other six co-channel base stations respectively. This model was used in the analysis to obtain the exclusion distance, E0 required for a SU transmitting with any of all possible DMO power classes (22.5dBm to 40dBm) with the assumption that the mobile PU transmitter is at the cell edge.

4.2.2 SU Exclusion Distances

For each SU power class, the exclusion distance (E0) that will be required between the SU located at X and any PBS 0 before transmission can be allowed was calculated by finding the closest possible distance, E0 such that probability of CIR being less than 19dB does not exceed 95%. The following calculation steps were implemented using MATLAB :

1. Mean received wanted power calculation: we assumed for this case that the PMS is located at the cell edge, therefore distance between the PBS and the PMS, Dp=1.52km. The mean received wanted power was estimated as follows:

$$P_{R,W} = P_{T,W} - L(Dp) \ \ (\text{dB}) \tag{4.6}$$

where:
P_t = PMS transmit power
Dp = distance between PBS and PMS

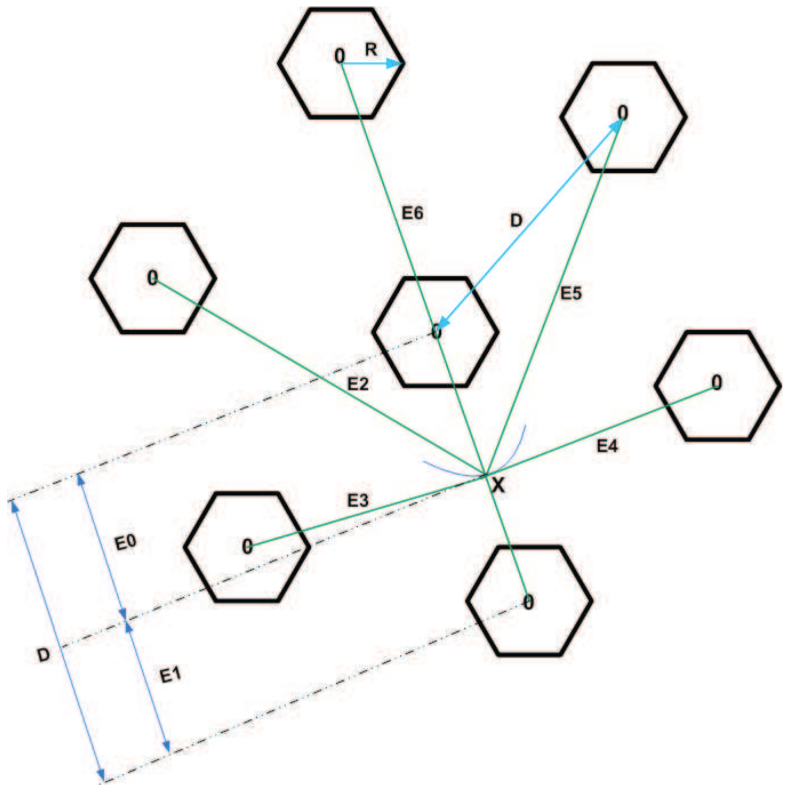


Figure 4.2: System Model I

$L(Dp)$ = Path loss between PBS and PMS (obtained using Hata model as shown in appendix A.4)

2. Mean received interfering power calculation: we otained this for a range of distances between the PBS and the SU, Ds as follows:

$$P_{R,I} = P_{T,I} - L(Ds) \ \ (\text{dB}) \tag{4.7}$$

where:
Q_t = SU transmit power
Ds = distance between PBS and SU (0 ≤ Ds ≤ 100 km)
$L(Ds)$ = Path loss between PBS and SU(obtained using CEPT SE 24 model as shown in appendix A.4)

3. Estimation of E0 for which Pr(CIR<19dB)=0.05: this was obtained from the CDF of CIR, $F_C(c)$ as follows:

$$F_C(c) = \frac{1}{2}(1 + erf(\frac{c - (\bar{w} - \bar{i})}{\sqrt{2(\sigma_w^2 + \sigma_i^2)}})) \tag{4.8}$$

Exclusion distance, E0 = Ds when $F_C(c) = 0.05$

The results shown in figure 4.3 presents the exclusion distance required between a transmitting SU any PBS receiving within the same frequency.

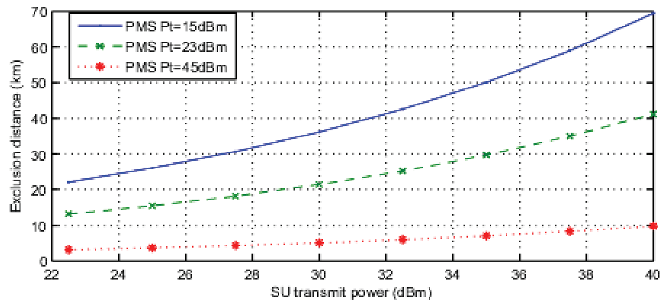


Figure 4.3: Required SU exclusion distance

Two deductions can be made from this result. First, the result indicates that higher SU transmit power classes require larger exclusion distances, which were expected. This is due to the fact that a SU transmitting with a higher power will need to be farther away from the victim PBS receiver in order to allow the interfering signal experience more path loss so that the CIR at the PBS does not fall below the 19dB target. In other words, more exclusion distance is required to ensure the probability of interference does not exceed 5%. Second, it can be observed from 4.3 that with higher PMS transmit power, lower SU exclusion distances are required. For instance, when PMS transmit power is 45dBm, the SU is allowed to transmit at 25dBm at a distance of about 5km away from the PBS - which would have been impossible if the PMS were transmitting at 23 dBm when an exclusion distance of 15km is required! This is because the carrier (wanted) power at the PBS becomes greater with an increased PMS transmitter power, thereby allowing more room for signals from the interferer without leading to a harmful interference condition. Now, these results have shown the constraints of the SU with respect to any co-channel PBS, but in the next section we will show that in principle, these conditions will not all be achievable within a cellular environment due to the impact of SU tranmsission on all co-channel primary user base stations.

4.2.3 SU impact on co-channel PU stations

In the previous section, we obtained the required SU exclusion distances relative to a particular victim PBS within the PU network. We should however realize that a transmitting SU can also interfere with other co-channel base stations within the PU network which are actively receiving within the same UL frequency. Therefore, if the SU is at a distance which is at least the exclusion distance, E0 away from all co-channel base stations, then it can transmit conveniently without causing harmful interference to any of these base stations. The distance, E1 in figure 4.2 represents the distance of the SU away from one of its co-channel BS if it were located at its exclusion distance, E0. Now, if E1≥E0, then transmission will be possible, otherwise if E1<E0, the SU will

harmfully interfere with the co-channel BS. From figure 4.2 we find that E2,E3,E4,E5, E6 > E1. Therefore when E1 > E0, then logically from our system model as shown in figure 4.2 E2,E3,E4,E5, E6 > E0. E1 can be estimated as the difference between the exclusion distance and frequency re-use distance. That is,

$$E1 = D - E0 \text{ (km)} \tag{4.9}$$

The results shown in figure 4.4 indicate that when the PMS transmits at 45dBm, a secondary user can only transmit provided it is transmitting with 22.5dBm and at an exclusion distance of at least 3.2km. On the other hand, when the PMS transmits at 23dBm, E1<E0 for all SU power classes indicating that under this condition, SU transmission will not be possible.

