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Cognitive Radio Systems in LTE Networks

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By

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Abstract

The most important fact in the mobile industry at the moment is that demand for wireless services will continue to expand in the coming years. Therefore, it is vital to find more spectrums through cognitive radios for the growing numbers of services and users. However, the spectrum reallocations, enhanced receivers, shared use, or secondary markets-will not likely, by themselves or in combination, meet the real exponential increases in demand for wireless resources. Network operators will also need to re-examine network architecture, and consider integrating the fibre and wireless networks to address this issue. This thesis involves driving fibre deeper into cognitive networks, deploying microcells connected through fibre infrastructure to the backbone LTE networks, and developing the algorithms for diverting calls between the wireless and fibre systems, introducing new coexistence models, and mobility management. This research addresses the network deployment scenarios to a microcell-aided cognitive network, specifically slicing the spectrum spatially and providing reliable coverage at either tier. The goal of this research is to propose new method of decentralized-to-distributed management techniques that overcomes the spectrum unavailability barrier overhead in ongoing and future deployments of multi-tiered cognitive network architectures. Such adjustments will propose new opportunities in cognitive radio-to-fibre systematic investment strategies. Specific contributions include:

1) Identifying the radio access technologies and radio over fibre solution for cognitive network infrastructure to increase the uplink capacity analysis in two-tier networks.
2) Coexistence of macro and microcells are studied to propose a roadmap for optimising the deployment of cognitive microcells inside LTE macrocells in the case of considering radio over fibre access systems.
3) New method for roaming mobiles moving between microcells and macrocell coverage areas is proposed for managing spectrum handover, operator database, authentication and accounting by introducing the channel assigning agent entity. The ultimate goal is to reduce unnecessary channel adaptations.

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Author’s Declaration

I hereby declare that the research recorded in this thesis and the thesis itself was composed and originated entirely by myself in the Wireless Networks and Communications Centre (WNCC) at Brunel University. I also certify that all the information sources and literature used are indicated in the thesis.

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List of Abbreviations

21CN	21st Century Network
AC	Access Category
AIFS	Arbitration Inter-Frame Space
AIFSN	AIFS Number
AP	Access Point
AR	Access Router
ASE	Area Spectral Efficiency
B3G	Beyond the third Generation
BER	Bite Error Rate
BS	Base Stations
BT	British Telecom
BW	Bandwidth
CAA	Channel Assigning Agent
CAK	Channel-Adaptation-acKnowledgement
CAP	Channel-Adaptation
CAR	Channel-Adaptation-Request
CBS	Central Base Station
CDMA	Code Division Multiple Access
CMN	Cognitive Mesh Network
CMT	Cell Migration Time
CN	Correspondent Node
CRAHN	Cognitive Radio Ad-Hoc Network
CRN	Cognitive Radio Network
CRoF	Cognitive Radio over Fibre
CSCC	Common Spectrum Control Channel
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CW	Contention Window
DCF	Distributed Coordination Function
DHCP	Dynamic Host Configuration Protocol
DIFS	DCF Inter-Frame Space
DL	Downlink

DL-SCH	Downlink- shared channel
DSA	Dynamic Spectrum Access
DSE	Dependent Station Enablement
EDCA	Enhanced Distributed Coordinated Access
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FFT	Fast Fourier Transform
FMIPv6	Fast Handover in MIPv6
FTTH	Fibre-To-The Home
GSM	Global System for Mobile Communications
HA	Home Agent
HCS	Hierarchical Cell Structures
IETF	Internet Engineering Task Force
IFS	Inter-Frame Space
IP	Internet Protocol
ISD	Inter-Site Distance
ISM	Industrial, Scientific and Medical
IUT	International Telecommunication Union
LSC	List of the Candidate Channels
LTE	Long Term Evolution
LTE-A	Long Term Evolution-Advanced
MAC	Medium Access Layer
MANET	Mobile Ad–Hoc Network
MCS	Modulation Coding Scheme
MFNN	Multilayer Feedforward Neural Networks
MIMO	Multiple-Input Multiple-Output
MIPv6	Mobile IPv6
MME	Mobility Management Entity
MTU	Maximum Transmission Unit
NNs	Neural Networks
NO	Network Operator
NUC	Number of Candidate Channels
OFCOM	Office of Communications

OFDM	Orthogonal Frequency-Division Multiplexing
PHY	Physical
PR	Primary
PRB	Physical Resource Blocks
QoS	Quality-of-Service
RAT	Radio Access Technology
RBS	Remote Base Station
RF	Radio Frequency
RoF	Radio over Fibre
RRM	Radio Resource Management
SB	Spectrum Broker
SCFDMA	Single-carrier Frequency-Division Multiple Access
SDR	Software-Defined Radio
SH	Spectrum Handover
SLS	Spectrum Load Smoothing
SM	Service Manager
SNR	Signal-to-Noise-Ratio
SON	Self-Organisation Network
SP	Spectrum Server
SPPP	Spatial Poisson Point Process
TBs	Transport Blocks
TCP	Transmission Control Protocol
TTI	Transmission Time Interval
UDP	User Datagram ProtocolF
UE	User Equipment
UL	Uplink
UL-SCH	Uplink- shared channel
USUC	Urgent Secondary Users Coexistence
VoIP	Voice over Internet Protocol
WG	Working Groups
WLAN	Wireless Local Area Network
WLANoF	Wireless LAN over Fibre
WRAN	Wireless Regional Area Networks

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Chapter 1

Introduction

1.1 Motivation

The Cognitive Radio over Fibre (CRoF) is proposed as a new technology solution to overcome the problem of spectrum unavailability through multi-access radio terminals with landline connections. The CRoF architecture is based on using the Radio over Fibre (RoF) to connect cognitive base stations. In this way, the new CRoF stations can choose to transmit to each other via fibre whenever they fail to formulate wireless links. One application of the CRoF system is the cognitive microcells. These CRoF microcells are positioned inside the primary macrocell coverage areas and in coexistence with the primary Base Stations (BSs). Accordingly, CRoF system would be able to utilise local spectrum holes efficiently, trade resources easily with primary networks, achieve reliable and short communications, and provide higher throughput to the secondary users [1 - 3].

Network Operator (NO) of the wireless Beyond the third Generation (B3G) era will need to be directing terminals to the most appropriate radio networks of its heterogeneous infrastructure. This requires advanced terminal management functionality for conducting optimal network selections, in a seamless to the user manner [4]. Although very few studies for an infrastructure enhanced secondary usage of spectrum can be found in the literature, some recent work has the potential to be adopted for such use. A good example is Code Division Multiplex Access CDMA-based Hierarchical Cell Structures (HCS) in which macrocell and microcell layers are sharing the same frequency band [5].

The links of Cognitive Radio Networks (CRNs) are generally opportunistic, asymmetric, or unidirectional, which creates challenges to feedback real-time and perfect information from the destination to the source (e.g., ACK). The opportunistic and unidirectional link is a special nature of CRN. Considering a link between CR node A and CR node B in CRN, node A having an opportunity to transmit to node B in certain time duration does not warrant an opportunity for node B to transmit back to node A [6] or even giving any feedback such as acknowledging packets. Obviously, only heterogeneous networks consisting of optical and wireless networks can respond to the requirements of the evolution of such a diverse mobile coexistence in future networks. Although, Cognitive radio over fibre techniques is not the first system that combines microcells services through fibre, its novelty is coming from exploiting the local spectrum holes of the allocated spectrum [7 - 9].

The all-important requirements of portability can be improved by the use of microcells. A microcell is a region served by a radio base unit, just as in current cellular systems, only smaller in area by one-to-two orders of magnitude [10]. There were different architectures presented for the radio-over fibre linking to the microcellular system. In one model, an optical source at the BS is shared between all microcells. Also, the coverage of each microcell is much smaller than that of the present macrocell so that the power consumption and size of the handset could be reduced significantly [11]. These logistics of application are incorporated with cognitive systems in order to achieve new models for cognitive network deployment with lower impacts on the current networks in operation.

1.2 Challenges

The rising demand in wireless communication for free available spectrum goes along with the challenges of managing the network access to spectrum utilisation, i.e., Quality-of-Service (QoS) requirements, as for instance in delivering services at high interruption loss. Efforts such as the EU-FP7 FARAMIR, CREW, and COST-TERRA projects [12 - 14] indicate the level of activity in the field which has the potential to develop an architecture that can be extended to include hybrid networks that are able to support both cellular type of operations and ad-hoc type of operations. The system architecture considers coordination between the different networks and elements that share the available spectrum. These approaches allow cognitive radios to support and guarantee QoS when sharing channels without requiring direct information exchange in observing past spectrum utilisation. The motivation comes from the major regulators in the USA and UK, Federal Communications Commission (FCC) and the Office of Communications (OFCOM), who have released many evaluations for the spectrum usage by TV broadcasters. These reports show a considerable "White Spaces" in the spectrum without any usage of the related frequency band by broadcasters. Particularly, in the area around and between major cities where the usage of the related bands by secondary spectrum access approaches can be envisaged [15, 16]. One key concern is to evaluate the expected amount of spectrum available to secondary users in dynamically changing wireless environments. The answer varies significantly according to the scenarios of application and the approach of establishing connections between the anticipated end-users and the access network.

The driven force behind this concern is that operators have limited flexibility when it comes to capacity step-upgrades to meet future demand. Inventors have pushed the efficiency of mobile technologies near to theoretical limits. Some gains are still possible, with the cognitive radio depending on the starting point, but much more than this is very difficult (or expensive). Spectrum is also limited and only becomes available infrequently when auctions are held. Even the most optimistic plans for spectrum release would only double the holdings for cellular networks so at best another factor of two gains. So relying on small-cell solutions will emerge as there are no other options for meeting capacity requirements.

At the heart of these challenges, lies the ability to exploit the best future for a country's wireless communications infrastructure and efficient resource management. In the UK, there is no organisation in charge with doing this - the regulator OFCOM is the closest the industry that has a national custodian for policy change. This is exactly the issue tackled in this work where the new models of cognitive radio networks are studied and evaluated with a particular attention to emerging radio access technologies and systematic performance.

1.3 Scenarios and Assumptions

The spectrum availability is a decisive factor for the continuity of CRN continuity of transmission. Cognitive networks lease the spectrum temporarily whenever the primary users are inactive. Thus, localised wireless changes within CRN cells rapidly affect the transmissions of the cognitive radios. This situation becomes more complicated for cognitive mesh networks when establishing a multi-hop link. Therefore, link formation failure may cause complete disruption at certain sites of the network. A mathematical model is first introduced to study the delay impacts of the spectrum unavailability in the cognitive mesh network which has been analysed as the most severe cause for the transmission failures.

The use of cognitive over fibre microcells to support cognitive mesh networks is a brand new idea. Therefore, none of the literature quantitatively addresses the impact of using alternative landline connections in the secondary networks such as the changes in the network architecture, cognitive practical capacity, balancing services and the quality of the data coverage. This thesis starts by achieving of robust local resources sharing using a developed Medium Access Layer (MAC) layer for efficient spectrum utilisation and less heterogeneous complexity that lead to the development of new algorithms of users' coexistence and Internet Protocol (IP) mobility managements. This reduces the collision in services due to primary users' activities by addressing the following questions:

i. What are the necessary modifications to the cognitive mesh network to achieve multi–tiered cognitive network with CRoF installation?
ii. What is the optimal number of CRoF microcells that can be installed inside LTE macrocell?
iii. How to arrange the spectrum coexistence of the new installed CRoF microcells with primary users transmitting in the existing band-channels?

To answer these questions, various CRoF radio access technologies are investigated for possible deployment in microcells. This provides a clear vision for network planning in the initial steps for cognitive network emergence. Then, new techniques for understanding the limits of cognitive users' numbers that can be served are identified under certain spectrum availability assumptions. In this regard, two approaches namely: Space Filling and Time Filling are proposed for sharing resources. Firstly, in space filled, cognitive microcells would be able to control and adapt their coverage areas from inter-lapping with each other. Practically, a cognitive macrocell is located amongst other microcells with different levels of awareness and independence, where any channel can be used by different non-adjacent microcells using the frequency reuse principles. Secondly, the microcells are installed randomly throughout the macrocell where their coverage areas can overlap and spectrum is used by all microcells as one common pool. In this regards, spectrum load smoothing is used to analyse the capacity of different Wireless Local Area Network (WLAN) and Long Term Evolution (LTE) base stations as an approach for exploring the number of stations that can coexist in a certain cell size.

The CRoF technology that installs microcells connected via fibre to the main macrocell station raises many questions about the validity of the CRoF solution because of the dynamic adaptation between channels named as Spectrum Handover (SH) for cognitive mobile users moving at different speeds. The handover here is not just a registration with a new operator station, but it is also a negotiation to get access to the available channels locally in coexistence with the primary users. Therefore, it is necessary to develop a new scheme for roaming new mobiles moving between microcells and macrocell coverage areas to reduce unnecessary channel adaptations. This is necessary to validate the applicability of the proposed CRoF technology for the next-generation network applications.

1.4 Aims of Research

Since the research presented in this thesis tackles multiple issues, the aims are multi-fold:

1. Considering a macrocellular scenario where users communicate in an orthogonal manner enabling local access to the spectral ranges at shorter links without interfering actual license owners. For the first time, our analysis attempts to quantify the achievable gain for various CRoF Radio Access Technologies (RATs) with respect to classical radio devices. In order to do so, a call diversion algorithm is introduced for diverting calls

between different microcellular and macroculler domains through landline network.

2. The coexistence of LTE macro and WLAN microcells is addressed to propose a policy for optimising the deployment of cognitive microcells inside macrocells in the case of considering radio over fibre access systems. The goal is to set limits for equipment density installation as a function of the free spectrum transmission opportunities, which is believed to be potential success factor for future cognitive radio network deployment and offer insights into how to design CRoF architecture. To LTE, a new algorithm for scheduling durations is proposed to improve spectrum access. To WLAN, a new transmission adaption scheme is proposed to discover new surrounding installed microcells and adapting the transmission domain features.
3. Where the cognitive radio behaviour is generalised to allow secondary users to transmit simultaneously with the primary system. Specifically, CRoF microcells are combined with multi-user diversity technology to achieve strategic spectrum sharing and self-organising communications through managing the mobility at various end-users speeds. In this field, the Channel Assigning Agent (CAA) is introduced in this thesis to allocate the same channel used by a cognitive mobile user as long as possible. This will prevents service interruption resulted from unnecessary spectrum handovers. The problem of congestion management due to the CAA installation is addressed to analyse the impacts of allocating channels on user selection strategy. More development for the channel allocation using multi-zoned network domains is proposed for future analysation and research.

1.5 Cognitive Radio over Fibre Solution

Restoring cognitive network services cannot be performed using the traditional procedures for link re-formulation in mobile communications. This is due to the dynamic nature of the spectrum holes’ availability, auction schemes on resources, and the reconfiguration methods to access resources. Therefore, a permanent solution is necessary to guarantee the transmission of the future cognitive mesh network. Thus, the most realistic solution is to combine the CMNs with the landline networks. This expands the broadcast options for the cognitive network in order to attain reliable delivery services. The fibre network is proposed as the promising landline technology for this new hybrid cognitive-to-landline arrangement. As a matter of fact, fibre networks are re-gaining high interest for their multiple product advantages, such as high bandwidth, low power consumption, and low cost. Furthermore, many undergoing projects are currently investigating the advantages for delivering many services via fibre networks. For example, the British Telecom (BT) 21st Century Network (21CN) programme [17], and the Japanese national institute of information and communications technology Fibre-To-The Home (FTTH) projects [18].

The integrated connection between the fibre network and the cognitive base stations can be easily made and in a cost effective way. This combination is named Cognitive Radio over Fibre (CRoF). This CRoF system is using the radio over fibre as the alternative land line connection between the new CRoF base stations in case of not being able to formulate a wireless link. Radio over fibre technology gives a lot of advantages, such as moving the complicated signal processing to the Central Base Station (CBS) location, therefore the overall system is cost effective and the Remote Base Station (RBS) is very simple, passive and compact (therefore it is transparent and its maintenance is easy). Such system is very cost–effective because of localisation of signal processing in CBS and also because the Base Station is simple. The reliability of the system is high due to the simple and passive structure of the RBS. This system can easily serve densely populated areas, such as shopping malls and airports, dead-zone areas and highways can be covered efficiently and economically. The system can also support multiple wireless standards. Because of the high bandwidth nature of optical fibre, Broadband services are more feasible using this technology [19]. For all the above mentioned reasons, the integration of optical and wireless systems is considered to be one of the most promising solutions for increasing the existing capacity and mobility as well as decreasing the costs in next-generation optical access networks [20]. Radio-over-Fibre is a suitable technology to provide a cost-effective solution for delivering high data rates, as well as for extending the range of the existing wireless access networks. The remotely located BSs are interconnected via a Central Office (CO) is using a low-loss optical fibre network [21]. Frequency independent low fibre loss, high bandwidth, and increasing availability of low-cost optoelectronic and RF integrated components are the major drivers for fibre optics RF solution [22]. Several key enabling technologies for hybrid optical-wireless access networks are raised by [20], including optical millimetre-wave (mm-wave) generation, up-conversion, transmission in a downlink direction, and full-duplex operation based on wavelength reuse by using a centralised light source in an uplink direction.