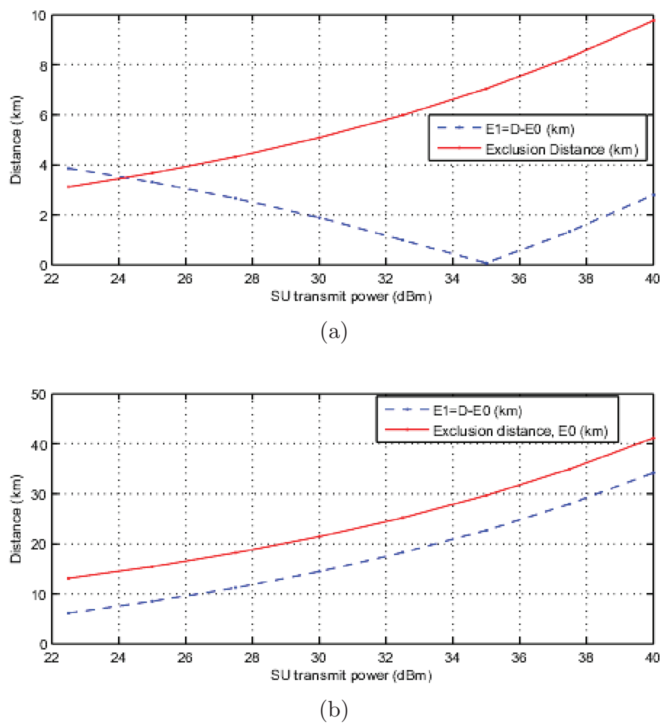
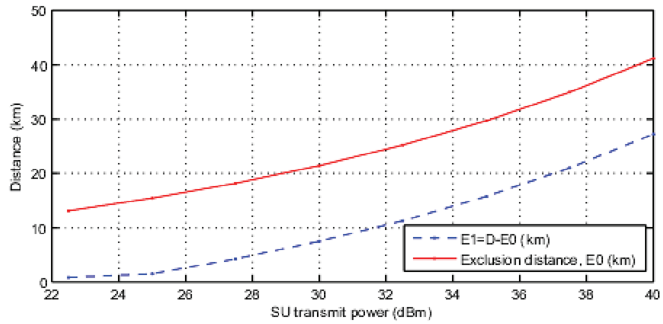


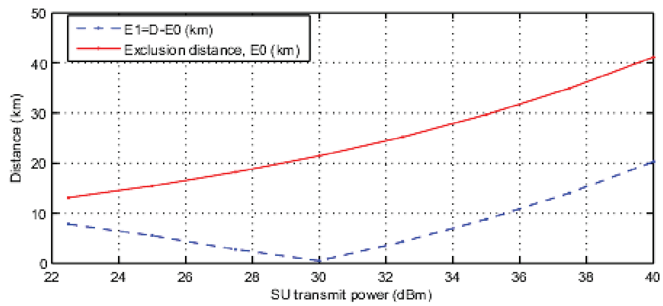
Figure 4.4: SU effect on co-channel receivers (a) PMS transmitting at 45dBm (b) PMS transmitting at 23dBm

From the results shown in figure 4.4, the required SU exclusion distances ranges from about 12km to 41km when the PMS is transmitting at 23dBm. This already extends beyond the first tier of co-channel PU stations since the frequency re-use distance is 6.97km. If we assume that the PU network consists of only 3 tiers, it was interesting to see the effect on the co-channel primary users in the 2nd and 3rd tiers. Figure 4.5 shows that E1<E0 for all SU power classes - therefore, we can conclude that no transmission is possible under this condition.

As earlier mentioned, these analysis have been based on the PMS being located at the cell edge and we have observed from the results that under this condition, the



(a)



(b)

Figure 4.5: SU effect on co-channel receivers (a) 2nd tier (b) 3rd tier

allowance for SU transmission is very small and infact, almost negligible! With the goal of seeking more allowance for SU transmission, a situation where the PMS transmits closer to its receiving base station was considered.

4.2.4 System Model II

Consider the model shown in figure 4.6 where the PBS is located as shown while the PMS can be located anywhere within a cell of radius, R = 1.52km. The distance between the PMS and PBS is denoted as Dp while the distance between the interfering SU and victim PBS receiver is denoted as Ds. Dp varies between 0 and 1.52km in steps of 0.152km. At each PMS location, the SU location varies within the range $0 \leq Ds \leq 1.5$ km. The Ds values where SU transmissions will not lead to harmful interference were estimated using this model.

4.2.5 SU transmission allowance

Simulations were run for all SU power classes to obtain the Ds values when SU transmission results in an interference probability less than 5% at the PU receiver. The results obtained in this analysis were collated and are represented as column graphs[6]

[6]We have not shown the raw results for each SU transmit power class here in order to maintain smooth readability. Please refer to appendix B.1 for these raw results.

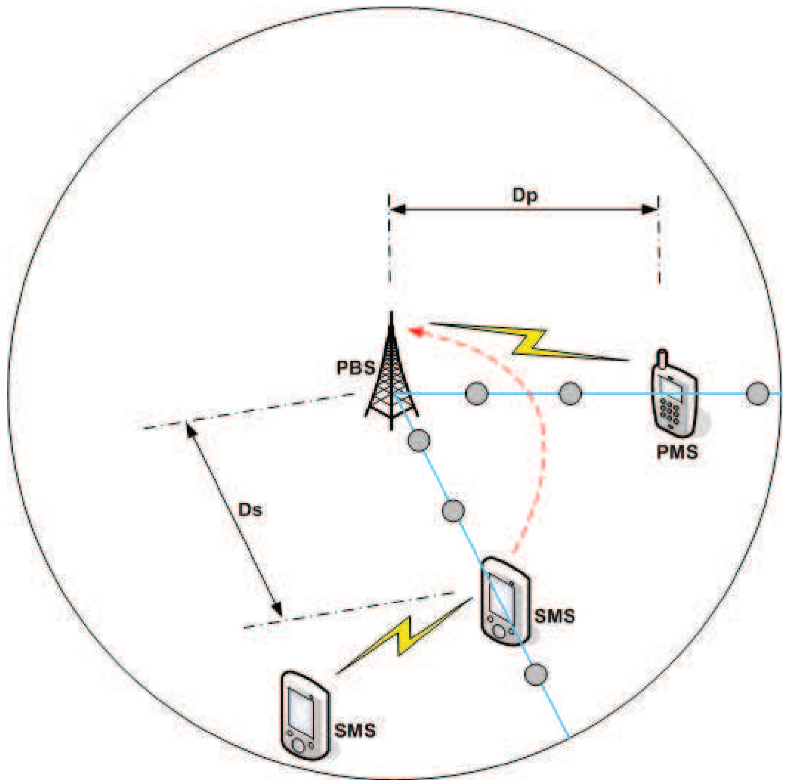


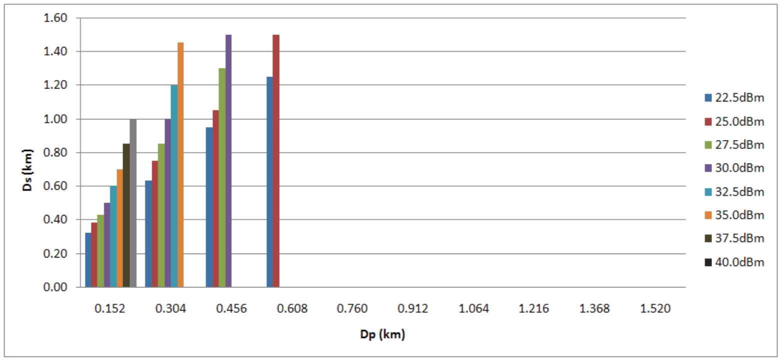
Figure 4.6: System model II

in figures 4.7(a) and 4.7(b) for cases when the PMS transmits at 45dBm and 23dBm respectively. The results indicate that when the PMS is transmitting at 45dBm, the SU can be allowed to transmit provided the PMS is at most 0.608km away from the PBS. The figure also shows the corresponding SU transmission power allowed corresponding to each Ds distance away from the PU. For instance, when PMS is at Dp = 0.608 km, the SU can transmit at 22.5dBm provided it is at least Ds=1.25km away; it can also transmit at 25dBm provided it is Ds=1.50km away.

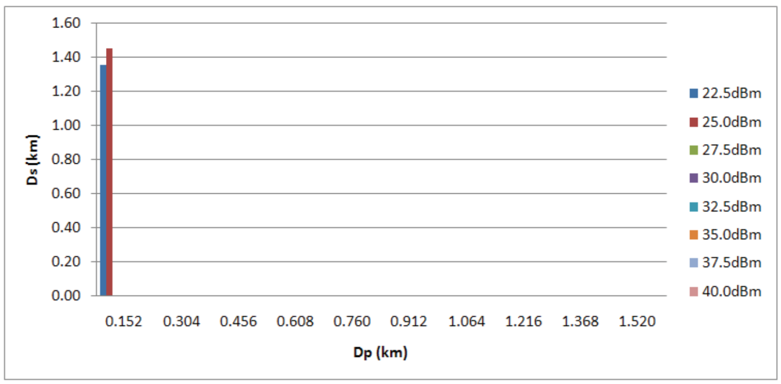
When the PMS transmits at the typical power level of 23dBm, the results shown in figure 4.7 show that the only possibility for SU to transmit is when the PMS is located at most 0.152km away from the PBS. In other words, the PMS has to be very close to the PBS for transmission by the SU to be possible. This indicates a slim chance for SU transmission.

4.3 Case Scenario 2

This represents the scenario where the Downlink(**DL**) frequency of the primary user is used by a secondary user, such that the primary user mobile station (PMS) is the victim receiver which receives wanted signals from the primary user base station (PBS) as well as interfering signals from a transmitting secondary user. In a practical PMR network,



(a)



(b)

Figure 4.7: SU transmission allowance when (a) PMS transmits at 45dBm(b) PMS transmits at 23dBm

the typical BS transmit power is 44dBm. This was therefore used for the analysis in this scenario while we also make use of PU cell radius of 1.52km (since this is required for 95% area coverage - see section 3.4.1.1) and a frequency re-use distance of about 6.966km. We analyzed the interfering link for signals originating from the SU and being received at the PMS. Therefore, a propagation model suitable for links between low antenna height systems was required as the SU and PMS are both handheld devices in this scenario. As a result, we adopted the CEPT SE24 urban model (Appendix A.5) which is used for direct links between low antenna height stations as described in [3]. In the following sections, we present the system models used and results of analysis performed for this case scenario.

4.3.1 System Model I

A system model similar to the model used in scenario 1 was used but in this case, with E0 being the exclusion distance between the SU and a PMS located at the PU cell edge. E1 is the distance between the SU and another PMS operating at the edge of a co-channel cell as shown in figure 4.8. The indicated PMS positions are used in

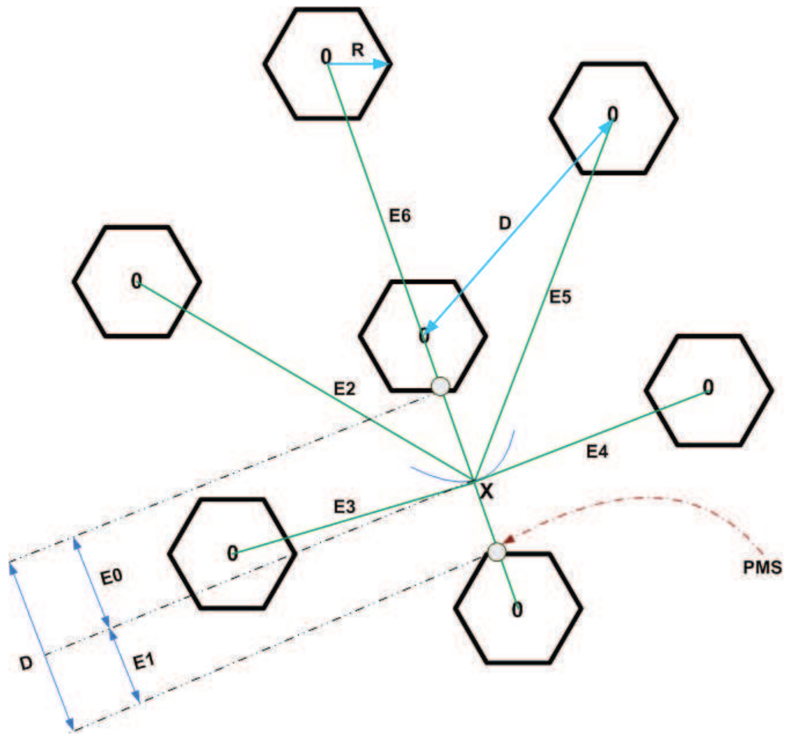


Figure 4.8: System model I (Scenario 2)

this model because these positions represent the worst case where the PMS experiences strongest interference from a SU located at X.

4.3.2 Exclusion distances and Impact on co-channel PU stations

The SU exclusion distances required for acceptable performance of the receiving PMS were obtained as shown in figure 4.9 which also indicates that a higher SU transmit power requires a larger exclusion distance. The result shown in figure 4.9 indicates that the required SU exclusion distance varies between about 1.0 - 2.56km. Again, the impact on a PMS receiving from a co-channel primary user base station was analyzed and we found as shown in figure 4.10 that the SU can transmit with at most 35dBm while maintaining E1>E0 but at higher power levels, E1<E0 indicating that SU cannot transmit at power levels higher than 35dBm under this condition.

Further analysis of a situation where the PMS is located closer to its PBS was explored in order to investigate if there are more possibilities for the SU to transmit at a higher power level.

4.3.3 System Model II

Consider the model shown in figure 4.11 where the PBS is located as shown while the PMS can be located anywhere along within a cell of radius R = 1.52km. Now, this is similar to the model used in case scenario 1 where the distance between the PMS

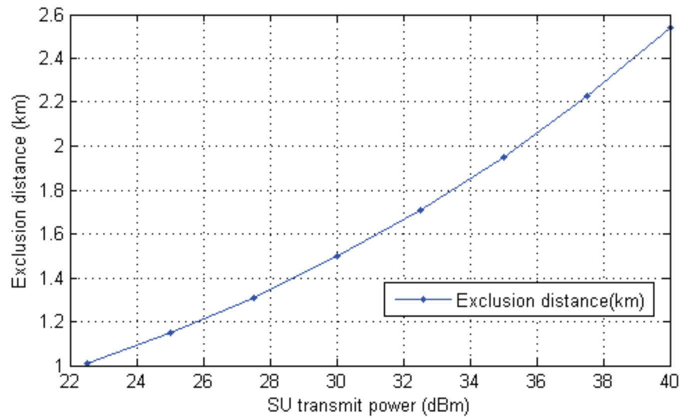


Figure 4.9: Exclusion distances

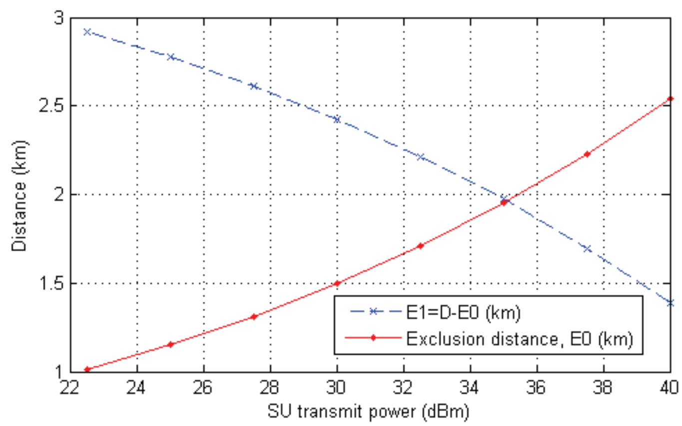


Figure 4.10: SU effect on co-channel PU receivers

and PBS is denoted as Dp. However, the difference with this model is that Ds now represents the distance between the interfering SU and victim PMS receiver as opposed to the previous definition. Dp varies between 0 and 1.52km in steps of 0.152km. At each PMS location, the SU location varies within the range $0 \leq Ds \leq 2.0$km and locations where SU transmissions will not lead to harmful interference were estimated.

4.3.4 SU transmission allowance

The results of this analysis showed that when the PMS is closer to its transmitting PBS, a lot of allowance is given for SU transmission. In this scenario, it is possible for the SU to transmit at power levels as high as 40dBm without harmfully interfering with the receiving PMS. Figure 4.12 shows the locations at which the SU can transmit as well as the corresponding transmit power levels allowed. This outcome shows much more promising allowance for SU transmission than the outcome of scenario 1 where primary user UL frequencies are used.