The CRoF system concepts need to develop a new radio that is equipped with fibre connections. The anticipated CRoF radio is an extended version for Mitola’s cognitive radio. Such an extension includes extra physical portals for accessing landlines and transferring signals on-time from wireless to wired modulation forms. This operation occurs whenever the CRoF radio failed to formulate a wireless link. This process should not take long time intervals during conversions in order to keep real time broadcasting between terminal handsets. This development can be done only by very powerful software programmable transceiver units that can adapt on demand promptly. The other major adjustment in the CRoF radio is to extend the intelligence of the cognition machine. This allows the CRoF radio to make on-time decisions and choose the efficient link between wireless and fibre connections. The extended cognition engine also helps to explore the surrounding wireless environment to select between the available short and long wireless links and fibre connections. All these transmission assessment challenges must be performed by this extended cognition engine. Actually, these modifications may impact the computational complexity of the suggested CRoF radio and increase the time of processing for various communication attempts. However, a small comparison between the pros and cons of the CRoF radio shows that the outcomes of the new radio system are much higher than setback factors as shown in later chapters. The most interesting thing about the CRoF is the high reliability in delivering the data, which is the main problem that cognitive radio is suffering from.

1.6 Contributions to the Knowledge

In this thesis, a roadmap is defined for installing the future cognitive radio network for efficient access to the spectrum and posing several constraints in the management and strategies for creating novel architecture using multiple access system. Within this setting, different system models are considered in which cognitive users compete for a chance to transmit simultaneously with the primary system. On the basis of these models, a specific resource allocation problem is defined to order insight how to design local access systems in a cognitive radio network environment. We initially integrate the cognitive wireless systems to the radio over fibre network to create a new access system namely as Cognitive Radio over Fibre (CRoF) to allow flexible selection for the transmission media and narrowing transmission wireless domains throughout the mesh network. Within this setting, a base station transmits over a certain time or frequency band only when no other user does and can choose to communicate through fibre with other stations to avoid major transmissions interruptions if the primary user returns to use its licensed band. Next, the CRoF concept is extended to include cognitive microcellular domains that transmit simultaneously in coexistence with the primary user over the same frequency band. This is performed as long as the level of interference with the primary user remains within an acceptable range and to slice the macrocellular area as a function for the spectrum availability. New schemes are investigated for allocating channels at different CRoF - RATs systems and user selection in a network consisting of multiple secondary transmitters and receivers communicating all together in the presence of the primary system. The emphasis is on the capability of the proposed approach to allow cognitive devices to support and guarantee QoS for the future Internet applications, while sharing spectrum. The main concern is to design a secondary heterogeneous network that does not interfere with existing licensed services.

In Chapter 2, the known architectures for cognitive networks are presented with the essential characteristics for dynamic spectrum interruption loss. The different performance metrics of different models are studied to develop the proposed system models and the assumptions used throughout most of this thesis. The coordination of spectrum sharing is considered in which the primary and the cognitive user wish to communicate, subject to allocation schemes and entities. The setback of the current proposals for cognitive network modelling is served by focusing on maintaining connections and service delivery. A mathematical model is proposed to analyse the additional time delays incurred by frequency adaptation between various cognitive mesh network base stations. The conclusions are used to investigate solutions and algorithms in later chapters.

In Chapter 3, a macro-to-macrocellular system is considered where users communicate in an orthogonal manner enabling local access to the spectral ranges at shorter links without interfering actual license owners. For the first time, our analysis attempts to examine the overall throughput gained from various CRoF-RATs with respect to classical radio devices. A new diversion call algorithm is proposed for this microcellular/macrocellular integrated network. This involves three different modules that are installed at the cell core server, macrocell, and microcell units. The ultimate goal here is create a heterogeneous model system of primary and secondary networks in coexistence and to obtain a characterisation of higher performance connections within such a scenario.

In Chapter 4, the coexistence of macro and microcells stations is considered in order to propose a policy for optimising the deployment of cognitive microcells inside macrocells. The goal is to set limits for users' density installation as a function of the free spectrum channels which is believed to be potential factor for future cognitive radio network deployment and offer insights into how to design CRoF architecture. The study is combined with the algorithms developed in chapter three and the given solutions for cognitive microcellular systems. Simulation results show the limits of newly hosted microcells in LTE cells that can maintain the best performance. At the end, models are presented for the deployment of micro sites that allow to significantly decreasing the area power consumption in the network while still achieving certain area throughput targets and efficient services delivery.

Results in Chapter 4 showed that cognitive microcells can be extended to allow the SU to transmit simultaneously with the PU over the same channels band. This is exactly the setup in Chapter 5, where the cognitive radio behaviour is generalised to allow secondary users to transmit simultaneously with the primary system. Specifically, it is proposed in this chapter to combine CRoF microcells with multi-user diversity technology to achieve strategic spectrum sharing and self-organising communications through managing the mobility at various end-users speeds. In this field, CAA is proposed to allocate the same channel to a cognitive mobile user as long as possible to prevent service interruption resulted from unnecessary spectrum handovers. The problem of fairness management due to the CAA installation on user selection strategy is addressed to assess the success of the proposed solution for targeted aim. Finally, the big sized cognitive network is divided into many zones of services at which CRoF-BS acts as the core of the zones. Therefore, a new paradigm for local resources sharing emerges through these architectural network modifications.

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Chapter 2

Challenges Facing Cognitive Networks Deployment

In this chapter, the known cognitive network models are presented with the main challenges that are facing the deployment of these network managements. The cooperative and non-cooperative architectures are considered in which the primary and the cognitive user wish to communicate with no interference. Additionally, the study focuses on the spectrum sharing challenge in distributed and centralised spectrum access cases. Due to users fully sharing the same spectral resource, spectrum availability is a decisive factor for the continuity of CRN services. Thus, localised wireless changes within CRN cells rapidly affect the transmissions of the cognitive radio base stations. This situation becomes more complicated for cognitive mesh networks when establishing a link over many transmission domains. Therefore, link formation failure may cause complete disruption at certain sites of the network. A mathematical model is introduced to show the delay impacts of the spectrum unavailability on the CRN's which has been analysed as the most severe cause for the CRN failures. System models and problem formulations are proposed in order to study the impacts of spectrum unavailability on uplink capacity for each of the CRN application scenarios, for which solutions and algorithms are investigated in this thesis.

2.1 Cognitive Radio Technique

Cognitive radios (CRs) are perceived as a possible solution to the future low availability of the radio spectrum. It is a key technology that could enable reliable, flexible, and efficient spectrum access by adapting the mobile operating features according to the surrounding wireless environment. CRs are facilitated by the rapid and significant development in radio technologies (e.g., Software-Defined Radio (SDR), frequency, and power control) and can be characterised by the utilisation of disruptive techniques such as real time spectrum allocation, wideband spectrum sensing, and real-time measurement dissemination.

This revolutionary and transforming technology represents a paradigm shift in the design of wireless systems, as it will allow the agile and efficient utilisation of the radio spectrum by offering distributed terminals or radio cells the ability of radio sensing, self-adaptation, and dynamic spectrum sharing. Cooperative communications and networking is another new communication technology paradigm that allows distributed terminals in a wireless network to collaborate through some distributed transmission or signal processing so as to realise a new form of space diversity to combat the detrimental effects of fading channels. Spectrum utilisation can be improved significantly by allowing a secondary user to utilise a licensed band when the Primary user (PR) is absent. Cognitive radio, equipped with sensing and adapting to the environment, is able to fill in spectrum holes and serve its users without causing harmful interference to the licensed user. To do so, the CR must continuously sense the spectrum it is using in order to detect the reappearance of the PR. Once the PR is detected, the CR should withdraw from the spectrum so as to minimise the interference it may possibly cause [1].

Several definitions for cognitive radio can be found from the research domain. The official definition for cognitive radio systems in ITU- developed by ITU-RWP1B in 2009 and published in (ITU-R 2009) states that a cognitive radio system is [2]:

> *“A radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to*

> *achieve predefined objectives; and to learn from the results obtained".*

In other words, once cognitive radios can find the opportunities using the "spectrum holes" for communications, cognitive radio networking to transport packets on top of cognitive radio links is a must to successfully facilitate useful applications and services. A mobile terminal with cognitive radio capabilities can sense the communication environments (e.g. spectrum holes, geographic location, available wire/wireless communication system or networks, available services), analyse and learn information from the environments with user's preferences and demands, and reconfigure itself by adjusting system parameters conforming to certain policies and regulations. For example, when a cognitive radio mobile terminal sensed that there are WiFi and Global System for Mobile Communications (GSM) systems nearby while spectrum holes exist in the frequency band of digital TV, it may decide to download files from a certain WiFi access point, make a phone call through GSM system and communicate with other cognitive radio users using those spectrum holes. A cognitive radio terminal could also negotiate with other spectrum and/or network users to enable more efficient spectrum and network utilisation. The negotiation procedure may be facilitated from the support of network/infrastructure or just proceed in an ad–hoc manner [3]. All these actions occur in a heterogeneous wireless environment as shown in Figure 2.1.

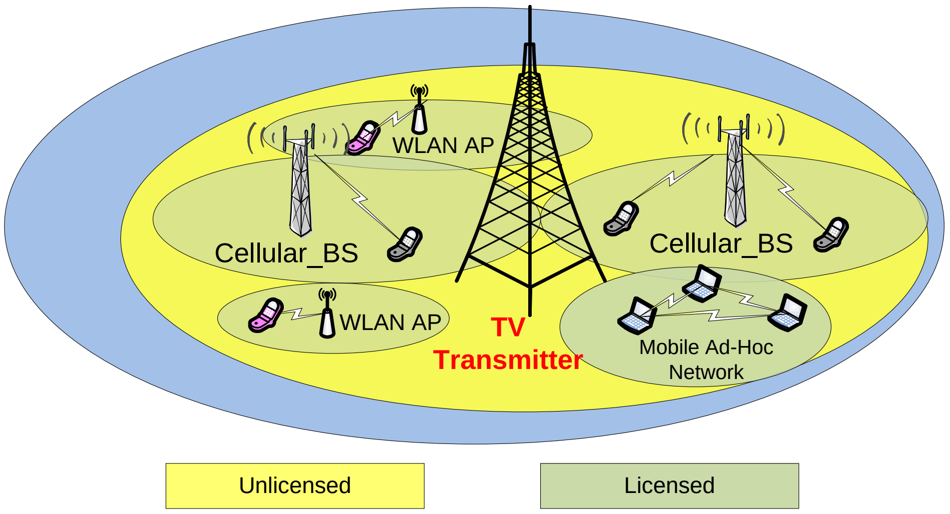

Figure 2.1: Spectrum allocations between different wireless domains

This chapter researches on the issues that had driven the focus on using fibre deeper into wireless networks and the approaches to gain more spectrum. It addresses the challenges in wireless access and communications for known cognitive network managements. The following analysis discusses several more specific cases which can be summarised in the following:

1. The link creation for cognitive networks.
2. Given the current cognitive network architectures, the challenges for significantly expanding future spectrum requirements to achieve reliable communications.
3. Understanding the extent of base stations reallocation in order to respond to the growth in wireless demand locally.
4. Increases in spectrum capacity based upon radio access technologies using unlicensed spectrum over the long–term, while following short–term solutions to meet the growth in wireless demand.

While the spectrum access process has undergone substantial modelling, the allocation and reallocation process has not. These have a geo-location function and there should be provided with a scheme to enable to check a database of broadcaster frequencies. The known cognitive network management functions were summarised and conclusions were applied as a proposed management in this study for the new CRoF network. The key issues to be addressed include, in particular, where, when and how a cognitive BS should access the spectrum and use resources, how to manage call exchange in the cognitive network, and how to utilise the relevant information to handle the diverse resources efficiently.

2.2 Cognitive Network Functions

2.2.1 Spectrum Mobility

Spectrum mobility refers to the agility of cognitive radio networks to dynamically switch between different channels. These secondary users have no guarantees for continuous spectrum access in any of the licensed bands due to the dynamic changes in the availability of vacant spectrum bands over time. Therefore, spectrum mobility becomes an important factor when designing cognitive domains. One of the primary factors affecting spectrum mobility is the delay incurred during spectrum handover. This delay adversely affects protocols employed at various layers of the communication protocol stack. Another important factor to be considered in spectrum mobility is the time difference between the secondary network detecting a primary transmission and the secondary users leaving spectral band. Transmissions from secondary users during this period will cause harmful interference to the primary users. The OFCOM has suggested setting upper bounds on the spectrum handover duration to avoid prolonged interference to primary users [4].

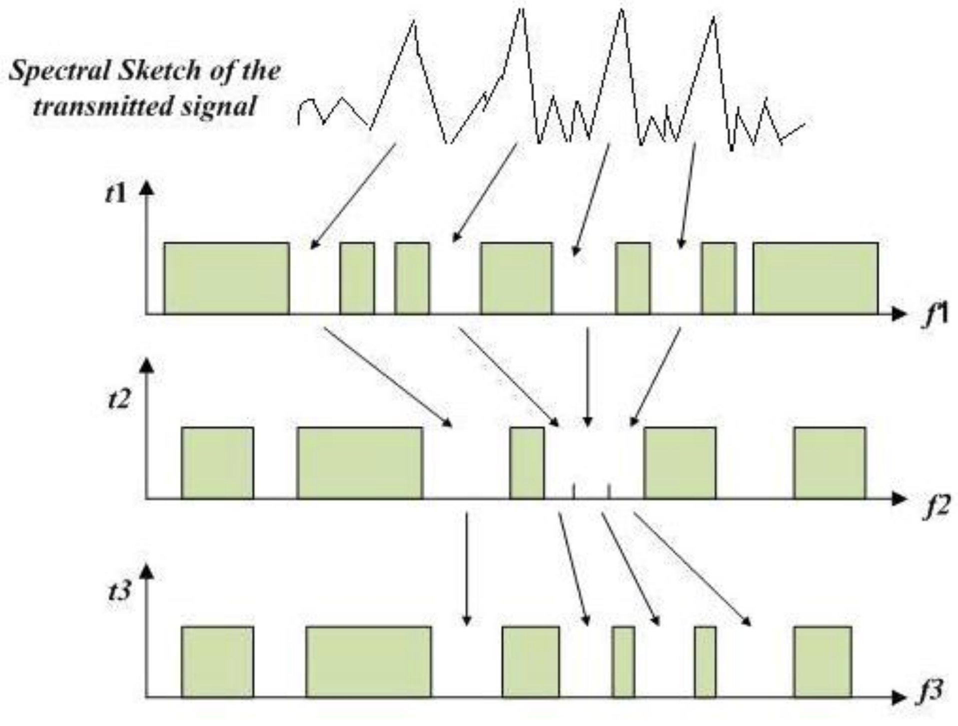

Figure 2.2: Spectrum mobility and handover process

Because of the flexibility in modulation and effectiveness in calculation, OFDM has been the preferred modulation for cognitive radio. Take the situation of 4 sub-carriers as an example: Figure 2.2 shows the OFDM sub-carriers handover process when spectrum holes shift with time (t1 < t2 < t3). Spectrum mobility is the process of cognitive user changing its own operating frequencies, and the key issue is spectrum handoff. In Figure 2.2, green squares denote spectrum which be occupied by licensed users, while empty slots denote spectrum holes that used by cognitive users [5].

2.2.2 Spectrum Sensing

One of the primary requirements of cognitive networks is their ability to scan the spectral band and identify vacant channels available for opportunistic transmission. As the primary user network is physically separated from the secondary user network, the secondary users do not get any direct feedback from primary users regarding their transmission. The secondary users have to depend on their own individual or cooperative sensing abilities to detect primary user transmissions [6].

Traditionally, there are two techniques which are used for spectrum sensing: energy detection and cyclostationary feature detection. The energy detector measures energy in each narrowband channel and determines the presence of a primary user if the energy detected in a narrowband channel is higher than a certain threshold. However, to achieve high receiver sensitivity, a low threshold has to be used. In some cases, the threshold has to be lower than the noise floor, in which case the detection fails. The problem is even more complicated due to the fact that the noise is most likely non-Gaussian because of the presence of CR user's interference. The other spectrum sensing technique is cyclostationary feature detection. Most of the signals encountered in wireless communications are cyclostationary, whereas the noise is stationary. As a result, the cyclostationarity of the primary signals can be used to detect their presence. The cyclostationarity of a signal is not reflected in the Power Spectral Density (PSD); however it is reflected in the Spectral Correlation Density (SCD) function which is obtained by taking the Fourier transform of the cyclic autocorrelation function. Therefore, spectral correlation analysis of the received data can be used to identify the signal source and occurrence [7].