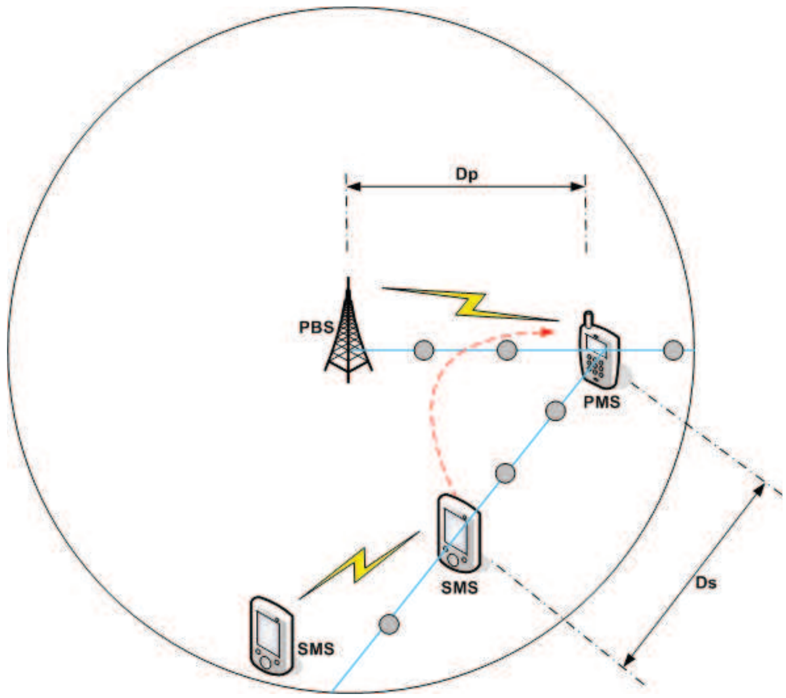


Figure 4.11: System model II (Scenario 2)

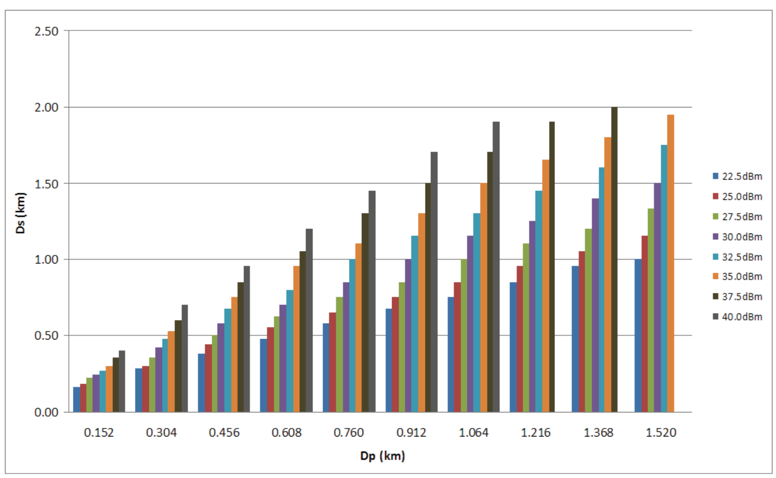


Figure 4.12: SU transmission allowance (Case Scenario 2)

4.4 PMS Location Uncertainty

In the previous sections, conditions for SU transmission in terms of 'where' to transmit and at 'what' power level to transmit were obtained with the valid assumption that the SU can by themselves determine their own location through an in-built Global Positioning System (GPS) locator. However, this analysis also has an implicit requirement for the knowledge of the PMS locations. This however is practically not feasible because the position of these PMS systems cannot be predicted since they are "**mobile**" stations and can therefore be expected to change their positions at any instant. A 'way-out' would have been for the Primary users to announce their positions to the secondary users but this is not an option in this work for the following reasons:

1. PMS announcing their positions will require a communication channel between the PU and the SU. This will result in a large communication overhead between the PMS and the PU as every new location of the PU will need to be updated. One of the motivations of this work is for the SU to intelligently co-exist with the primary user without direct cooperation from the PU.
2. From the primary user's perspective, relaying the user system's position to the secondary users could be a violation of privacy which they will most likely not welcome in a real-life scenario.

The question now will be: "*what then is the way out?*"

Now, suppose we have a PU cell with uniform node distribution, the position of the PMS at any point in time is therefore based on probabilities. Figure 4.13 shows a PU located at X (Dp away from the PBS) and the SU located at point Y (Ds away from the PMS). Based on this model, we find allowed SU transmission power levels and required proximity to the PU that will ensure that probability of interference does not exceed 5%

Considering our model shown in figure 4.13, the probability of SU causing harmful interference to the PU, $Pr(I)$ is a composite of two probabilities:

1. Probability that PMS is located at X, $Pr(A)$
2. Probability that CIR at PMS is less than 19dB, $Pr(B)$

Events 1 and 2 are mutually independent, hence the joint probability, $Pr(I)$ can be represented as follows:

$$Pr(I) = Pr(A) \times Pr(B) \tag{4.10}$$

Where:

$$Pr(A) = \frac{2X^2}{R^2} \tag{4.11}$$

$$Pr(B) = F_C(c) = \frac{1}{2}(1 + erf(\frac{c - (\bar{w} - \bar{i})}{\sqrt{2(\sigma_w^2 + \sigma_i^2)}})) \tag{4.12}$$

It can be deduced from equation 4.11 that the PMS has higher probabilities of being located very close to the cell edge. The model was developed to find conditions under which the SU can transmit such that $Pr(I)$ caused to the PMS does not exceed 0.05. The SU exclusion distances required to satisfy this condition were obtained by