2.2.2.1 Cooperative Sensing

In a fading environment, spectrum sensing is challenged by the uncertainty arising from the channel fading since the secondary user now has to distinguish between a white space, where there is no primary signal and a deep fade, where it is hard to detect the primary signal. As such, under channel fading, a single user relying solely on local (signal) processing may be unable to get an accurate detection results, required by the regulator, in a reasonable time limit. To tackle this issue, different secondary users may share their measurements and cooperatively determine whether the primary user is present. The diversity gain achieved through such cooperation effectively cancels the deleterious effect of fading. This raises a natural question: how much processing and cooperation is needed, respectively, in order to achieve a certain performance level? This can be characterised as a tradeoff between the local processing and the user cooperation [8].

2.2.2.2 Cyclostationary Detection of Undefined Secondary Users

The possibility that a certain CR may transmit illegally falls outside the current definitions of cognitive networks. These cognitive radios can use their advanced radio technologies to adapt their carrier frequencies to transmit on a certain licensed channel when the primary user is off. However, they still need to transmit using different signal parameters to keep their broadcast dedicated to their end users. This action may occur at any time and can happen rarely or even constantly. A novel monitoring system is required to grant the competency to detect such behaviour immediately at the basic base stations. The Fast Fourier Transform (FFT) Accumulation method is presented as the algorithm for analysing the cyclic spectrum. This method is derived from the cyclostationary method which is widely accepted as the most effective sensing procedure for the cognitive radios [9, 10].

2.2.3 Flexibility and Agility

Flexibility and agility is the ability of the CR to change the waveform and other radio operational parameters on the fly. In contrast, there is a very limited extent that the current multichannel-multiradio can do this. Full flexibility becomes possible when CRs are built on top of SDRs. Another important requirement to achieve flexibility, which is less discussed, is to use reconfigurable or wideband antenna technology. Thus, a new paradigm of wireless communications emerges with adaptive physical and medium access layers. These allow the spectrum agile radio to change its transmission features in order to react to changes in the external radio environment and the dynamic spectrum access policies. An internal architecture of an individual agile radio is depicted in Figure 2.3.

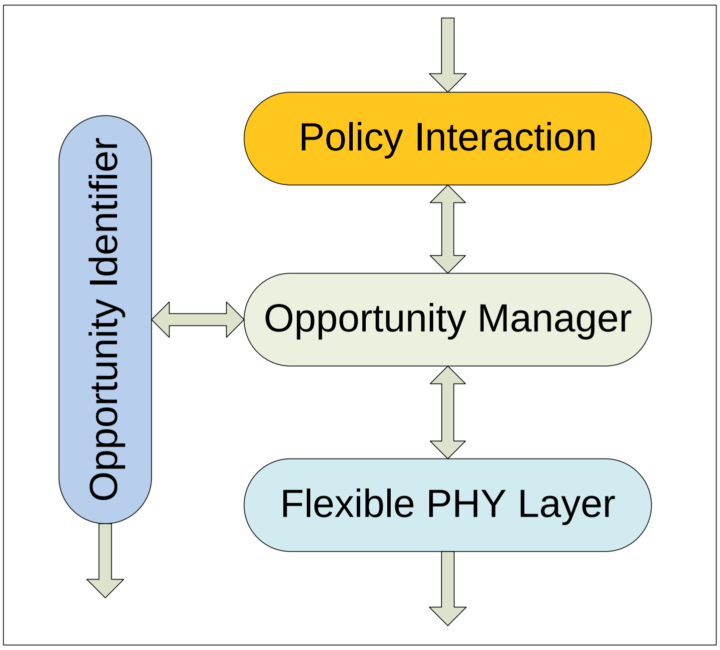

Figure 2.3: Architecture of a spectrum agile radio

The important modules of this architecture are: Opportunity identifier, Policy interaction, Opportunity manager, and Flexible Physical (PHY) layer. The opportunity identifier is responsible for determining whether a particular band in the spectrum is an opportunity or not. This is done by sensing the medium for available white spaces, and by estimating the duration these opportunities in those spectral bands. The results of the identification process are then passed to the opportunity manager. The policy interaction is responsible for understanding the policies set by the regulatory body (e.g., the OFCOM) for the target bands and the results of its interpretation is passed to the opportunity manager. The flexible PHY plays a critical role and is responsible for taking the inputs from the opportunity manager and shaping the waveforms so that they comply with the transmission policies set by the regulatory body. The opportunity manager forms the core of this architecture that manages the functioning of the different operations [11].

2.2.4 Learning and Adaptability

The ability to analyse sensory inputs, to recognise patterns, and modify internal operational behaviour is based on the analysis of any new situation, not only based on existing algorithms but also as a result of a learning mechanism. In contrast, the IEEE 802.11 MAC layer allows a device to adapt its transmission activity to sense channel availability. However this is achieved by using a predefined listen-before-talk and exponential backoff algorithm instead of a cognitive cycle. These might need to be improved with further techniques and schemes in order to increase the awareness of the CR systems in the wireless environment and achieve better control of the radio technical features that enables high levels of configurability and interoperability. This can be done by integrating the neural networks with future CR to provide these radios with the ability to recognise different transition states. This is explained as follows:

2.2.4.1 *Scenario:* Neural Network approaches for CR

Neural networks have been used in many researches for cognitive radio applications to improve the intelligence capacities. Zhang [12] proposed four layer Back-Propagation Neural Network which can be used for different applications including the CR. Each layer consists of a number of neurons that receive inputs from other neurons in the previous layer. If the weighted sum of the inputs exceeds a threshold level then the neuron will produce an output and distribute it to the neurons in the next layer.

Multilayer Feedforward Neural Networks (MFNN) was used by [13] as an effective technique for real-time characterisation of the CR system performance. This is based on measurements carried out by the radio and therefore offers some interesting learning capabilities. Simulations were used to obtain a set of data characterising the performance with respect to these measurements. A subset of this data was used to train a MFNN; afterwards, the rest of the data was set to compare the performance of the prediction provided by the trained MFNN with the actually experienced performance.

Potential solution presented by [14] argues to assist the cognitive radios in the derivation and enforcement of decisions regarding the selection of the desired radio configuration that optimises its QoS. The proposed solution is based on Neural Networks (NNs) motivated by the fact that NNs are widely different from conventional information processing as they have the ability to learn from given examples, thus being also able to perform better in cognitive tasks. Two NN-based learning schemes have been set up and tested: the ‘basic’ and the ‘extended’ one. While the former aims at building the framework for developing such learning schemes and applying them into future cognitive radio based systems, the latter stresses that such a learning scheme should be extensible, i.e., flexible in incorporating further information data in the learning process, given that this can bring an objective merit to the process.

In the given solution, classic MFNN is used to implement multi-layered leaning machine capable of sharing information about previous experience using a common group port. Therefore, new aware CR is created that can join immediately a group of CR devices at a certain place and understands how they used spectrum in the past. Steps for the design of the new learning system are explained in the next section.

2.2.4.2 *Solution:* Multilayer Feedforward Neural Networks Framework

A MFNN is composed of several neurons connected in a feedforward fashion and arranged into *L* layers. The basic element of a MFNN is the single neuron or *perceptron*, which implements the relation between its inputs and its output. It is necessary to determine the values of the weights and biases for each input which provide the desired approximation; this operation is referred to as training [13].

The known learning schemes for the cognitive radio are using the sensors' observed data and the self-learned events as the only inputs for their evaluations. This assumes that the cognition engine for the CR will be able to make the right decisions using its own experience. Under many circumstances the CR learned data is not enough to take the necessary decisions that prevent interference with other radios or to achieve an efficient spectrum utilisation. This is likely to happen as a result of turning on a CR for the first time with no previous experience. The same scenario is expected for secondary radios when they are relocated to work at new districts. Moreover, single autonomous and self-directed secondary users may not be able to conduct the appropriate viewing for the surrounding wireless environment and make their own judgement for suitable transmissions independently. Thus, it is preferable to share experiences and evaluations between cognitive radios which are identified by the same network. This allows an efficient and collaborative access to the spectrum and to avoid any possibility of interference. The new designed learning scheme is shown in Figure 2.4. The

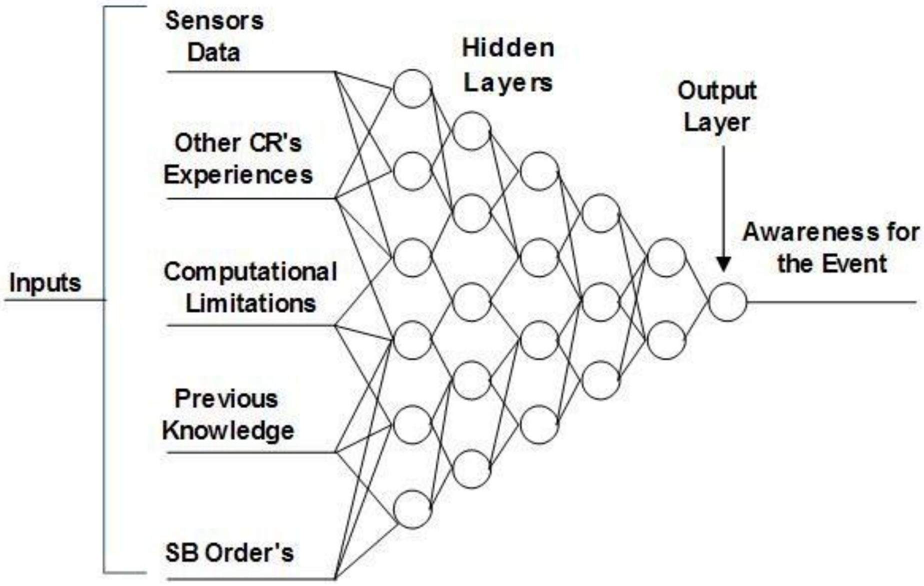

Figure 2.4: Designed MFNN learning model for dependent CR

The proposed design makes it possible to share previous experiences directly between secondary radios' learning systems. The shared information with the CR sensors data are then evaluated with equal weights of significance for each input. This model is flexible enough to enable the CR to work independently and dependently from other network cognitive devices. The decision on such individuality should be done by the spectrum management entities that regulate the spectrum users' activities [15].

Sensors data could be evaluated with other parameters using the formulated weights of each factor. Weights may be set dynamically according to inputs' importance. These data are physical factors, such as Bandwidth (BW), Bite Error Rate (BER), Signal-to-Noise-Ratio (SNR), Data Rate, and Latency. The obtained metrics are then processed with other inputs using equal weights. Other entries are: previous CR experiments and CR device limitations for example cost, channels used, and adaption abilities. Another entry comes from the Spectrum Broker (SB).

This new extension in the CR awareness will provide the secondary users with the necessary experience at the first run by downloading knowledge from other CRs learning machines. This can be achieved through certain protocols and hardware ports for a group of CR devices. This can be done only in a collaborative way and whenever it is needed by any secondary users within the same network. Comparisons can always be made whenever requested to match up to the way that other CRs understand an action. Final assessments are function for all the inputs and the best evaluated learning conclusions. It is similar to someone who reads a book on history and learns from people who experienced similar situations at similar times.

It is unreasonable to let the cognitive users in future to act without any supervision from the spectrum management entities for example the SB. Such monitoring will ensure the reliability of the secondary users' system and prevent the illegal usage of the spectrum. The decisions taken by these entities are also fed for assessment in this proposed learning model. The final conclusions are then sent to the decision makers. These modules are the states responsible for running the CR and deciding the following actions of transmissions and adaptions.

2.2.5 Dynamic Spectrum Access

Dynamic spectrum access is the process of increasing spectrum efficiency via the real-time adjustment of radio resources; this is done via a process of local spectrum sensing, probing, and the autonomous establishment of local wireless connections among cognitive nodes and networks, as shown in Figure 2.5. As originally proposed, cognitive radio is envisioned for real-time spectrum auctions among diverse constituencies, used for one purpose, such as cellular radio, spectrum allocation and public safety. These allow improving the resources utilisation and increasing the revenues of trading the spectrum commercially during peak periods.

Although that initial example has yet to be fully realised, the FCC encouraged the application of that technology to the secondary use of underutilised television spectrum, such as in ad hoc, short-range WLAN in the spectrum allocated to another primary purpose, such as broadcast television. In addition, the principles of cognitive radio for dynamic spectrum access also apply to enhance the efficiency of use within and across each "lane in the road," such as via the intelligent selection among multiple alternative PHY-MAC layers (alternative lanes in the spectrum road) by cognition across network, transport, and application layers of the protocol stack [16].

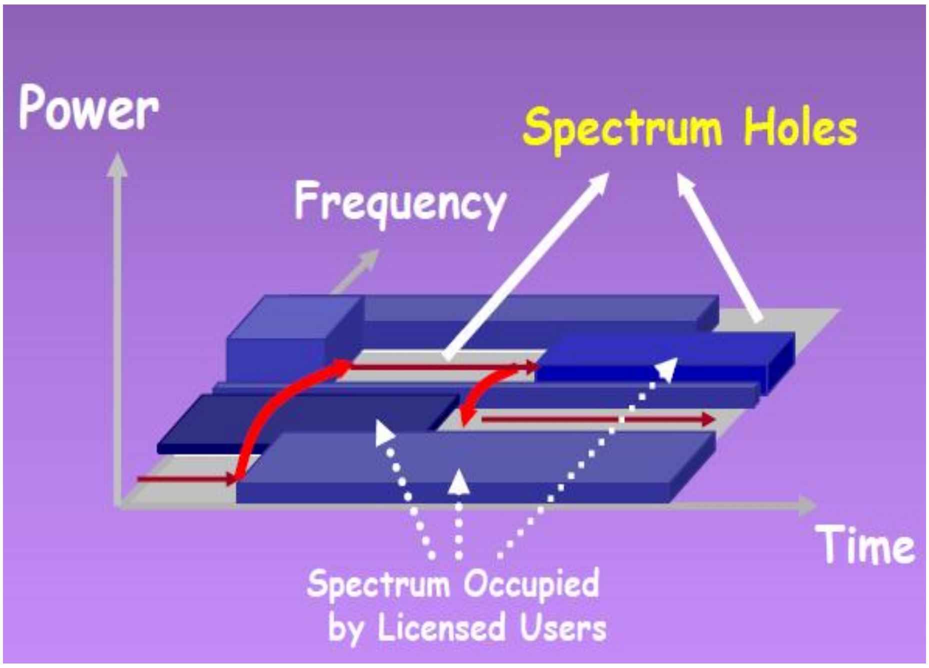

Figure 2.5: CR adaptations between various transmission opportunities

Wireless implementation of Dynamic Spectrum Access (DSA) in cognitive networks requires:

- Knowledge of available spectrum through wide-band spectrum sensing, policies, changes in the spectrum availability.
- Real-time spectrum management, provisioning and release of radio bandwidth.
- Network infrastructure and/or endpoints that support these technologies and actions.

Thus, wireless DSA networks may require “new architectures and associated signalling and control protocols” for their real-time spectrum management component [17].

2.3 Network Planning

The end goal of this thesis is to propose practical planning for the CRN infrastructure and resource allocation with the view of: improving the spectral efficiency, and maintain reliable high QoS cognitive communications which will thus be our main figure of merit. In order to characterise the performance limit of such systems, the criterion is set to be directly dependent on the application requirements. Therefore, in order to design relevant network infrastructure for real-time service, it is necessary to identify the network connectivity as a function to the primary user activities [18].

Although most of the research works are focused on the spectrum sensing and access methods, network capacity analysis is also an important research topic of cognitive networks. For example, the optimal capacity value is the upper bound of the network bandwidth which provides an ideal comparison value for different channel allocation algorithm. Another important motivation is for the network planning when considering different nodes' density and traffic demands. Even in network layer, the capacity of a specific route is crucial to provide an ideal index for the design of routing algorithm. In the cognitive network, the significance of network capacity is more important. First of all, primary users are strictly undisturbed by secondary users, the extent that secondary users can access the temporal available channels needs to be calculated. Then the spectrum allocation algorithm will have an upper bound for comparison [19].

Consider a TV station which broadcasts in a currently licensed and exclusive band. Despite the high prices paid for these exclusive bands in spectral auctions, measurements show that white space, or temporarily unused time or frequency slots, are alarmingly common. Notably, TV bands are wasted in geographic locations barely covered by the TV signal. This has prompted various regulatory and legislative bodies to put forth procedures which would open up TV channels 2-51 (54 MHZ - 698 MHz) for use by secondary devices. These devices, often cognitive radios would be able to dynamically access the spectrum provided any degradation they cause to the primary license holders' transmissions is within an acceptable level [20]. However, major interruption in cognitive services is expected when the band is used by the PRs. This represents the worst case of outage probability for CRN [21]. The most probable situation is a major increase in the time required for a packet delivery over dynamic spectrum availability in coexistence with the primary user [22].