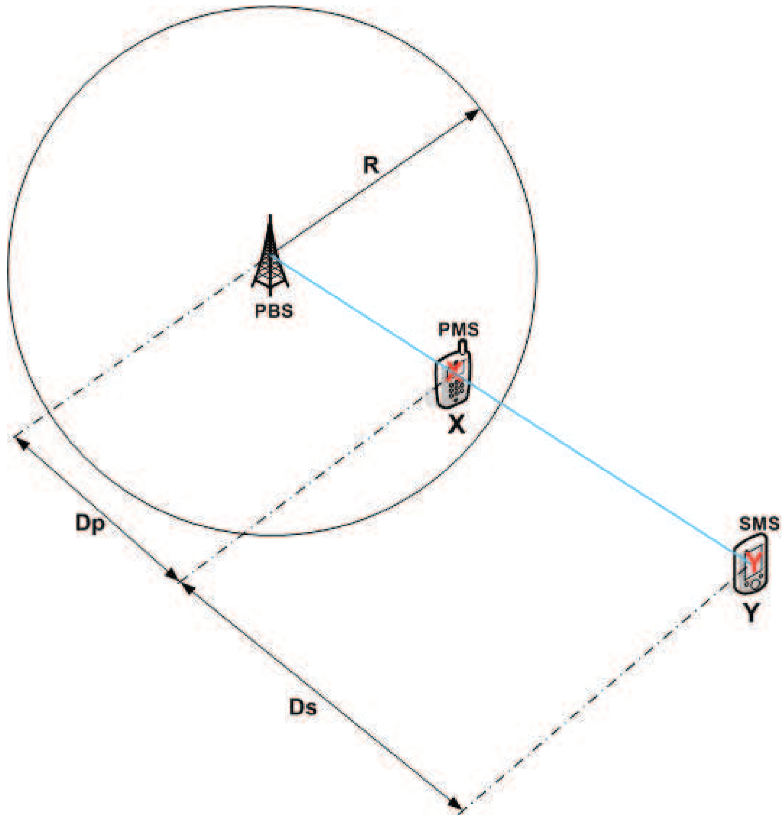


Figure 4.13: PMS location uniformly distributed in PU cell

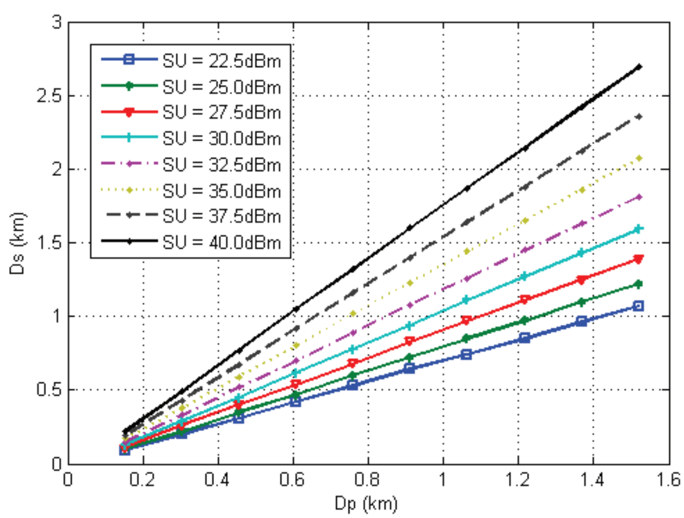
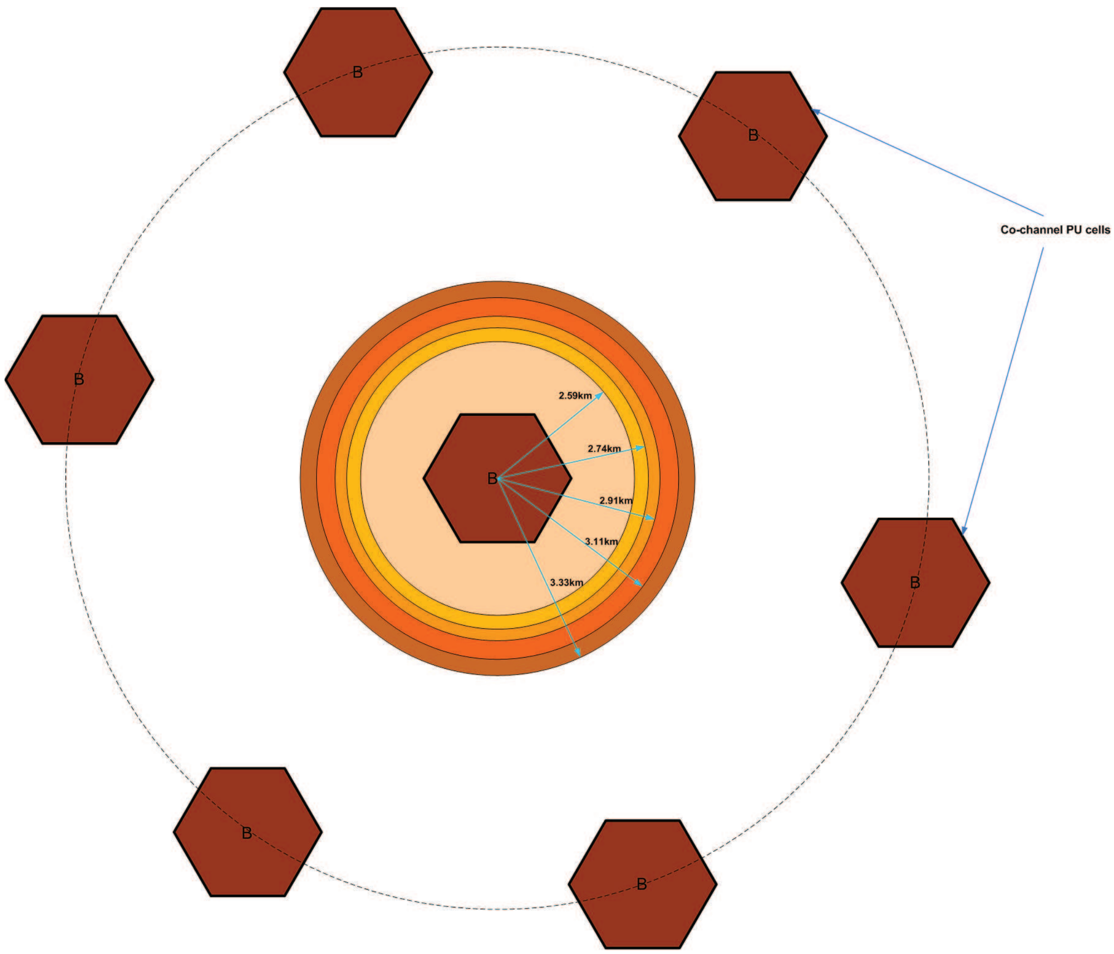


Figure 4.14: PMS location uniformly distributed in PU cell

running a simulation of the analytical model which calculates for each SU power class, distance Ds that will result in a $Pr(I) \leq 0.05$.The results of this simulation as shown in figure 4.14 indicate that when the PMS is located at very close to the cell edge ($Dp \approx 1.4 - 1.5km$) ,the SU systems can still be allowed to transmit at exclusion distances of about 1.0 - 2.8km away from the receiving PMS. This result also indicates the maximum SU transmit power that can be tolerated by the PU depending on the proximity to the SU. For example, figure 4.14 shows that the secondary users can be allowed to transmit at 30dBm provided it transmits at an exclusion distance of 1.6km from a primary user at the cell edge.

If we consider other PMS within the PU network that are located in co-channel cells, we will find from figure 4.10 that an exclusion distance of at least 1.96km is required. We can then deduce from figure 4.14 that this condition is satisfied when SU transmit power is in the range 22.5 - 32.5dBm. This therefore suggests that the maximum transmit power allowed will be 32.5dBm. We can also deduce from figure 4.14 that at SU transmit power of 32.5dBm, the exclusion distance required will be 1.81km. If the locations of the PU base stations are known, the SUs can therefore transmit 3.33 km (1.81+1.52)away from these base stations without causing harmful interference (since the PU cell radius is 1.52km) to the receiving PU mobile stations. This shows that even though PMS locations may be unknown, valid conditions can still be specified under which secondary users can transmit without harmfully interfering with the primary users. Figure 4.15 shows a representation of the regions where SU transmission is prohibited when transmitting at the indicated corresponding maximum power.

The next chapter presents the conclusions that can be drawn from this research study based on the results that have been obtained and carefully analyzed in this chapter.



COLOUR					
MAX SU TX POWER	22.5 dBm	25.0 dBm	27.5 dBm	30.0 dBm	32.5 dBm
EXCLUSION DISTANCE	2.59km	2.74km	2.91km	3.11km	3.33km

Figure 4.15: SU transmission conditions

Conclusions and Recommendations 5

5.1 Conclusions

The current 'command and control' type of licensing process has resulted in tight restrictions in the usage of the frequency spectrum. Although this effectively minimizes interference between systems, it has also resulted in underutilization of the spectrum space. In this work, we analyze a case which addresses spectrum inadequacy of public safety organizations for increasing broadband communication demands - an issue which is currently being deliberated upon within the public safety sector. We consider the option of public safety communication systems' employing cognitive radio technology to aid ***dynamic*** access to underutilized spectrum space belonging to commercial PMR systems as an alternative to the currently deliberated 'Digital Dividend' solution which involves additional access to ***fixed*** spectrum.

The main idea in this study was to explore the feasibility of such public safety communication system making use of additional spectrum space by co-existence within the spectrum licensed to another user system such as the commercial Private Mobile Radio (PMR) systems (as a case example). In such a scenario, the primary users (PU) of the spectrum are therefore the PMR systems while the secondary users (SU) are the public safety systems. The utilization of this spectrum should then be based on specific conditions that will protect the PU systems from harmful interference. We have considered cognitive radios to be the right candidates for implementation in such a scenario. These radios can intelligently detect underutilized spectrum bands and dynamically adjust their transmission parameters with respect to pre-specified regulatory constraints. These regulatory constraints are based on conditions under which the cognitive radios can operate without degrading the operational performance of the primary users of the spectrum they are utilizing.

During this study, we considered a cellular-based primary (licensed) user system and a direct mobile-to-mobile secondary user communication link. The scenarios explored involved the SU utilizing either PU Uplink or Downlink frequencies. We focused on investigating the distance away from primary user receivers (exclusion distance) where secondary user transmission will be possible and the maximum transmit power levels allowable such that target carrier-to-interference ratio (CIR) at the PU is achieved. The implication of this is that the secondary users will have to adjust their transmission power levels based on their proximity to a receiving primary user. We observed that when the PU mobile station is located at the cell edge, there is more possibility of transmission for an SU which transmits with downlink frequencies than an SU transmitting with uplink frequencies. The results showed that with uplink frequency utilization, the SU is not allowed to transmit at all when the PU operates at a typical TETRA handheld transmit power of 23dBm, but when the PU transmits at 45dBm, the SU is allowed to transmit at an exclusion distance of 3.11km and with maximum power level of 22.5dBm. On the other hand, when downlink frequencies are utilized, the SU is allowed to transmit closer to the PU with power levels as high as 35dBm!