In what follows, known cognitive network's architectures are studied with the challenges that face each of them to motivate the development of our contributions throughout this thesis. Specifically, three schemes employing varying levels of hierarchy are presented as follows:

1. Distributed, where the cognitive users access the primary user's channel autonomously.
2. Centralised, where the cognitive users access the spectrum based on coordinated management schemes.
3. Hybrid, where there is a mixture of the above two methods to arrange cognitive users access to the spectrum and calls scheduling.

The obtained conclusions are used to devise the concept for the CRoF system.

2.4 Distributed Network Architecture

Network management is essential to control and optimise the network operations in response to the dynamic changes in end-users’ requirements. Management includes the initialisation, monitoring and modification of the network functions. Thus, architectures of the network management enable to guide and to distribute hardware and software modules that implement the required functions over the various systems in the network [23].

2.4.1 Network Management Scenario

Let us first consider a single channel scenario where the primary and two cognitive users are attempting to communicate over this channel using different base stations at the same area with no interference (see Figure 2.6). If PR turned to $T_{pr,off}$ then both CR1 and CR2 will start a competition for holding access time along i-channel band. Both CRs sense the channel availability individually and start to transmit when access time is obtainable. The Spectrum Server (SP) owned by each operator will be the core information contributor to identify the surrounding operators. Under the expectation that the primary users’ signal is known, any secondary users’ signal will be recognised by all other CRs.

In such multi-access systems, the acknowledgements received are proportional to the number of cognitive users, this means that feedback overhead may be too large and thus the reverse-link channel capacity may be greatly wasted. To reduce the feedback information in such cases, CRoF communication system which will be studied in this thesis to can be used reduce the impacts of long time delays due to waiting for acknowledgement responses.

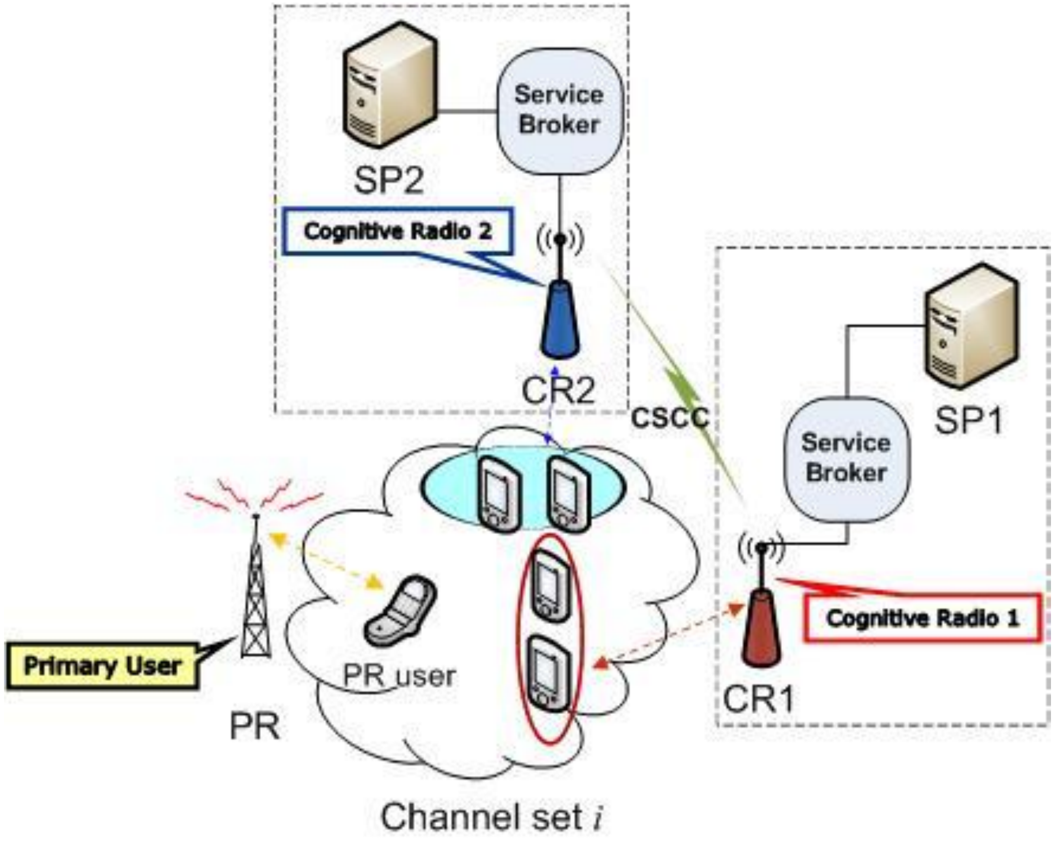

Figure 2.6: Distributed spectrum management solution

Each secondary user learns the other CRs behaviour and tries to use the unoccupied time of channel set i. It is usual that each CR will be selfish and try to transmit most of the free i-time. Hence, interference is likely to occur if the CR2 tries to access the channel unless there is an acceptable level of cooperation between CR1 and CR2. The best solution is to design new regulation protocol for *Urgent Secondary Users Coexistence (USUC)* spectrum access. With *USUC*, CR2 can send a request for urgent time admission to get access to channel set *i* using the *Common Spectrum Control Channel (CSCC)*. The call should refer clearly that the CR2 asks for a limited transmission time on i-channel. CR1 needs to know also other details, for instance IP address and the coverage area, of CR2 in the requesting packet. CR1 should respond directly by accepting CR2 request. CR1 will be the responsible for generating the backhaul numbers for

CR2 and gives CR1 the opportunity to start transmission firstly at any time. If any of these secondary users decides at any time to leave the channel it should notify the other group CRs on such a decision. This scenario is more complicated for n-CRs in a wide sized cognitive network that employs many bases stations. In such an arrangement, CR1 will be the master and other CRs are the slaves in such group. If CR1 at any time went out of channel i group, other CRs will elect a master that heads the group and to generate the backhaul numbers that decides the transmission sequence between these radios. Consequently, a state transition backhauls will be updated with new space time to other occupiers [24].

2.4.2 The Heterogeneous Network Scenario

As mentioned before, there are a considerable numbers of unused spectrum holes that are available temporally in the licensed spectrum band. Therefore, CRN networks are deployed to utilise these transmission opportunities through cognitive communication techniques. As a general framework, Figure 2.7 represents a heterogeneous architecture where the cognitive network coexists with the primary network at one site and accesses the same spectrum band using microcellular domains.

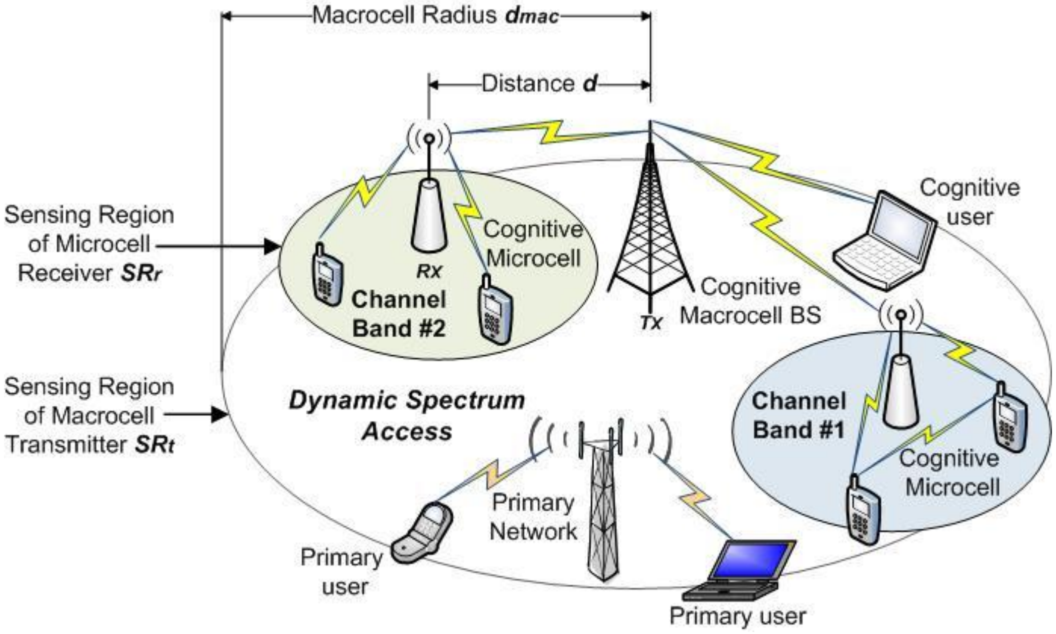

Figure 2.7: The underlying architecture in cognitive network employing distributed microcells

The criterion for success in the CRN is to determine the best available spectrum by detecting the presence of primary users. This becomes more complicated in a dynamically changing wireless environment that employs different technologies, operators, and users. The channel capacity of the spectrum holes may change also as a function of the place of availability and nearby primary users. As a secondary user, cognitive networks have to avoid interference with primary users at all times. Furthermore, the cognitive users should vacate the current channel and move to the new channel immediately, whenever the primary users return to transmit; this is called spectrum handover. In the above architecture, the available spectrum band is sliced by creating small transmission domains of cognitive networks. This multi-access system allows better coexistence and spectrum trade between primary and cognitive users. Such an accurate modelling of the cognitive network infrastructure is a key to understand the actual advantages brought by secondary users. It can be noticed that the system model presented in this section is related to a single operator model; however, modelling is also applicable to heterogeneous model case as well. The challenge here is to set the hierarchical modelling of spectrum access authentication and the necessary power adaptations between various wireless domains. The goal is to prevent multiple access points from interfering each other and the main LTE macrocell base station.

2.4.3 System Model

A key factor for the mesh-cognitive radio networks is the establishment of link path connections between many base stations. This demands the availability of free spectrum channels at all domain sites that a link is passing through. The spectrum unavailability at one or more sites can cause major interruptions in the secondary network services. This spectrum unavailability can be resulted from [25]:

- The absence of some operational cognitive nodes along a trajectory between two points when the primary users occupy the entire spectrum band. This blocks the cognitive stations for unpredicted time periods until spectrum ‘white spaces’ are revealed again.

- Cognitive base stations may become selfish and ignore the requests to formulate links with other neighbouring stations. This behaviour triggers a significant degradation in the performance of the cognitive network especially if this action was spread across many network sites.

Therefore, channel assignment algorithms used in cellular networks are not applicable for cognitive radio networks. As the optimal channel assignment problem in cognitive radio networks takes into account new factors like dynamic spectrum allocation, new algorithms are required to enable flexibility in accessing the spectrum and coexist with users at no interference. The problem is extended further when considering the link quality constraints. The link quality constraints refer to the signal-to-noise ratio or the distance ratio for using a channel, while fairness refers to equally distribution of the available channels to users in operation.

2.5 Centralised Network Management

2.5.1 Joint Spectrum Allocation

In realistic applications, the centralised network system is hard to implement. All primary and secondary operators should be connected to the SB. Consequently, it is mandatory for any CR, which intends to transmit at any channel to get the SB approval. This process is performed using the hierarchal levels shown in Figure 2.8. A request for transmission is initially passed by a CR to the Service Manager (SM) in the operator and then to the SB. The broker acts as the main complementary provider for information gained from networks' sensors and service managers in operators. The SB will then undertake the necessary arrangements to allocate the usage time for multi-users that intend to share i-channel set. SB generates the backhaul link necessary for intermediate fairly sharing of the available time among secondary users. While this seems to be an effortless way to share one channel, the time engaged for processing the CRs' request is significant and may cause the waste of pricey time during processing at any various system levels. However, such a system may be the best to avoid interference between CR users themselves or CR and primary users.

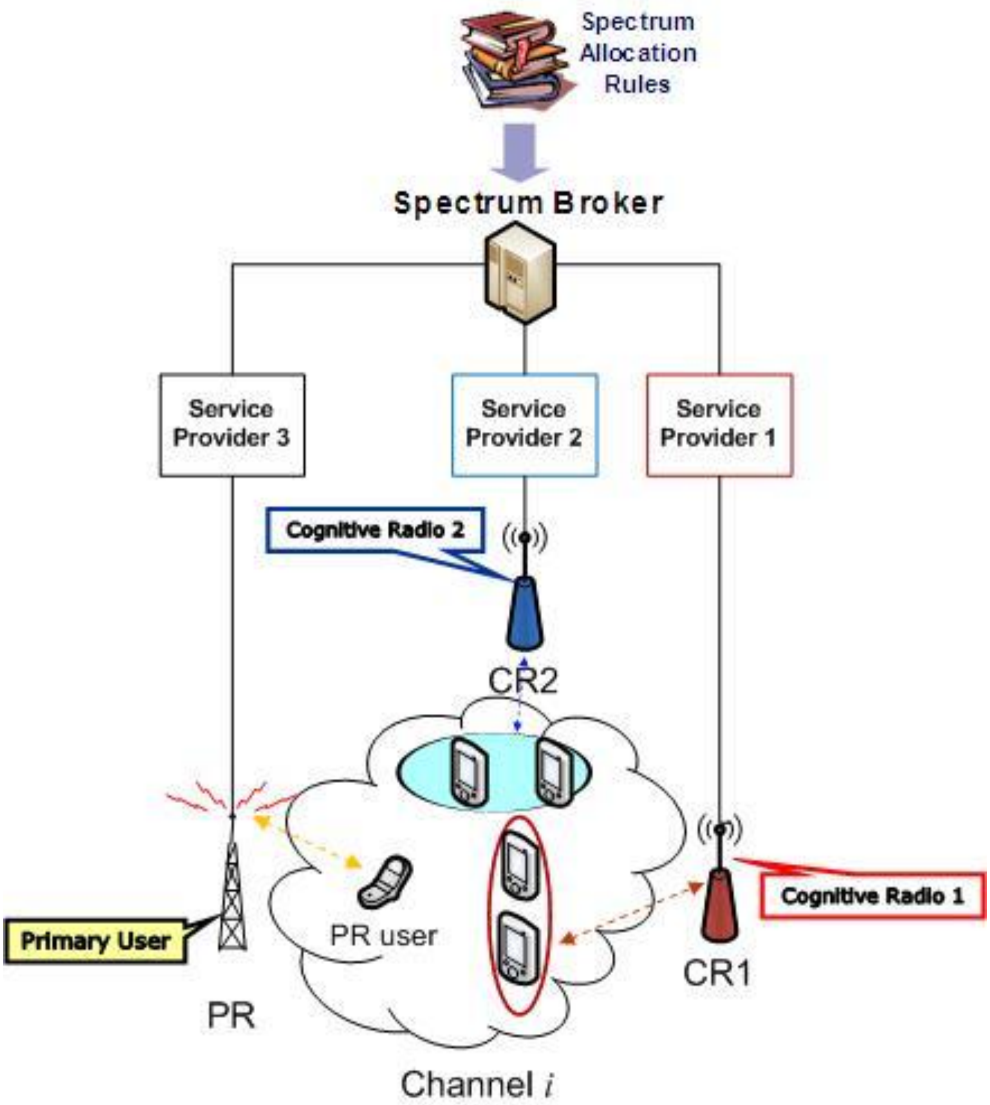

Figure 2.8: Centralised spectrum management solution

Earlier to any transmission, CR may download the PR parameters (modulation, coding, transmission power, routes, and coverage area) from the SB. These information help CRs to adapt to a suitable transmission parameters and steer away, if the PR returns to transmit suddenly. This model application assumes high level of collaboration between the various radios and the main spectrum governing entities.

2.5.2 System Model

In spectrum broker approach, server can be used to enable coexistence of primary and secondary radios in a shared environment in a centralised fashion. The centralised spectrum server obtains information about surrounding and interference through local measurements from different terminals and then offer suggestions to the efficient spectrum use. Service providers and users of the networks do not a priori own any spectrum; instead they obtain time bound rights from a regional spectrum broker to a part of the spectrum and configure it to offer the network service [26].

The main purpose of the SB is to achieve minimum connection blocking probability through optimally controlled dynamic spectrum access. Therefore, it is reasonable to have low- and high-priority spectrum users. The highest priority is always assigned to the licensed users. The prioritisation between two unlicensed users should include the minimum guard band. Hence, the number of transmission admissions accepted from unlicensed users should not exceed the number of free channels at a time period. This is a great task for the success of cognitive networks that employ centralised spectrum sharing fashion models. This growing numbers of calls against fewer numbers of transmission opportunities will lead to incredible numbers of declined calls and blocked connections. This situation may become worse with so many systems approach the SB at one time. The time consumed to contact the SB, getting temporary access licence and then performing adaptation to access certain channel may cause missing so scarce transmission opportunities. Therefore, it is necessary to understand the type of services expected from a SB as a function to the network size and white spectrum in order to reduce any complexity or disturbance. This can be done while deploying new networks or planning any modifications for the functioning of the management of the network. It is also very important to understand the type of authority given to the various SBs for being local, regional, or even international. Additionally, what sort of SBs connections in place and if they are connected to either primary and secondary networks or just the cognitive network.