When the PU mobile station (PMS) is located closer to its base station (BS), we observed more allowance for SU transmission. We conclude that when utilizing uplink frequencies, SU transmission is only possible provided the PU is not farther than 152m away from its BS and the maximum SU transmit power allowed is 25dBm. However,when utilizing downlink frequencies, SU transmission is possible irrespective of the distance between the PU mobile station and its BS. This implies that the frequency being utilized will have an effect on how much allowance the SU has in terms of its maximum transmit power as well as the allowed proximity to the PU.

These observations showed that the utilization of **downlink** frequencies is more promising for the secondary users. However, we pointed out that when the downlink frequencies are being utilized, the location of the PU mobile stations will be of importance. This is because the PU mobile stations are the victim receivers in such a scenario and the secondary users require knowledge of their proximity to these victim receivers in order to adapt their transmit power levels appropriately. Unfortunately, it is not practically feasible for the secondary users to predict PU mobile stations' locations. We therefore considered a scenario where the PU cell contains uniformly distributed PU mobile stations - these mobile stations have higher probability of being located towards the cell edge. Analysis of this scenario showed that even though the PU mobile station locations are unknown, SU transmission is still possible within the PU spectrum without leading to harmful interference under specified maximum transmit power and minimum exclusion distances.

At this juncture, it is important to point out that despite the fact that these solutions seem attractive, they are not enough to conclude the feasibility of co-existence between the secondary users and primary users - several challenges may be faced in the process. Therefore, further research will need to be carried out before the feasibility of deploying these cognitive radios for use within such a primary user network can be adequately proven. Suggestions for these future research areas are given in the next section.

5.2 Recommendations for Future Research

In this study, finding constraints for cognitive radio operation within a PU network has been an interesting practice. However, we have identifed the following areas for further research:

1. We have focused on considering a single secondary user interferer link operating within the primary user network at a time. Further analysis can be carried out to determine conditions under which multiple SU interferer links can simultaneously use the PU operating frequencies without causing harmful interference.
2. Determining the conditions to govern SU transmission behaviour within the spectrum of a licensed user has been an interesting task but a step further would be to define policy rules based on these conditions. These policy rules may then be embedded in a software platform to run as a policy engine for the cognitive radio.

The SU will therefore, only transmit when it has received permission from the policy engine to do so.

3. The propagation paths may be modeled to suit more realistic and perhaps the more scenario-specific cases as well. In this work, existing propagation models such as Hata model and CEPT SE24 models have been used to predict the propagation losses within the PU and SU networks respectively. For future work, the propagation modelling may be improved to address an unwanted link scenario where a station is receiving from an unwanted transmitter. This will specifically model the propagation paths involved, which we expect to increase the precision of constraints to be specified.

4. In order to reduce the complexity of this work, we have assumed ideal spectrum sensing capabilities of the cognitive radios - which implies that the secondary users can accurately detect the presence or absence of the primary users at any point in time. In reality this assumption is far-fetched, we therefore recommend that in future work, considerations of probabilities of false or missed detections should be incoporated in the analysis.

5. This work has focused on systems which use TETRA technology. It was stated in this report that this technology makes use of Time Division Multiple Access (TDMA) which involves the use of timeslots. This implies that several secondary users can share the same carrier frequency while occupying different timeslots. Future research may therefore involve investigating the regulatory constraints for-timeslot sharing scenario between primary and secondary users.

Appendix A

A.1 CIR estimation at Victim PU Receiver

$$\text{PDF of wanted power, W:} f_W(w) = \frac{1}{\sigma_w\sqrt{2\pi}} exp(\frac{-(w-\bar{w})^2}{2\sigma_w^2}) \quad (A.1)$$

$$\text{PDF of interferer power, I:} f_I(i) = \frac{1}{\sigma_i\sqrt{2\pi}} exp(\frac{-(i-\bar{i})^2}{2\sigma_i^2}) \quad (A.2)$$

From probability theory as explained in [7], if S is a sum of two independent normally distributed random variables w and i (all on dB scale), the probability density function of S will be a convolution of $f_W(w)$ and $f_I(i)$. The pdf of S is therefore:

$$f_S(s) = \int_{-\infty}^{\infty} f_W(w) f_I(c-w) dw \quad (A.3)$$

The basic theorem of fourier transform can be used to resolve this convolution by finding $C_1(\alpha)$ and $C_2(\alpha)$ which are the characteristic functions of w and i respectively. The resulting pdf of S will be the invere fourier transform of the product, $C_1(\alpha)C_2(\alpha)$

$$\begin{aligned} C_1(\alpha) &= \int_{-\infty}^{\infty} e^{j\alpha w} f_W(w) dw \\ &= \frac{1}{\sigma_w\sqrt{2\pi}} \int_{-\infty}^{\infty} exp(j\alpha w - \frac{(w-\bar{w})^2}{2\sigma_w^2}) dw \\ &= exp(j\alpha\bar{w} - \frac{\sigma_w^2\alpha^2}{2}) \end{aligned} \quad (A.4)$$

Similarly,

$$\begin{aligned} C_2(\alpha) &= \int_{-\infty}^{\infty} e^{j\alpha i} f_I(i) di \\ &= \frac{1}{\sigma_i\sqrt{2\pi}} \int_{-\infty}^{\infty} exp(j\alpha i - \frac{i-\bar{i})^2}{2\sigma_i^2}) di \\ &= exp(j\alpha\bar{i} - \frac{\sigma_i^2\alpha^2}{2}) \end{aligned} \quad (A.5)$$

The characteristic function of S is:

$$C_s(\alpha) = C_1(\alpha)C_2(\alpha)$$

Therefore,

$$f_S(s) = \frac{1}{2\pi}\int_{-\infty}^{\infty} C_1(\alpha)C_2(\alpha)e^{-j\alpha c}d\alpha$$

$$\begin{aligned}
f_S(s) &= \frac{1}{2\pi}\int_{-\infty}^{\infty} exp(j\alpha\bar{w} - \frac{\sigma_w^2\alpha^2}{2})exp(j\alpha\bar{i} - \frac{\sigma_i^2\alpha^2}{2})exp(-j\alpha c)d\alpha \\
&= \frac{1}{2\pi}\int_{-\infty}^{\infty} exp(-\frac{\alpha^2}{2}(\sigma_w^2+\sigma_i^2) + j\alpha(\bar{w}+\bar{i}) - j\alpha c)d\alpha \\
&= \frac{1}{\sqrt{2\pi(\sigma_w^2+\sigma_i^2)}}exp(\frac{-(s-(\bar{w}+\bar{i}))^2}{2(\sigma_w^2+\sigma_i^2)})
\end{aligned} \tag{A.6}$$

However, in our scenario we have the Carrier-to-Interference Ratio as the ratio between the wanted power and the interfering power . Therefore we are are dealing with the difference between two independent normally distributed random variables w and i

$$C(dB) = W(dB) - I(dB)$$

Therefore,

$$f_C(c) = \frac{1}{\sqrt{2\pi(\sigma_w^2+\sigma_i^2)}}exp(\frac{-(c-(\bar{w}-\bar{i}))^2}{2(\sigma_w^2+\sigma_i^2)}) \tag{A.7}$$

where

$$\sigma = \sqrt{\sigma_w^2+\sigma_i^2}$$

A.2 Area Coverage and Boundary Coverage

The figure below shows a family of curves relating percentage of total area coverage to the probability of received signal at the boundary rising above the wanted threshold level(boundary coverage). This relationship is a function of the path loss exponent and the standard deviation of the variation due to lognormal shadowing. This figure was used to derive the required cell radius and frequency re-use distance for the primary user network used in our case scenario. With σ = 6dB and n = 3.5, $\sigma/n \approx 1.7$ the figure shows that for a total area coverage of 95% requires a 75% boundary coverage.