2.6 Hybrid Network Management

2.6.1 Overview

Both the above scenarios centralised and distributed are bridged together to create a new hybrid spectrum sharing management. In this model, if CR2 intends to transmit on channel set i, it sends a request to the spectrum broker. The SB, as shown in Figure 2.9, assesses i-time ease of use. Keeping in hand the general rules for transmission and coexistence etiquettes, the spectrum broker has the authority to assign different numbers of CRs that intend to coexist on channel set i.

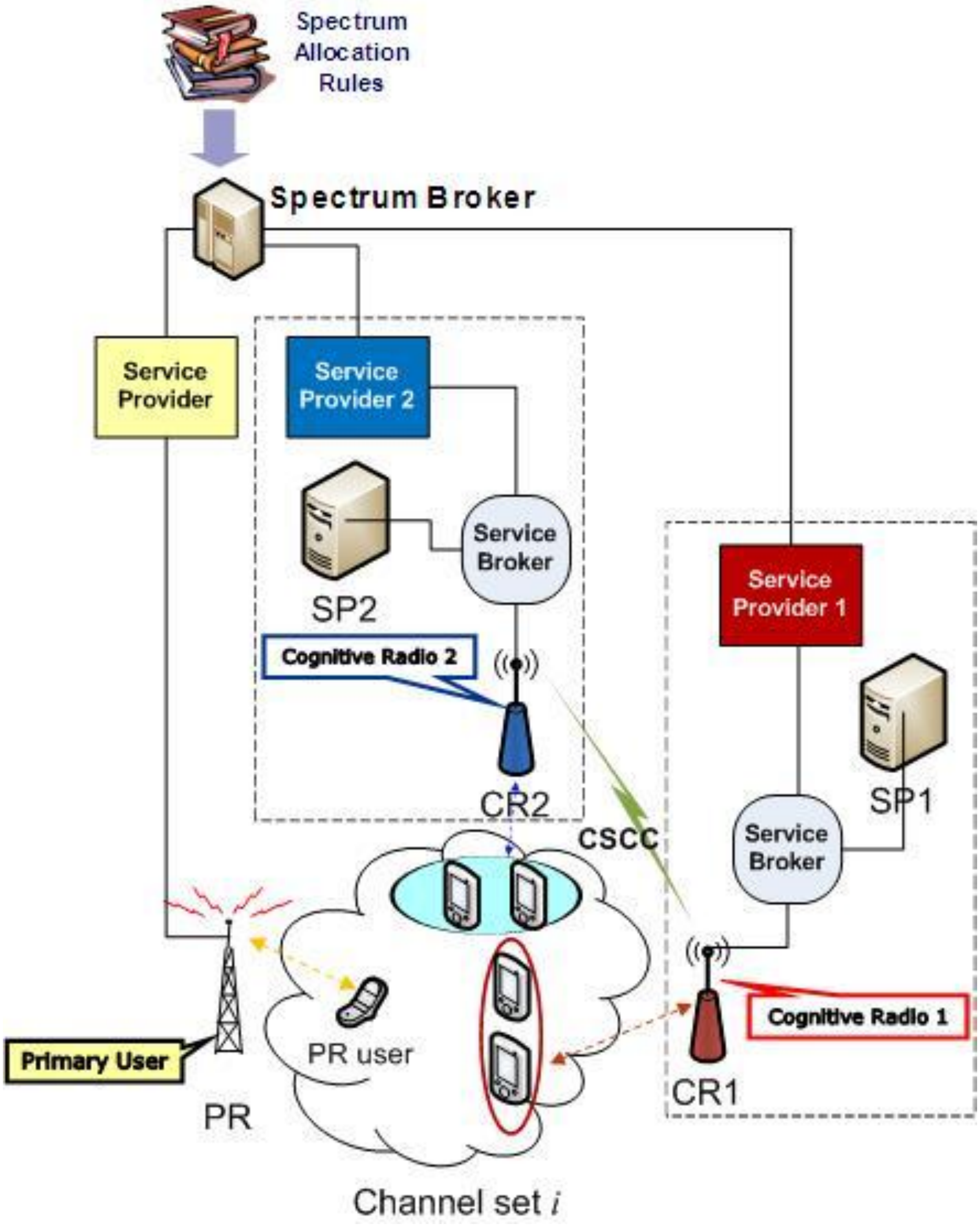

Figure 2.9: Hybrid spectrum management solutions

Equally, CR1 and CR2 are sharing the available band according to the end-users' demands. Both CRs can talk to each other using CSCC and exchange experience and knowledge in addition to the information exchanged through SB link. Once the users have been set by the SB, one of those CRs will be the master and the other is slave. The senior i-user is to head all other n-secondary radios for its long experience on the channel band. Therefore, spectrum access activities are managed by CR1 along with negotiations between all CR set, while all updates should be passed to the SB by the master. This will allow the SB to deal with other operator matters and to vacate the information channels for other users.

When any of the CRs leaves the channel set i, the senior CR informs the SB and a new sequence for using the spectrum is generated immediately to assure efficient usage and fairness between different users. This scenario is more compatible for future heterogeneous networks where flexible DSA is required to achieve robust usage for scarce spectrum.

2.6.2 System Model

The main challenges here are how to plan this kind of network and configure various domains to optimise the available spectrum holes. The EU FP7-E3 project investigates and defines solutions for managing and controlling interoperability, scalability and flexibility in wireless networks. These solutions had taken into account both the BSs, as well as the core network elements providing the end-to-end service (e.g. gateways, access controllers, authentication servers) [27].

In our model, we focus on the channel selection for the network access points. Therefore, we assume that a cognitive Access Point (AP) has the ability to sample the available spectrum transmission opportunities and periodically adapt according to the spectrum dynamic changes and traffic. Therefore, the activity of a given channel is defined as the mean number of frame transmissions occurred, averaged across all sample durations within a particular time. Cumulative activity of a channel not only represents the activity of a particular channel, but also considers the activity in other overlapping channels. For example, the cumulative activity is estimated by the following equation [28]:

$$CA_i = \sum_{k=i-COF}^{i+COF} A_k, \qquad k \in CH \tag{2.1}$$

where CA_i represents the cumulative activity in channel i, COF is the channel overlap factor which in 802.11b is three, CH is the set of channels in the system (set of channels 1 to 11 in 802.11b), A_k is the activity in a given channel k. Therefore, the cumulative activity is the sum of the activities in the overlapping neighbouring channels.

The cognitive network chooses the best possible channel based on the following equation [28]:

$$Operating\ Channel = arg\ min_i\ CA_i \qquad (2.2)$$

2.6.3 Multi–hop Problem

A route discovery and formulation process has a different procedure in a cognitive network than in other networks. An established link over many APs may collapse due to dynamic wireless changes at different transmission domains. One of the current suggested solutions involves ‘holding the data or simply buffering them until re-stabilising the same route. Another solution is that a new route can be discovered and created. Obviously, both of those operations will cause considerable delays to network communications. Also, the buffering node that holds the data at a certain location may be lost completely and communications would not be recovered again for some time due to spectrum unavailability. The other expected direct effects are: service interruption and traffic congestion.

To explain this, let A, B, C, D, E, F, and G be the positions where the cognitive BS nodes are positioned within a cognitive network as shown in Figure 2.10.

Each Node (N) is assigned to a certain wireless domain. A packet of data is sent from A to E using route (1). Suppose that a sudden interruption in service occurs at node C due to wireless changes at node D. Then, the holding delay time t_h resulting from buffering the packets at node C is derived as [21]:

$$t_h(N_c\ ) = t_{leaving} - \mathrm{t}_{\mathrm{arrival}} \qquad (2.3)$$

where $\mathrm{t}_{\mathrm{leaving}}$ and $\mathrm{t}_{\mathrm{arrival}}$ are the time of packet arrival and leaving at Node C respectively.

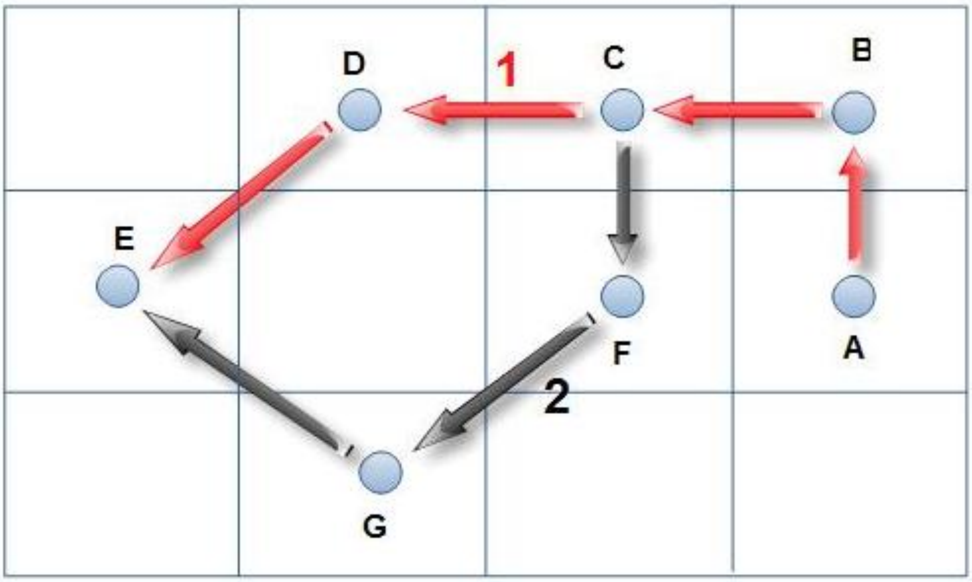

Figure 2.10: Routing scenarios in cognitive network

Assuming that node N_c will hold the data until a new route is discovered and that route (2) is chosen as the new trajectory for the requested QoS, hence the time spent during the packet diversion from the service provider to the end user (T_{rec}) is given as:

$$T_{rec} = t_h(N_c) + \sum_{n=1}^{m} t_d \tag{2.4}$$

where t_d is the time delay spent during adaptation of each cognitive node along the link, and m is the number of cognitive nodes.

The time spent for multiple switches between many routes for a certain link should also be considered in final end-to-end time delay evaluations, as:

$$t_{rd} = T_{rec} + \sum_{n=1}^{i} t_s \tag{2.5}$$

where t_s is the switching time, which is a function of the data trajectory.

An additional service interruption loss overhead may result from the consequent node delays along the chosen link leading to new values of overall Interruption Loss (IL):

$$IL = \int t_{rd} \,.\, I_l.\frac{dl}{dt} \tag{2.6}$$

where I_l is the service interruption loss per cell.

As a result, the possibility of route collapse $P(R_c)$ is increased due to the growth in the time delays overhead. This relation is applicable mainly for long routes passing through wireless congested areas. Therefore, the probability of link collapse can be written as:

$$P(R_c) = \frac{IL}{\mathrm{N}i.C_d} \tag{2.7}$$

where C_d represents the call duration.

2.7 Cooperative and non-Cooperative Spectrum Sharing

The fact that there are no access priorities between various cognitive users who are accessing the same band of channels raise an important point for discussion about the level of cooperation required between them during call admission. The cooperation can be expressed in terms of exchanging information about interference measurements, compliance with predetermined spectrum policy rules and/or willingness for individual performance degradation. On the one hand, there are approaches that assume full cooperation of the entities sharing the spectrum [29]. A common technique used in these schemes is forming clusters to share interference information locally. This localised operation provides an effective balance between a fully centralised and a distributed scheme [30]. Such a scheme can be applied for mesh networks where the mesh router and the mesh clients supported by it form a cluster. Here, the mesh clients send their individual sensing results to the mesh router, which are then combined to get the final sensing result. For cognitive ad-hoc networks, where no central network entity, this cooperation should be implemented in a distributed manner [31].

The ability of a cognitive radio to adaptively switch between channels: spectrum mobility offers tremendous scope to optimise performance. The dynamic spectrum access is challenging in a distributed type network, particularly when the devices lack cooperation. Game theory is a mathematical framework that provides a natural platform to study the effects of players' decision strategies and equilibrium solutions in a competitive environment with limited resource constraints. In game theoretical analysis, the optimising parameter and the definition of utility function characterises the resulting equilibrium solution, provided that they exist. Such a proposed game theoretic distributed adaptive channel allocation scheme for cognitive radios is formulated to capture selfish and cooperative behaviours of the players. Non-cooperative channel allocation and load balancing algorithms and spectrum utilisation maximisation are the main challenges in this type of communications. The channel selection in a distributed non-cooperative type network is less explored and the discrete nature of the problem makes it relatively difficult to model [32].

In the next chapters, this study propose to create a cooperative network model, then analyse the performance once the network users and access cognitive radios turn to the non-cooperative behaviour.

2.8 Conclusion

This chapter presents a comprehensive survey for the cognitive network management models from the outage capacity and spectrum utilisation perspectives. As for the network management aspect, most literature explores the known network architectures without identifying a key problem case to compare performance metrics for successful network deployment. Thus, research on network management needs to be extended to multi-user and/or multi-tier cell cases as well as considering the practical issues, such as transmission-associated availability of spectrum channels, which is of great significance to practical system design. Regarding spectrum utilisation that will be used in future wireless systems; existing research has shown that larger users' services can be achieved through efficient network design. The challenges proposed in this work are necessary in order to investigate potential topics, such as those listed in this chapter, as well as such originating from future wireless network models. The novelty of this research is that it investigates the spectrum efficiency problem through major changes in the network planning and installation. As the cognitive network has not been deployed yet or commercially used, the novel given approaches in this thesis can be initiated as a starting point to find the best network planning architectures even before cognitive network starts. This helps to save the cost of changing the network after deployment and use ant resources efficiently at the first run time.

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Chapter 3

Cognitive Radio over Fibre and Uplink Capacity for Microcellular Applications

3.1 Inrtoducation

In a two-tier cognitive network employing Orthogonal Frequency-Division Multiplexing (OFDM) transmissions with universal frequency reuse, spectrum pooling causes very different outage performances. This chapter presents the design of system architecture of flexible access algorithms and schemes. The spectrum-sharing problem is formulated towards an optimal scheme that allocates the band channels locally to the secondary network various transmission domains. Firstly, this chapter presents the network installation model and radio access technologies used throughout most of this thesis. Both new CRoF network and traditional CR network architectures are considered for which the primary and the cognitive users wish to communicate, subject to variable transmission intervals. Then, a mathematical model is introduced to evaluate the bandwidth savings gained from the using of access system supported fibre network. The new system incorporates access points at microcells and distributed interworking network using topology and wireless interfacing modifications to improve spectrum utilisation and minimise service disconnectivity. Extensive simulations proved that the proposed CRoF models show an improved performance compared with the existing cognitive network schemes that ignore fibre connections.

3.2 Motivation

Cognitive Mesh Networks (CMNs) are presented as a future solution for cellular communications due to the impending spectrum crunch. The spectrum availability is analysed as the main barrier against the success of CMNs using temporarily transmissions. Thus, CRoF is proposed as a solution for small enterprise microcells services in CMNs. The CRoF architecture is based on using the RoF to connect cognitive BSs. The vision for deployment assumes that CRoF stations are positioned inside the primary macrocell coverage areas and in coexistence with the primary Base Stations. Accordingly, CRoF would be able to utilise local spectrum holes efficiently and provide higher throughput to secondary users through trade-off of specific channels at certain domains. As a result, new resource management of multi-microcellular-base stations are proposed as a key development of cognitive, heterogeneous backbone wireless systems. Thus, a network operator will be able to dynamically adapt the spectrum occupation strategy and the choice of the suitable RATs depending on the wireless environment changes and the services requested by the end-users. New radio resource management strategies are developed on a time-variant network side configuration as microcellular transmission domains. The objective is to extend existing DSA in order to exploit heavily heterogeneous systems which are based on collaborative and autonomous distributed decision-making principles.

Considering the scarce availability of radio resources and ease of deployment, the same channel bandwidth was made available for all stations. The system capacity in such a macrocell-microcell arrangement with shared spectrum is determined by the local coverage of the macrocell and microcell transmission domains, subject to an outage probability constraint per BS. The focus of the research is to answer the following questions:

- What is the two-tier uplink capacity in a typical macrocell with randomly scattered microcells of the traditional and new proposed cognitive network infrastructures, assuming a randomly distributed population of actively transmitting users per tier domain?
- Is it possible to accurately characterise the utilisation of local spectrum transmission opportunities? How much benefit is accrued by macrocell sectoring and time hopping cancellation using fibre network?

- What is the difference between the various RAT in operation for cognitive applications and adaptive coverage?

By addressing these questions, this work provides a comprehensive study for the best network infrastructure management using capacity and time delay evaluations in two-tiered cognitive network and in coexistence with primary network. The final conclusions show that creating a suitable infrastructure using CRoF can actually increase the uplink capacity for a shared spectrum network.