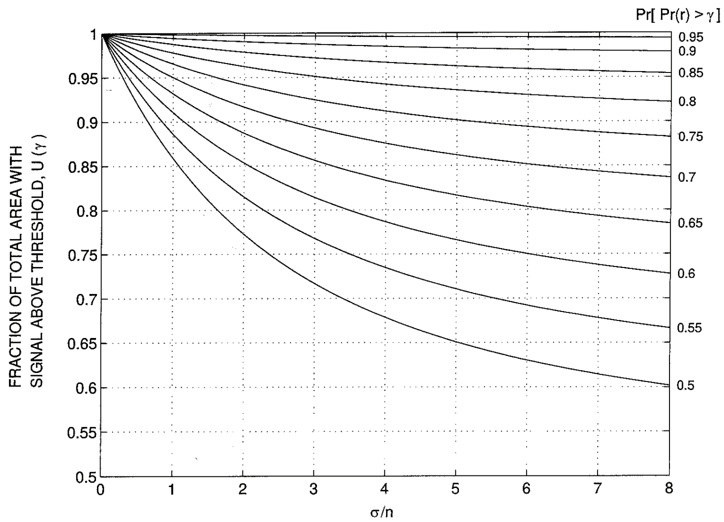


Figure A.1: Family of curves relating fraction of total area with signal above threshold (area voverage) to the probability of signal above threshold on the cell boundary (boundary coverage)[27]

A.3 Main TETRA Parameters

The main parameters of TETRA technology as found in [13] are given in the table A.1

A.4 Hata Model

The Hata Model which is also known as the Okumura-Hata model (since it is a developed version of the Okumura Model), is the most widely used radio frequency propagation model for predicting the behaviour of cellular transmissions in built up areas. This model implicitly considers the effects of diffraction, reflection and scattering caused by city structures. This model also has three variants which are suited for transmission

Table A.1: Main Parameters for TETRA

Channel Spacing	25kHz
Modulation	$\pi/4 - $DQPSK
Modulation rate	36kbps
Number of bits per symbol	2
Voice Coder Rate	ACELP (4.56kbps net)
Access format	TDMA with 4 timeslots/carrier
User data rate	7.2kbps per timeslot
Maximum data rate	28.8kbps
Protection data rate	Up to 19.2kbps

in Urban, Suburban Areas and Open Areas. In this work, the Hata model for Urban areas was used in finding the path loss along the wanted link as:

$$L = 69.55 + 26.16 \log f - 13.82 \log h_B - A_h + (44.9 - 6.55 \log h_B) \log d \tag{A.7}$$

$$A_h = 0.8 + (0.1 \log f - 0.7)h_M - 1.56 \log f$$

where, h_B = height of base station antenna (unit: meters(m))
h_M = height of mobile station antenna (unit: meters(m))
f = frequency of transmission (unit: Megahertz (MHz))
A_h = antenna height correction factor
d = distance between the base and mobile stations (unit: Kilometers(km))

A.5 CEPT SE24 Model

The CEPT SE24 model was adopted from the ERC report [1] to find the path loss along the interfering link in scenario 2 (use of PU downlink frequencies) since this describes a direct link between two mobile stations. This propagation model was first proposed in ITU-R Recommendation model SM. 329-6 [29], afterwhich it was used in the compatibility studies studies described in ERC Report 68 [1]. It incorporates antenna heights and has been modified to suit cases where antenna heights are below 10m. This propagation model is valid for frequencies between 150 MHz and 1500 MHz. The propagation loss is derived as:

$$L = 69.6 + 26.2 \log f - 13.82 \log h_{tx} - a(h_{rx}) - a(h_{tx}) + (44.9 - 6.55 \log h_{tx}) \log d \tag{A.6}$$

Where:

$$\begin{aligned} a(h_{tx}) &= (1.1 \log f - 0.7)\text{Min}(10, h_{tx}) \\ &\quad - (1.56 \log f - 0.8) + \text{Max}[0, 20 \log \frac{h_{tx}}{10}] \\ a(h_{rx}) &= (1.1 \log f - 0.7)\text{Min}(10, h_{rx}) \\ &\quad - (1.56 \log f - 0.8) + \text{Max}[0, 20 \log \frac{h_{rx}}{10}] \end{aligned} \tag{A.5}$$

Appendix B

B.1 Raw Results

This section shows the raw results from the analysis performed to determine the required SU exclusion distances under the following conditions in the order in which they are presented:

1. **Case Scenario 1**; PMR transmitting at 45dBm
2. **Case Scenario 1**; PMR transmitting at 23dBm
3. **Case Scenario 2**; PBS transmitting at 44dBm

In general, the figures indicate the exclusion distances required to be satisfied by the SU for transmission to be permitted without harmfully interfering with the PU. The horizontal axis represents distance between the PU and SU while the vertical axis represents CIR at the receiving PU base station in figures B.1 and B.2 and CIR at the receiving PU mobile station in figure B.3. Each curve represents the results obtained for each PMS position relative to the PBS. For each of these positions, the points on the horizontal axis where the CIR at the receiving PU station is exactly 19dB represent the exclusion distances. Each figure depicts exclusion distance required for each SU power class possible.

These results were collated and made into column graphs as represented in sections 4.2.5 and 4.3.4 of chapter 4.

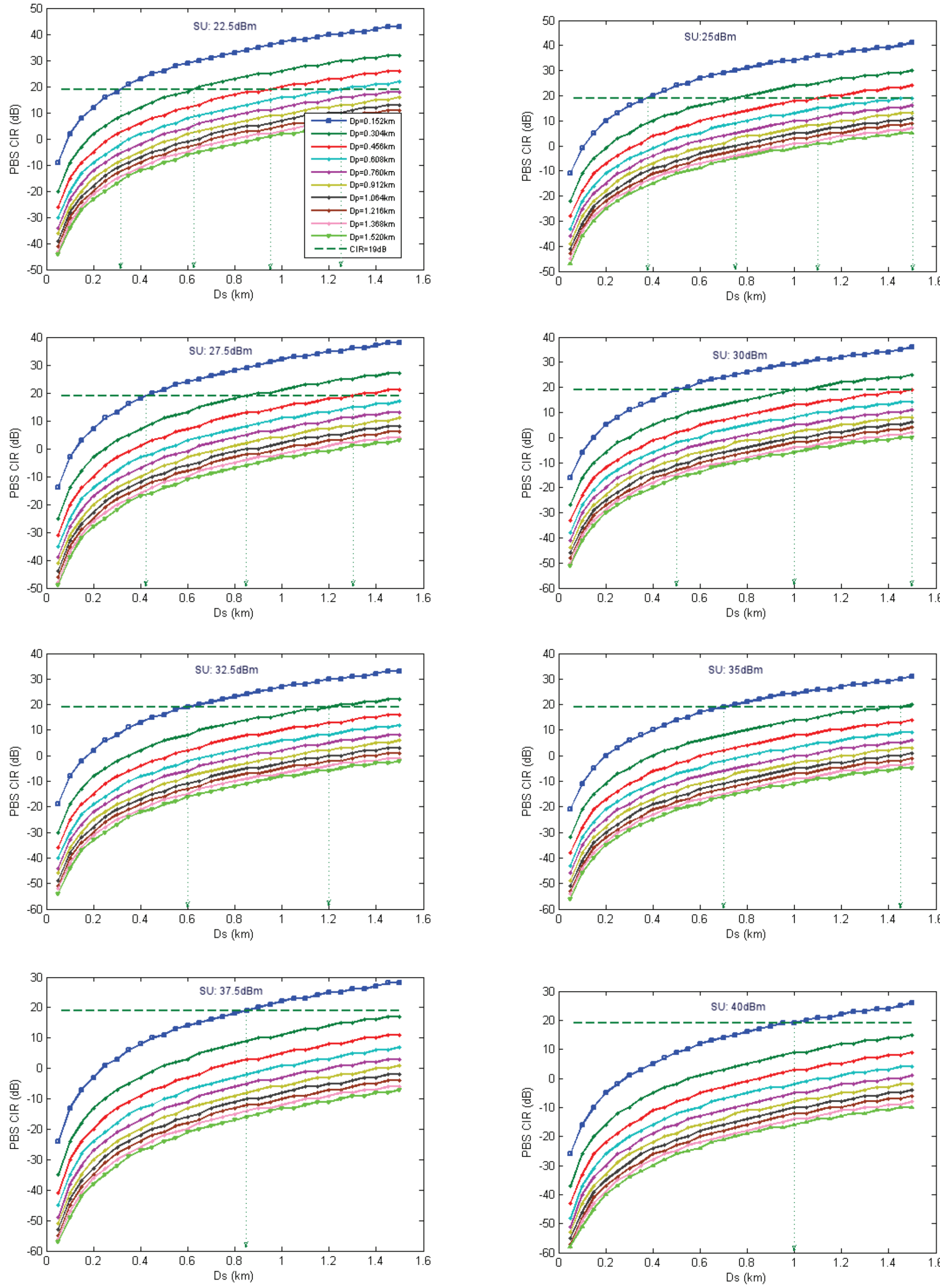


Figure B.1: Case Scenario 1; PMR transmitting at 45dBm

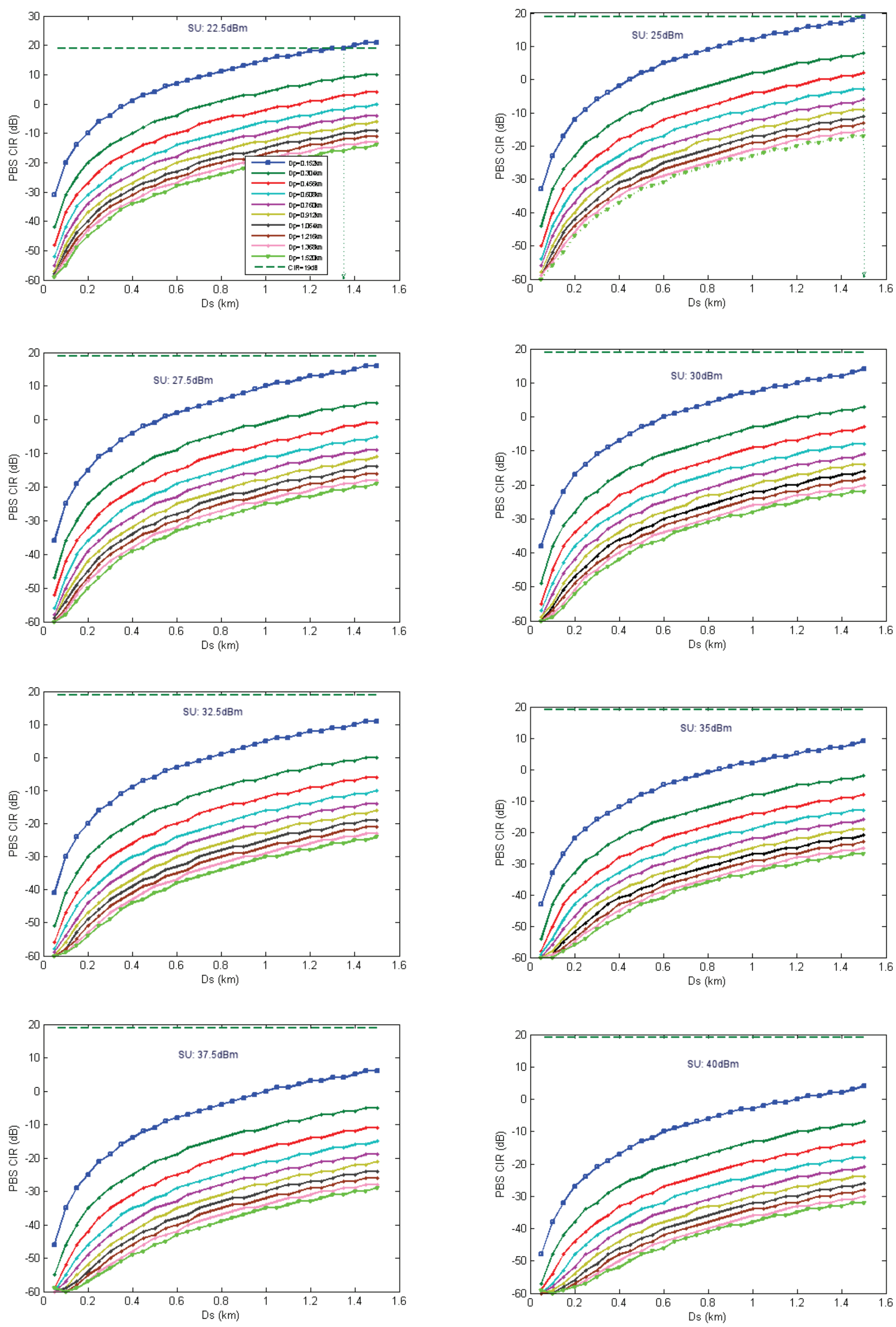


Figure B.2: Case Scenario 1; PMR transmitting at 23dBm

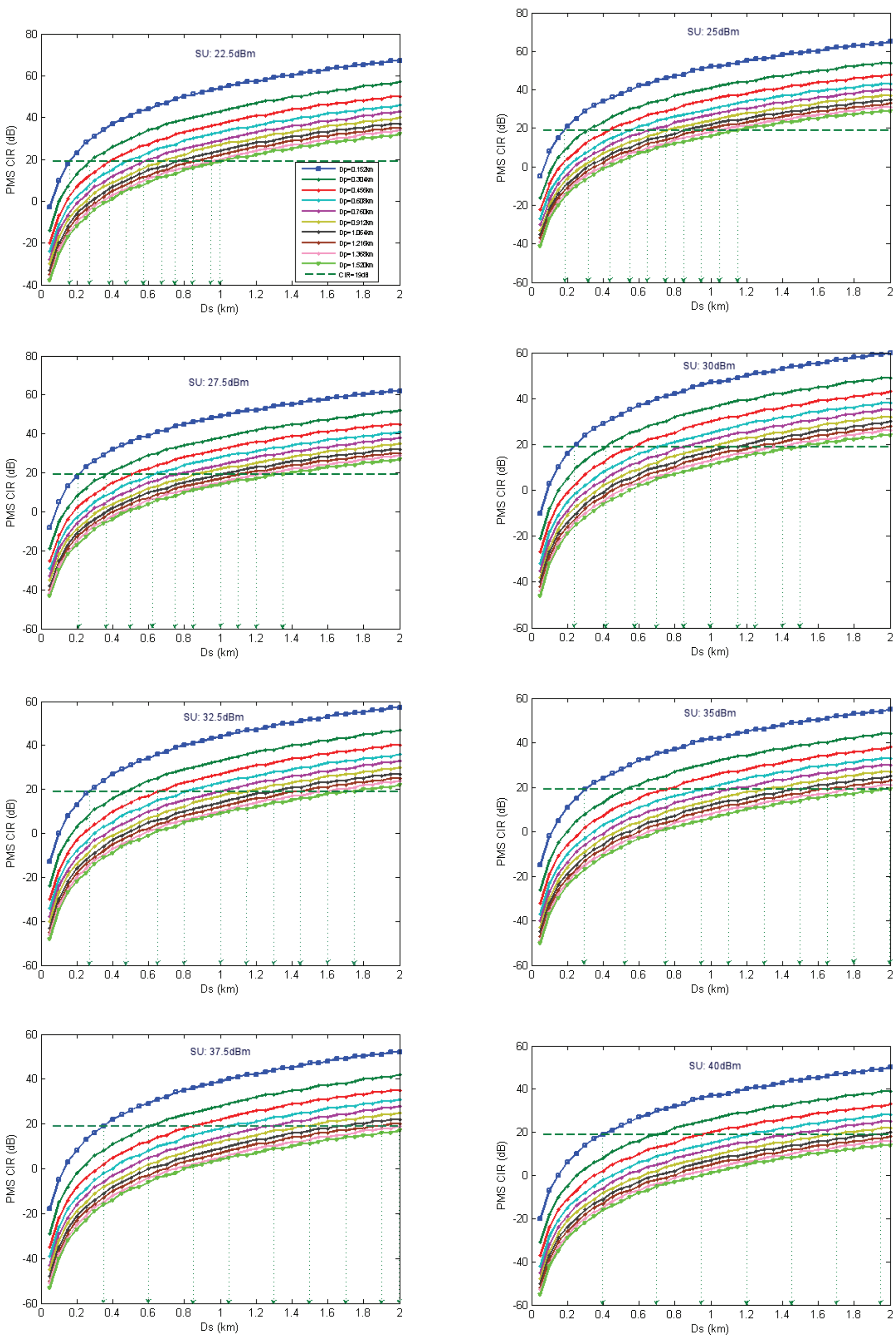


Figure B.3: Case Scenario 2; PBS transmitting at 44dBm

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