3.3 Related Work

The combination of cognitive microcells to the radio over fibre infrastructure and the methodology for local resources allocations is uncovered problem area for the 4G networks that employ secondary communications. Existing solutions for addressing the local resources management in cognitive networks are addressed in the following:

To overcome the drawback caused by the limited knowledge of network topology and spectrum availability, all spectrum management functions are based on cooperative operations, where CR users determine their actions based on observed information exchanged with their neighbours. As an example, Cognitive Radio Ad-Hoc Networks (CRAHNs) require assimilation of information during sensing from several users to improve accuracy and for fair sharing of the detected spectrum resource through cooperation [1].

Spectrum Assignment in Infrastructure has been used to improve the performance of the network [2]. The authors suggested a new algorithm in order to maximise the average bandwidth per flow, and avoid the spectrum waste by idle secondary base stations. While, in [3], the authors proposed to transfer UWB sensors data through radio over fibre for cognitive optical access networks applications.

The Self-Organisation Network (SON) functionality includes all possible technical functions that a network manages in an autonomous way. SON follows the paradigm change for excellent network performance and operational efficiency. The self-x framework is analysed as well as the problem statement from several perspectives in terms of dynamic self-organised heterogeneous wireless network segments, spectrum management, self-configuring protocol and self-optimised network devices [4].

Resent work in Wireless LAN over Fibre (WLANoF) systems has developed a centralised processing for the power of cognitive AP. The goal is to perform dynamic radio resource management over a wide radio coverage area in order to minimise the interference with other coexisting systems. The proposed cognitive AP can provide a cost-effective and efficient method for devices to equally share the Industrial, Scientific and Medical (ISM) radio bands by taking advantage of cognitive radio ability in a collaborative way. This system is proposed for indoor communications and looks into very short distances [5, 6].

In [7], authors have investigated the CRoF which are applied for microcells. A combination of WLAN and RoF access points and WLAN bridges were proposed to solve the problem of high end-users demands and spectrum unavailability for future cognitive networks. Also, the CRoF was proposed as a joint subnet in [8] to support wide-sized cognitive mesh networks. The previous work done in [7] is developed by analysing more probable radio access technologies for the CRoF deployed microcells.

3.4 Technical contributions

This work employs a framework for modelling the overall outage of spatial distribution of cognitive microcells, in contrast to prior work [8, 9, 10, and 11]. Spectrum availability are likely to vary from one cell-site to another, and be opportunistic rather than planned: Therefore a capacity analysis is set to show all the dynamic changes across domains to provide more accurate results and more plausible insights.

The mobile users’ locations are assumed to be randomly distributed as a Homogeneous Spatial Poisson Point Process (SPPP) [12, 13, 14] within their main transmitters’ domains. The three key contributions of this work are given below:

- First, robust network coexistence model is shown to enable two-tier cognitive networks with universal frequency reuse to achieve higher user capacity. With interference avoidance, an equitable distribution of users between macrocell and microcell tiers is shown to be achieved with an order-wise difference in the ratio of their coverage powers.

- The CRoF concept for spectrum saving is based on the concept of utilisation of an existing resource in the form of microcells connected through radio over fibre. In such scenarios, the traffic is diverted through landline in such a way that the diversion will not affect the user service requirements. A mathematical model has been developed to estimate the amount of spectrum that can be saved through CRoF. The model has evaluated to demonstrate the percentage of spectrum that can be saved. The spectrum thus saved can be used for increasing the number of mobile users without any addition to the existing mobile network infrastructure.
- Finally, additional network modelling scenarios using a combination of microcells bridging and tier selection based microcells transmission domains results in a flexible model of network deployment options. This suggests that at least for small microcells sizes, time hopping, and cell division offer the largest gains in user capacity for shared spectrum two-tier networks.

3.5 System Model

3.5.1 Dynamic Spectrum Access for Cognitive Network

In this section, a spectrum sharing model is proposed between small different transmission domains with spectrum pooling. To allow the secondary users to access the licensed channels bands as one pool of spectrum, all secondary networks are set to employ OFDM as the underlying physical-layer transmission technique [15]. This enables the secondary networks to be highly flexible in accessing the spectral gaps left by the primary users while they are offline. OFDM modulation is proposed as the best option for such temporary rental coordination as it makes it possible to leave a set of unused subcarriers to fill the spectral gaps [16 - 18].

The fundamental design of OFDM spectrum pooling is to match the bandwidth of one subband of the primary network with an integer number of subcarriers used in secondary networks. Figure 3.1 shows an example of three subcarriers of cognitive users that are using one licensed subband.

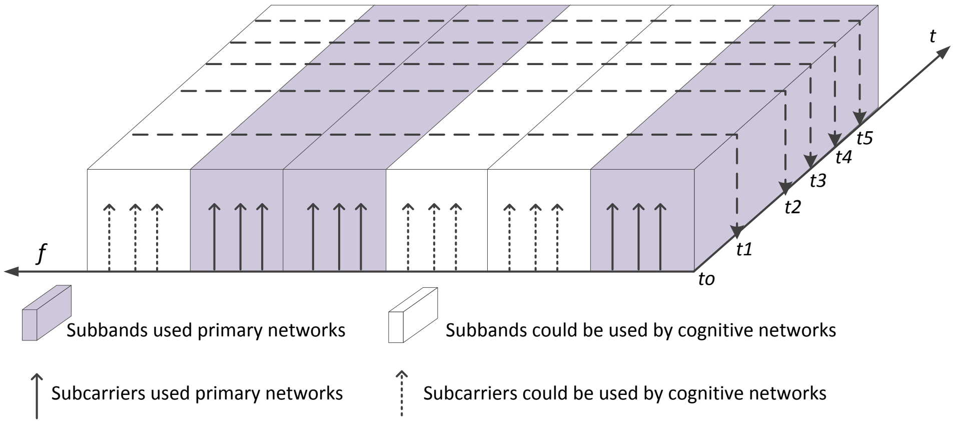

Figure 3.1: Allocating users in dynamic spectrum access model

To model the coexistence between the primary and secondary users and the spectrum allocation of the available channels in spectrum pooling model, various transmission time slots are set for the channels available for the both networks. In Figure 3.1, at each time chunk t_d^5 , d = 0, 1, 2, 3,.., a new band-allocation assessment is made to use any free holes in the spectrum. Therefore, secondary networks are assigned to the new slots according to their cell site and their transmission requests. These are the two key variables in spectrum access tactic here, in addition to the spectrum efficiency, as spectrum is a very valuable resource.

The proposed model is using a semi-independent microcellular system thus, it is important for the spectrum-sharing algorithm to be fully distributed among the participants in the network model. Additionally, the algorithm complexity should be kept low in order to match the flexibility requirements to adapt between various channels in secondary networks. Any high levels in computational load may lead to lost scarce transmission opportunities and increase the time consumed in assigning channels to new users. This impacts the creditability of cognitive mission in spectrum utilisation and the ability to attain short time transmission opportunities. Therefore, transmission decision is made by evaluating the channel state. Assuming the subbands has a fixed bandwidth limit of w. Due to the dynamic wireless changes, the number of available spectrum subbands is variable and is given by k.

The total number of cognitive users is assumed to be B. Assuming that $b, 1 \leq b \leq B$, hence, the number of set-n users at period t_d can be given as $u^n(b, t_d)$, where $1 \leq n \leq N$, where N represents the number of available service types. In addition, $k(b, t_d)$ is used to represent the number of subbands occupied by the cognitive network base stations b at period t_d. Let $k(t_d)$ denote the number of free subbands in the spectrum pool at period t_d and the arrival and departure processes of mobile users in cognitive domains are assumed to be Poisson process as in [15]. For b network, the expected user arrival and departure rates of set- n users are represented by $v_u^n(b)$ and $\mu_u^n(b)$, respectively. In the same way, the free spectrum holes arrival and departure processes are also assumed to follow Poisson processes, with v_k and μ_k as the expected arrival and departure rates respectively.

3.5.2 Problem Solution for Spectrum Sharing

The spectrum sharing is formulated for the investigated models as a stochastic process at which only one of the b cognitive base stations is set to be active to make use of the new available spectrum subband.

There are five expected network changes at any period t_d, during $1 \leq d \leq T - 1$, where T is the maximum number of periods considered in this analysis. These are listed in Table 3.1 below.

Table 3.1: Transition States for Cognitive Network Spectrum Access

State	Description
I, t_d^1	Cognitive base station starts transmitting
II, t_d^2	Cognitive base station stops transmitting
III, t_d^3	Spectrum subband becomes available to cognitive network
IV, t_d^4	Cognitive network losses a subband due to the primary network returns to transmit
V, t_d^5	Cognitive users losses a suband due to clashes between various domains transmissions

As there are no guarantees for the time of spectrum availability durations and futuristic wireless changes from cognitive network prospective, the transmission decision options at any time period is defined as:

$$o(b, t_d) = \begin{cases} 0, \text{if network } b \text{ is online} \\ 1, \text{if network } b \text{ is offline} \end{cases} \tag{3.1}$$

In the studied coexistence models, one period of transmission is allocated for each base station. This allows overcoming any probability of interference occurrence between various spectrum users. This also subject to the decision of transmission in place and is and the admissions of any new users. Final transmission decisions are a function for the maximum number of users in network b and the maximum numbers of subcarriers that are available at a time for network b. The users' admissions are modelled in this study as a random process to allow a real representation of coexistence between primary and secondary networks.

3.6 CRoF Framework

The concept of cognitive radio over fibre is presented in terms of network model that incorporates different base stations at different levels with one main processing unit. The method used assumes high level integration of units provided by the necessary algorithms allow the functioning of the new system to achieve the anticipated goals. The main goal is to access spectrum holes locally and time-efficiently. Figure 3.2 shows the proposed framework for CRoF multiple transmission two-tier cells. Without loss of generality, the system used here has two cognitive microcells as an example to demonstrate the concept of spatial accessing to the spectrum. For simplicity, the distance between these two microcells are assumed to be long enough so that the interference effects are negligible. Both microcells are connected by a radio over fibre to the main CRoF-core without any packet loss and enough bandwidth for all transferred packets through the landline connection. In the same way, the conversion time for channel conditioning between wireless BSs and RoF is assumed to be much lower than the propagation delays induced by the wired link.

The CRoF core functionality must be put in place to enable performing identify function of the cognitive system. There are a number of methods available to determine spectrum usage over a given band. These range from energy detection to analyse the features of the signal of the primary users.

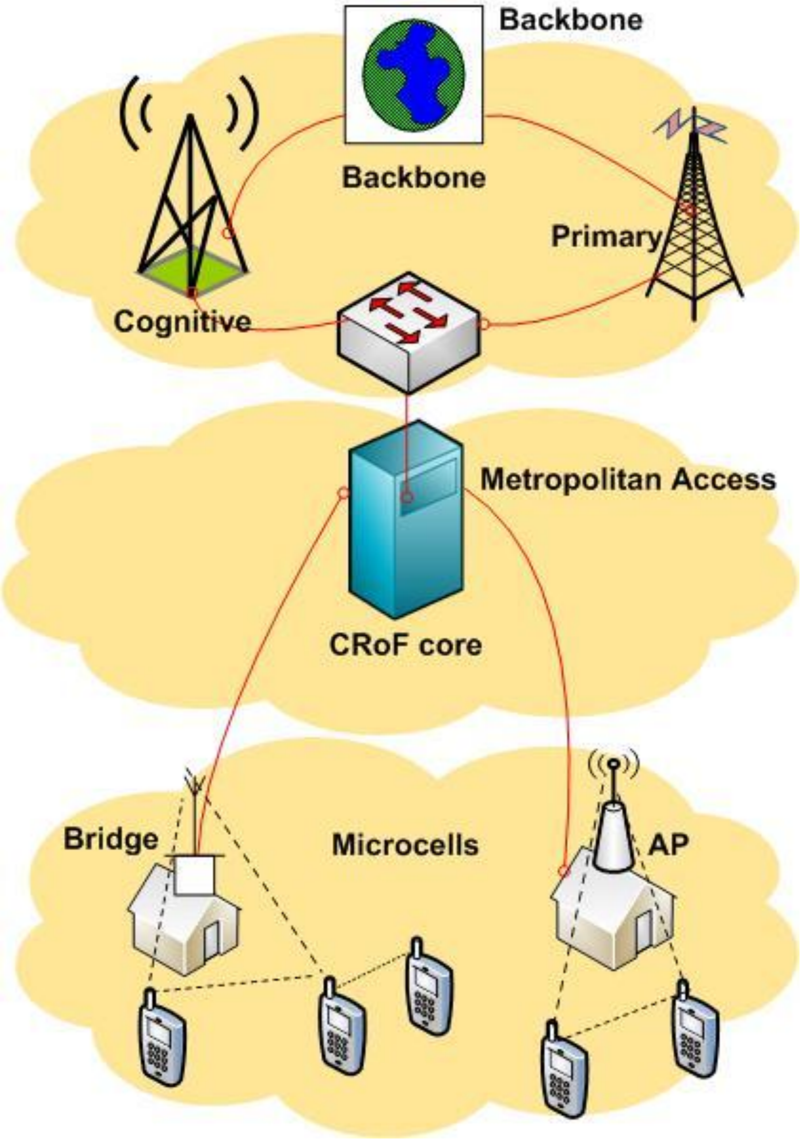

Figure 3.2: CRoF system frameworks

User connections are limited to the intra-cell domains with some users that are capable to perform inter-cell connections with a user located in another cell/sub-cell (e.g., scenario CRoF_PR_AP). The resource allocator needs to analyse the system according to the transition states given in Section 3.5.1 to get the channel information of all links, and then performs distortion control. All cognitive users can use any of the bandwidth available channels to send data at any time instance whenever they can and following the distributed access policy. In this two-tier system, two transmitters are located at different microcells in coexistence with the main macro-CRoF BS and in coexistence with other primary users in the field. The major challenge for each of these users is how to consider the available transmission opportunities and how to access resources to each user in each link in order to maximise resources sharing.

Fibre optic radio access networks are optical backbone networks for radio access systems, where fibre links have the function of transferring radio signals into remote stations without destroying their radio format, such as RF, modulation format, and so on [22]. Therefore, we propose the radio over fibre landline connections as an alternative choice for replacing the wireless links of the cognitive network. The combination of CR nodes to the RoF creates a new type of reconfigurable bases stations namely CRoF. There is no development made to the RoF as it is used only for connecting the CR BSs. On the other hand, CR models are upgraded to include the fibre connections as an option in communicating with other base stations. This new mesh CR-fibre system simplifies the complexity of DSA by introducing a new scheme for spectrum slicing and sharing based on local spectrum access. Therefore, instead of using the traditional centralised, distributed, and hybrid network managements, CRoF is the first secondary system wired with landline network. In addition to the effective allocation for the available resources, the new proposed network model reduces the time spent during service approval.

In CRoF network, BSs remain able to communicate with each other via wireless connections. The actual role of the fibre here is to maintain connections for spectrum unavailability, link budget, and fallen in QoS scenarios. Thus, CRoF BSs behave as CR and CRoF models at the same time. One additional advantage from using the fibre here is the spectrum savings gained from transmitting using fibre connections rather than wireless links. As a result, the CRoF frees up more resources for the cognitive network in a spectrum pool model. This increases the cost effectiveness and the reliability of future cognitive networks in maintaining communications in very dynamic wireless environments.

The successful deployment of CRoF microcellular bases stations is a function for the available free channels at the different cell sites, number of expected end-users, and forecasted future demands and outcomes from cognitive communications. The wide distribution of CRoF domains result in shorter wireless links while BS-to-BS transmissions are directed through fibre connections. Obviously, the cost of setting up is significantly impacts the deployment sites if the new system. The throughput barriers for long routes, discussed in Chapter 2, justify the need for CRoF system. Initially, the CRoF can be proposed as a long term solution for cognitive networks in metropolitan areas. The direct expected outcomes for CRoF installation are:

- Increasing network capacity by freeing more links and channels across the network for other cognitive radio operations.
- Establishing new independent sub-network capable of supporting variable downloading speeds for the secondary systems.
- Avoiding overhead delays at high interruption loss.
- New approach for green communications.

3.7 System Models

The adoption of RoF coupled with cognitive radio networks provided with advanced interface radio access technologies can ease the traffic congestion resulted from the spectrum unavailability. One of the main features of the CRoF network is to efficiently use the underutilised resources of existing infrastructure by diverting the transmissions between mobile and fibre networks in order to recover services. This research quantifies the amount of spectrum that can be saved from using fibre for intermediate communications between CR-BSs. A spectrum saving model is introduced to analyse the increase in numbers of subscribers in the cognitive network due to modifications in the infrastructure that targets to improve the quality of service.

3.7.1 Call Diversion Algorithm

A method of diverting calls between BSs using fibre network is integrated to CRoF system in order to interconnect various base stations to the CRoF core unite. The algorithm assures the reliability of a call using the landline network. To achieve this, call forwarding algorithm is activated to allow calls diversion from/to a certain BS using fibre connections. In this way, any of the systems' BSs can enable the call forwarding scheme if the dialled mobile phone is outside the zone of their coverage area. This requires the identification of the target mobile user position and the serving BS.

The forwarding location of the mobile call is determined using a mobile location technology. The mobile location technology refers to the attaining of the position of a mobile phone at a time whether it was stationary or moving. Localization is performed via multilateration of Radio Frequency (RF) signals between different BSs of the network and the mobile phone. This performed through socialising that a mobile sends during roaming with the next nearby BS with no need for any real active call. The measured signal strength allows specification of the domain where that mobile phone exits at that time. The mobile positioning, which includes location based service that discloses the actual coordinates of a mobile phone, is very important for cognitive networks to decide the channels allocated for communications and the spectrum savings expected from using the call diversion scheme. Therefore, the more proper locating scheme refers to the purpose rather than a positioning process. In this model, the prior art of the call forwarding method at the BS is initialised once and when the mobile user moves into its transmission domain. The proposed scheme does not include any new functions with existing mobile phones and does not require additional mobile phone hardware or software to implement.

Figure 3.3 shows the model of the remote command process for diverting calls or messages between base stations. This is an algorithm that enables a CRoF core to remotely command other BSs to divert calls or messages using fibre network to the new mobile location. The algorithm is embedded in the CRoF core and all BSs at the macrocellular and microcellular domains.

The scheme works as follows: in step #1, a mobile phone is starts moving between CRoF domains. As the mobile phone starts the normal registration with the nearest BS in #2, a remote command is forwarded by the BS to the CRoF core for diverting calls to the newly registered mobile phone. Then this command is set to OFF in #3 in waiting for CRoF core response.

Once it has been confirmed that the mobile phone is registered with the new BS, the remote divert program in step #4 is initiated and starts running. Then, the activated program will read and evaluate the mobile location in #5. The program will check the mobile phone position if there are more than one request for diversion which is issued from macro/micro CRoF-domain, in #6.

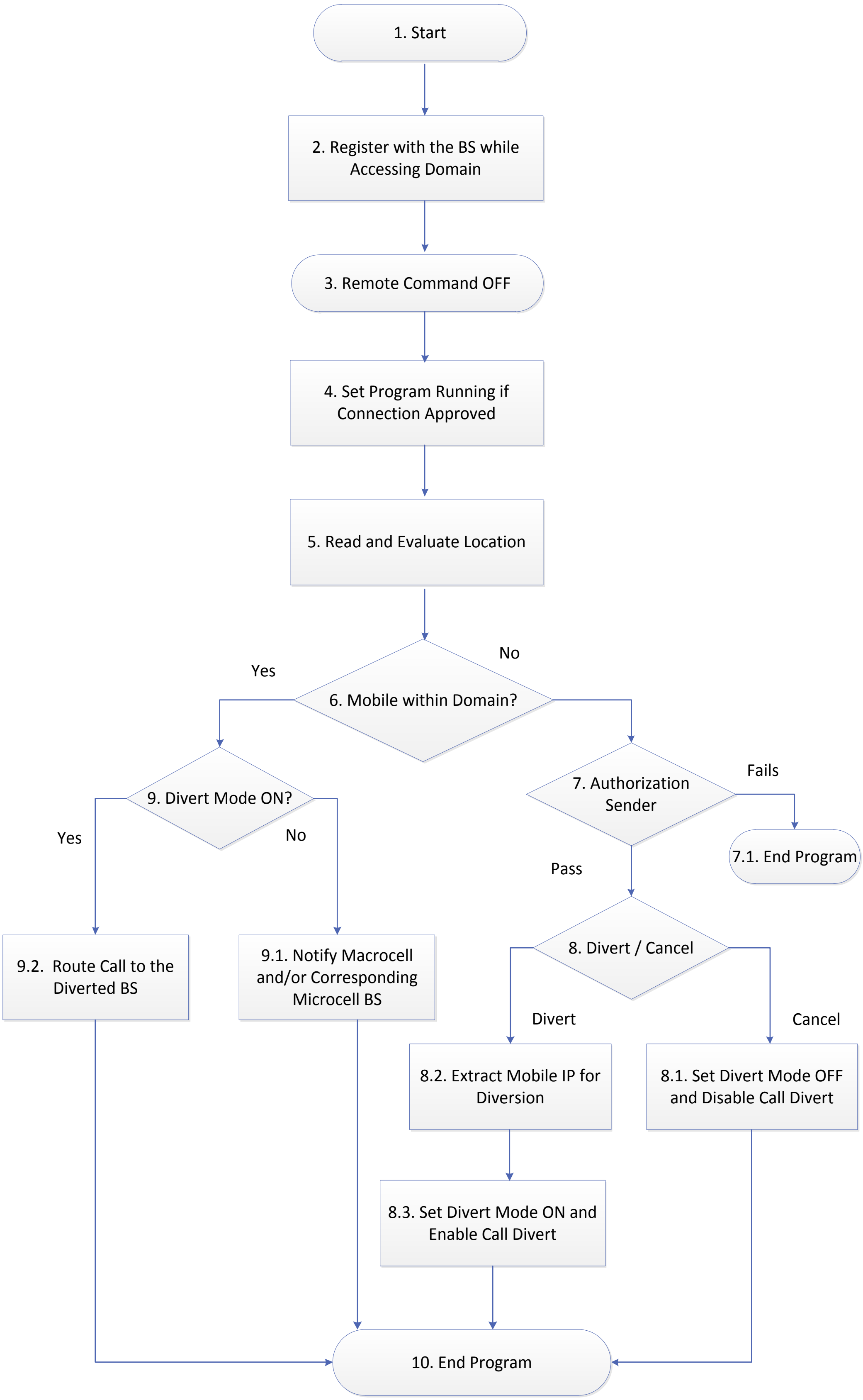

Figure 3.3: Call diversion scheme

When the CRoF core is not be able to identify the position of the mobile phone especially if it was moving between two transmission domains, the program will authenticate the sender as in #7, if this fails the program ends in #7.1. If the authentication passes, the program will identify the command to either divert calls of cancel diversion as in step #8. When cancel command is received, the program will set the diversion mode to OFF and stops further diversions from other BSs as in step #8.1. If the divert is approved, the program will extract the mobile phone location as in #8.2. Then, a command is issued to set the diversion mode ON and enable the diversion of calls to the mobile's new location as in step #8.3. The diversion of calls continue until further notification is received from another BS that the mobile phone has moved into new domain then the program starts again.

Once it has been confirmed that the mobile phone is registered with the new BS, the remote divert program in step #4 is initiated and starts running. Then, the activated program will read and evaluate the mobile location in #5. The program will check the mobile users positions and if there are more than one request for diversion which is issued from macro/micro CRoF-domain, in #6.

When the CRoF core is not be able to identify the position of the mobile phone especially if it was moving between two transmission domains, the program will authenticate the sender as in #7, if this fails the program ends in #7.1. If the authentication passes, the program will identify the command to either divert calls of cancel diversion as in step #8. When cancel command is received, the program will set the diversion mode to OFF and stops further diversions from other BSs as in step #8.1. If the divert is approved, the program will extract the mobile phone location as in #8.2. Then, a command is issued to set the diversion mode ON and enable the diversion of calls to the mobile's new location as in step #8.3. The diversion of calls continue until further notification is received from another BS that the mobile phone has moved into new domain then the program starts again. When mobile location is identified within one of the CRoF-BSs, the divert mode is examined in #9 and all the calls are being routed to the BS where the mobile user is registered in #9.2. Otherwise, macrocell and the corresponding BSs are notified to allow direct connection between macrocellular BS and mobile phone to overcome call latency as in #9.1. The program ends at #10 and returns to #3.

The algorithm used when a mobile is identified within the CRoF core is shown in Algorithm 3.1.

```
//*****  Algorithm 3.1:  CRoF Core-Call Diverted   ********//
Divert command received from the BS
Set program to run once connection to mobile approved
For each divert command received
{
    Read BSS identifier
    BS not specified
    Authenticate issuer
If divert command approved
    Extract IP of designated precipitants
    Activate call diversion to route calls to the extracted IP
    Set divert mode ON to route any future calls received
  Else
    Cancel command determined
    Deactivate call diversion features
    Set divert mode OFF for calls
  End if
    BS specified
  If divert mode on received
    Send out received calls to the designated IP
  Else
    Notify macrocell to start urgent wireless link
  End if
}
Return
```

This algorithm provides a method for remotely directing BSs to divert calls to a designated BS recipient where the mobile phone is connected.

If the CRoF–core was unable to identify the transmission domain at which the mobile is located, then the algorithm for divert mode at the remote BSs is described in Algorithm 3.2.

//* Algorithm 3.2: Remote BS-Call Diversion Declined ***//**

```
Parse message
If divert command not received
Target BS not specified
{
    Authenticate issuer
  If divert command approved
    Extract IP of designated precipitants
    Activate call diversion to route calls to the extracted IP
    Set divert mode ON to route any future calls
  Else
    Cancel command determined
    Deactivate call diversion feature
    Set divert mode OFF for current and future calls
  End if
  If call is received
     Set divert mode ON received
    Send out received calls to the designated IP
  Else
    Notify macrocell to start urgent wireless link
  End if
}
End if
```

If the remote BS has tracked the mobile user and requested to set the divert mode, then the algorithm for divert mode at the remote BSs is described in Algorithm 3.3.

```
//***  Algorithm 3.3:  Remote BS-Call Diversion Request   ***//
Parse message
If divert command is received
{
    Read BSS identifier
  If divert command approved
    Set divert mode ON to route any future calls received
  Else
    Cancel command determined
    Notify other BSs to stop routing calls
  End if
  If call is received
    Send out received calls to the designated IP
  Else
      Notify macrocell to start urgent wireless link
  End if
}
End if
```

The objectives and advantages of this scheme are clarified further in the following sections in order to show the improvement in the uplink capacity compared with the traditional cognitive network models.

3.7.2 Spectral Efficiency of CRoF Microcellular Model

3.7.2.1 Model Formulation

The following method is developed to calculate the mobile bandwidth savings obtained as a result from CRoF installation. This method shows the motivation behind the development of the CRoF system and the justification for the subsequent developments. The scheme is based on the average time the subscribers spend moving between the macrocellular and microcellular areas, the number of fibre connected microcells, and the average traffic generated by each mobile, as shown in Figure 3.4. To simplify the calculation, the model considers only the savings gained from the microcell fibre access of the CRoF system. This is performed under the assumption that call diversion mode requests are issued only by microcells BSs.

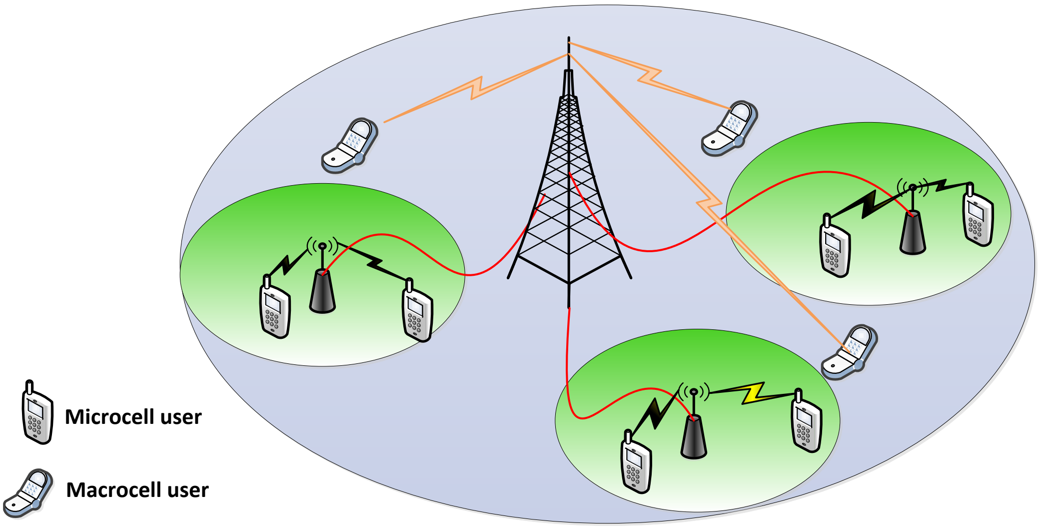

Figure 3.4: The general CRoF marco/micro two-tier model

The bandwidth saving due to the use of fibre depends on the ratio of the average number of calls initiated/received by a microcell BS and diverted through fibre. Hence, let that:

N_{mac} is the number of mobile subscribers connected to the macrocell BS.

N_{mic} is the number of microcell BSs connected to the macrocell through fibre .

In all our models during this chapter, we assume that every microcell has at least two mobile subscribers and that, $\mathrm{N}_{mac} \geq \mathrm{N}_{mic}$. As the microcells might be deployed all over the cell sites, then a mobile subscriber will spend an average time of $\mathrm{T}_{\mathrm{mic}}$ in hours at the microcell area compared to average time of $\mathrm{T}_{\mathrm{mac}}$ in hours spent at the macrocell area (T_{mic} is counted within T_{mac}, so $\mathrm{T}_{mac} \geq \mathrm{T}_{mic}$). Then, let:

C_{mic} average number of calls initiated/received by a mobile subscriber while at microcell in an hour.

C_{mac} average number of calls initiated/received by a mobile subscriber while at macrocell in an hour.

T_{pk} number of peak hours over which the entire traffic initiated/received.

As the final values of calls in macrocell area include the calls made within microcells, then $\mathrm{C}_{mac} \geq \mathrm{C}_{mic}$. The number of calls initiated/received during peak hour traffic by a mobile subscriber at CRoF microcell can be defined as:

$$\mathrm{N}_{pkh,mic} = \frac{\mathrm{C}_{mic} \times \mathrm{T}_{mic}}{\mathrm{T}_{pk}} \tag{3.2}$$

The number of calls initiated/received during peak hours of traffic by a mobile subscriber in the macrocell area is given by:

$$\mathrm{N}_{pkh,mac} = \frac{\mathrm{C}_{mac} \times \mathrm{T}_{mac}}{\mathrm{T}_{pk}} \tag{3.3}$$

Then, the ratio of number of calls initiated/received during peak hours of traffic by a mobile subscriber between microcells and macrocell base stations is given by:

$$\mathrm{R}_{mic/\,mac} = \frac{\mathrm{N}_{pkh,mic}}{\mathrm{N}_{pkh,mac}} \tag{3.4}$$

Assume that all calls received by mobile subscribers at microcell area are diverted to macrocell via fibre then:

% of total spectrum saved in a microcell area through call diversion to fibre =

$$\mathrm{BW}_{pkh,mic} \times 100\% = \left(\frac{\mathrm{C}_{mic}}{\mathrm{C}_{mac}}\right) \times \left(\frac{\mathrm{T}_{mic}}{\mathrm{T}_{mac}}\right) \times \left(\frac{\mathrm{N}_{mic}}{\mathrm{N}_{mac}}\right) \times 100 \tag{3.5}$$

In the above analysis, uniform average calls duration for all categories of subscribers has been assumed.

3.7.2.2 Model Evaluations

In order to verify the concept of increasing the network performance and spectrum savings due to the use of microcells, the above mathematical model is evaluated using analytical analysis. The assumptions used are given in the following Table 3.2.

Table 3.2: Assumption values for BW savings Evaluations

Parameter	Description
C_{mic}	Each mobile user performs 10 calls/hour. This value overall calls value increases as the number of mobile users increases
C_{mac}	We assume one mobile attached to the macrocell base station with 10 calls/hour. However, this value includes also the numbers of C_{mic} calls
T_{mic} and T_{mac}	These values are evaluated according to the speed and size of the macrocell and microcells of 1 and 0.2km^2
N_{mic}	2 and increased later to 4.
N_{mac}	5-32 in steps of 2
T_{pk}	3 hours

The estimations shown in Figure 3.5 depict that significant spectrum savings can be achieved with the installation of higher numbers of microcells.

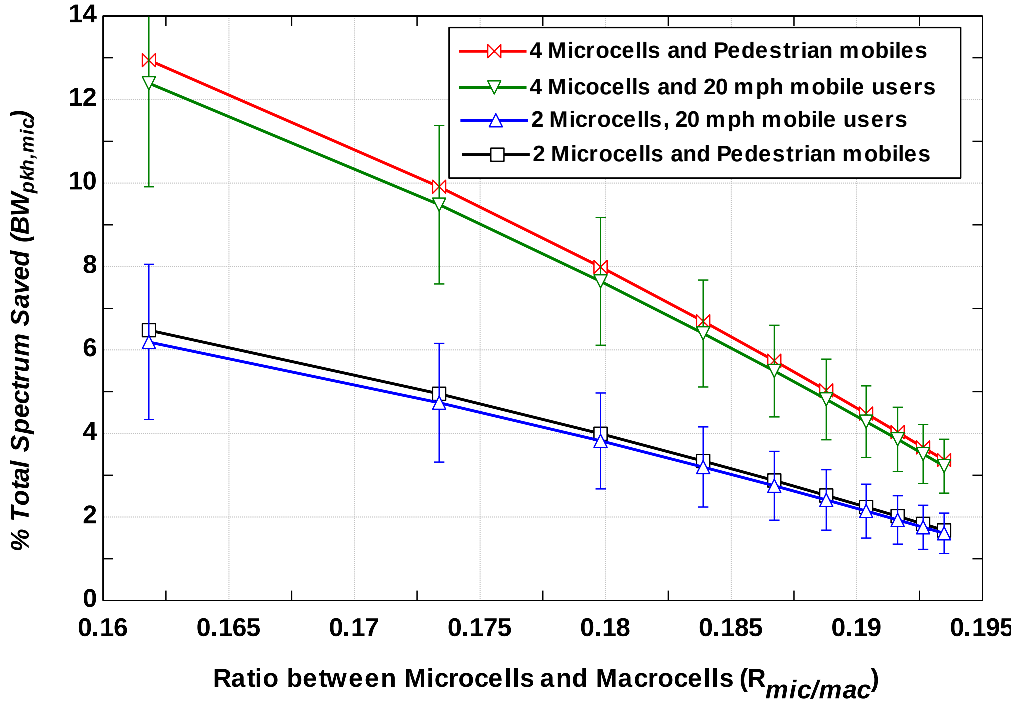

Figure 3.5: The Spectrum savings vs. ratio for microcells/macrocells

The results show that the diversion of calls allows more spectrum saving in multi-access small wireless system placed inside a macrocell. These results are the motivation for the following contributions of identifying the best RAT for the microcellular system and the coexistence challenges with the macrocell in cognitive communications. Two main questions can be raised here? Firstly: what is the highest numbers of microcells that can be hosted inside a macrocell before performance starts to decline? The answers will be discussed in Chapter 4. The second question is: what is the impact of speedy mobile phones on spectrum savings. From the Figure 3.5 the speedy moving mobile phones results in slightly less spectrum savings due to the fact that they move faster between the fibre connected access microcells and the macrocell domains causing the loss of more scares spectrum transmission opportunities. This becomes very critical in secondary communications and escalates the numbers of spectrum handovers when moving between different domains working at different frequencies. The solutions for this problem will be given later on in Chapter 5 of this thesis.

3.8 Radio Access Technologies

As the main application for the CR is in cellular communications, traditional cells boundaries of the primary mobile networks can be used as the transmitting edges for future cognitive network base stations for installations and coverage zones. In this way, spectrum trade between the primary and secondary systems can be efficiently coordinated to achieve the best spectrum utilisation and to prevent any confusion in services between the two networks. This might help also to understand the sources of any interference that results from overlapping of services between different spectrum users and to ease the way of charging secondary users.

In this research, two kinds of CRoF base stations are studied that consider different coverage area: macrocellular unit known as CRoF core. Similarly, microcells domains are served by CRoF wireless terminals. These terminals perform all transmissions to secondary users at microcells. These two tier models of BSs are connected to each other wirelessly and through a fibre network. The CRoF core is assumed as the governing station responsible for all final transmission decisions within the macrocell area while transmissions are handed over to microcells whenever a mobile unit moves inside microcells and vice-versa. However, communications within the wider network and with other macrocells are provided through CRoF core. Practically, this means that the CRoF core can decide to approach a secondary mobile user across CRoF core wireless connections or through its peripherals at microcells. In the same way, the CRoF core is responsible to detect and serve any mobile cognitive user as soon as it goes into its coverage area.

The proposed system reduces: the complexity of traditional cognitive networks by dealing with small-sized network partitions which can adapt their features according to the spectrum situation and the kind of data transferred. This is better than managing a huge and heterogeneous network topology. Additionally, these small local networks reduce the time spent to serve local customers by reducing signalling with the main service providers. Obviously, moving the switching centre duties to local small controllers for example CRoF core results in major time savings during spectrum access decisions. This is very important matter for a network based originally on temporary transmissions.

The RATs for CRoF applications can be put into operation using four corresponding interfaces.

3.8.1 CRoF as Independent System

The model formulation of the CRoF system is proposed here as an independent system that coexists with other primary networks in the field and shares resources with them collaboratively. Therefore, two networks of primary and cognitive mobile operators are defined with explicit set of BSs functioning in the same area with predefined transmission domains.

3.8.1.1 CRoF_AP

The CRoF system uses APs as a microcellular wireless interface terminals, as shown in Figure 3.6. The CRoF system is composed mainly of two main parts: a core at macrocell main area and microcells APs. The CRoF core is presumed to be the main governing authority that directs the network actions and spectrum access to the most efficient services outside microcells. The CRoF-APs can work independently in their coverage areas but they are slaves to the core system. This means that CRoF core can transmit wirelessly, if it chooses, to any mobile user within a microcell even if there is an available link between the microcell AP and that user. Otherwise, if a mobile moved from macrocellular area to inside a microcell, the CRoF core would terminate direct communications and handover them to the microcell AP.

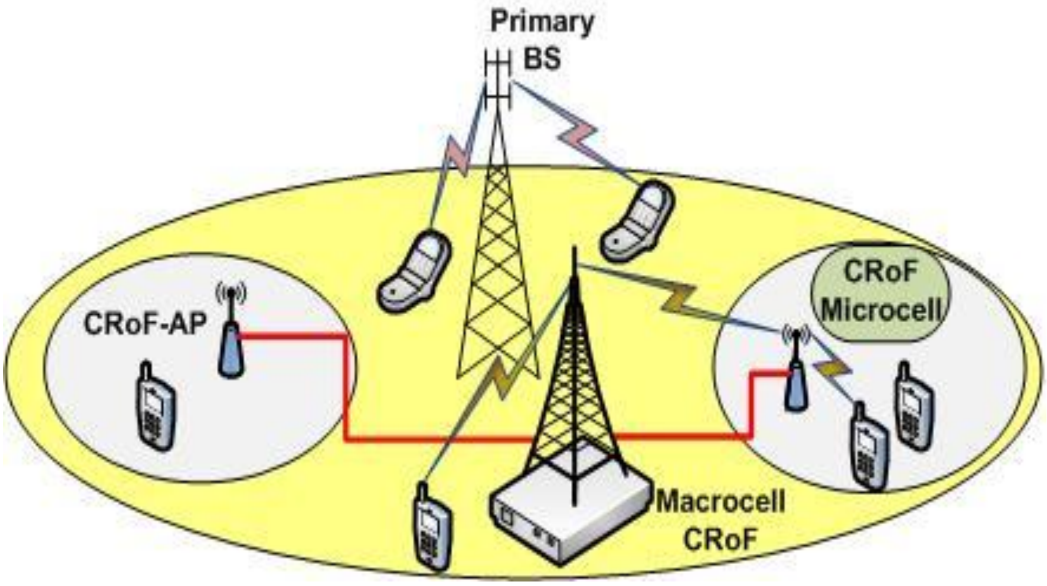

Figure 3.6: CRoF system using APs

The short range-links established by the microcell AP results in less consumed power and higher throughput. The less power means less possible interference to the primary system and to other CRoF terminals while higher throughput secures the necessary downloading speeds for wireless Internet coverage. In this case scenario, the macrocell CRoF core can communicate with the microcell AP using cognitive wireless links and using the fibre connections. This dual option of switching from wireless to fibre can be decided according to the wireless environment situation and end-users' demands. Thus, fibre connections are used whenever the primary user is active or there are huge requests for data which exceed the time slots available for cognitive transmissions.

In this scenario, the handover of communications between neighboured microcells and between CRoF core and individual microcells is organised on a scalable order as a function of the transmission domains. As a result of so many distributed CRoF-APs, there will be a better detection for spectrum holes if the costs considerations of network installation are neglected. The transmission options are always decided in a distributed mode to ensure matching the optimisation of any available white spectrum.

3.8.1.2 CRoF_bridge

In this method, the CRoF system is composed of the main CRoF core and bridge units at microcells. These bridge units hold cognitive WLAN transmitter/receiver systems, as shown in Figure 3.7. This scenario is based on centralised management for spectrum access. Thus, transmissions' decisions can be only issued by the CRoF core once an opportunity to access the spectrum is identified and there is a request for a transmission. This is because of the technical features of bridges as they have only two layers: physical and MAC. In this case, the CRoF core is the responsible for identifying individual customers' needs, available resources, necessary fluctuations in routes, and final transmissions' decisions. Communications can be performed between microcells bridges themselves wirelessly using point-to-point pairs or using CRoF fibre network. Hence, CRoF bridges can be used easily to relay communications between different macrocell portions and to save resources through local transmissions rather than using macrocell global wireless resources.

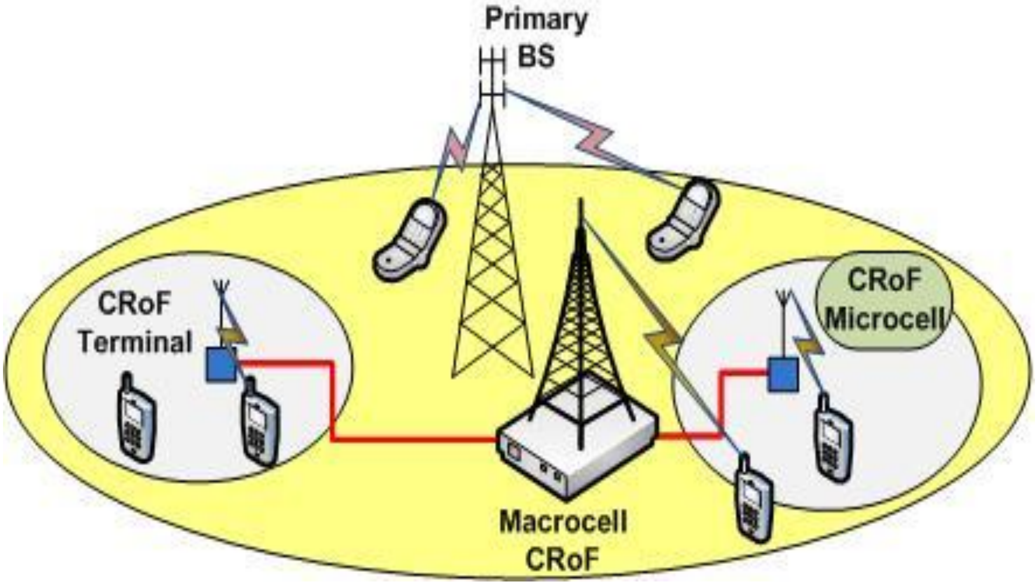

Figure 3.7: CRoF system using bridges

Although the outcomes of such system may remain less efficient than the previous model scenario, the decision of choosing between any end–terminal wireless technologies depends mainly on the ultimate requirements of the network services and expected end–users interfacing technologies.

3.8.2 CRoF as Depenedent System

A new combination of secondary and PR networks is proposed by connecting the novel CRoF system to the primary network. In this method, CRoF can be implemented by combining it with the PR macrocell to share the same resources collaboratively. Here, CRoF has no macrocellular wireless transmission system and the CRoF core here is just the computational server that manages the calls between microcells and the primary macrocell BS. The CRoF system in this case, does not have a cognitive wireless access to the backbone as in Section 3.8.1. Instead, CRoF is composed of microcell terminals and fibre connections. Practically, CRoF here is a subnet to the PR system that can achieve local transmissions as a secondary spectrum user. Technically, there should be a limitation for the number of cognitive users added to the PR system to overcome flooding in services. In this way, CRoFs at various macrocells can only talk to each other via primary BSs. This combination between primary and secondary systems offers a lot of opportunities for sharing resources, establishing new protocols for exchanging information and to prevent inference. Additionally, this combination might form the initial steps for deploying cognitive network towards fully independent operational networks in the evolutionary steps.

3.8.2.1 CRoF_PR_AP

In this scenario, CRoF can be implemented using multiple numbers of microcell APs. The communications between CRoF core and microcells is achieved mainly using fibre, as shown in Figure 3.8.

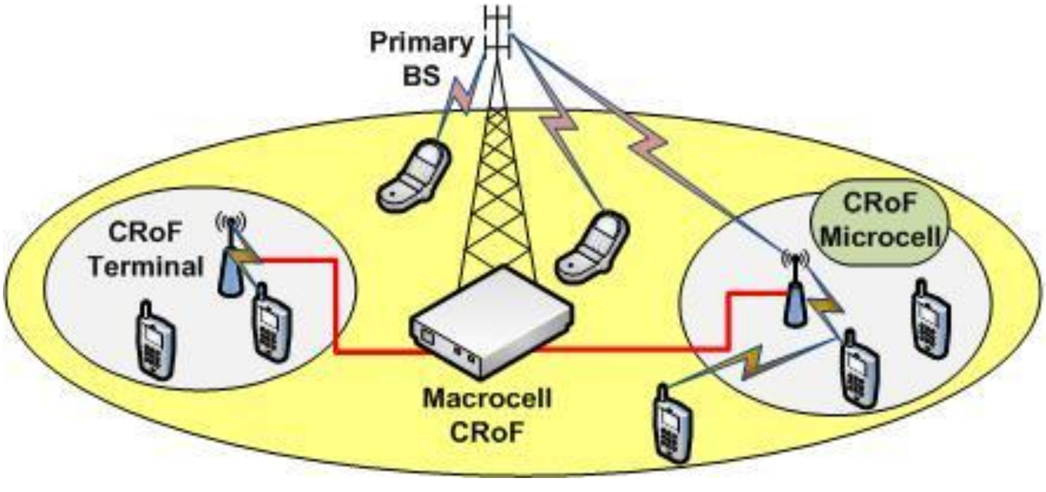

Figure 3.8: CRoF to primary using APs

The PR–BS is supposed to be able to communicate with all CRoF–APs via wireless links using the quad–band channels. This requires that PR system has identified all the APs in the system as terminal users. For the CRoF core, the criterion to choose between the two options of connections to approach APs depends on the available resources of the primary network. Also, the microcells' APs can send wirelessly to each other directly for being fully autonomous CR-BSs.

To perform the cognitive communications outside microcells' domains, three possible solutions are presented here: Firstly, cognitive ad-hoc communications, where any mobile user can exchange data with the CRoF-AP using Mobile Ad–Hoc Network (MANET) protocols as cognitive users as in [1]. Secondly, create a chain of neighbouring microcells can achieve local and global macrocellular cognitive services. Thirdly, mobile operators may design new handsets that can communicate and register with primary and cognitive networks at the same time. As a result, the primary network may assign a number of its end-users to CRoF microcells in order to save spectrum and to satisfy the needs for higher throughput requests. In such case, the cognitive systems work as a subnet to help the PR and not as a separate communications operator.

3.8.2.2 CRoF_PR_bridge

As mentioned earlier, the CRoF system can be implemented using bridges. This solution is also applicable for CRoF attached to the primary network, as shown in Figure 3.9. Hence, bridges are used to perform the local secondary communications at microcells.

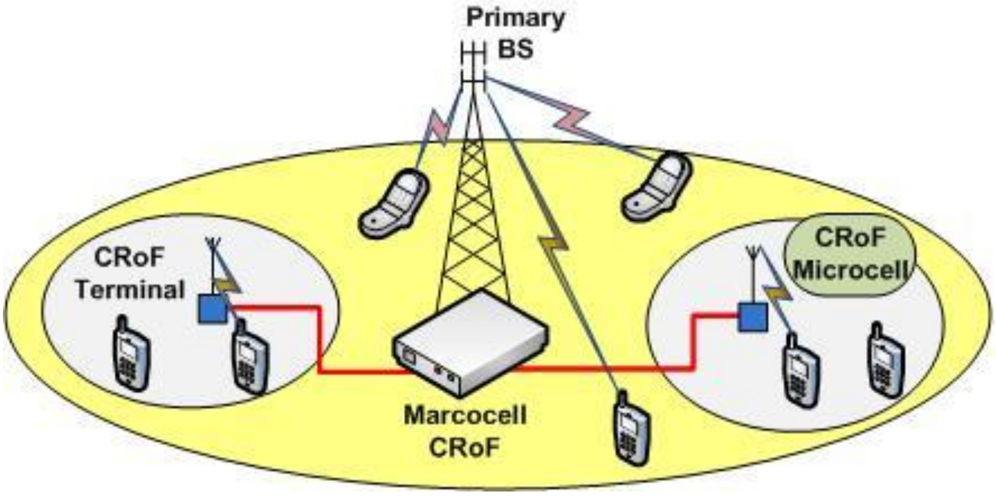

Figure 3.9: CRoF to primary using bridges

In this scenario, the CRoF can transmit to the microcells' bridges using RoF only. The reason for this is that bridges are not aware radios and not able to adapt and receive the primary wireless transmissions as in CRoF-PR-AP scenario. Therefore, the bridge will work as local secondary wireless terminals for a landline CRoF system.

The combination of cognitive microcells to the primary networks seems to be a promising step forwards in network systems managements. Additionally, this hierarchical distribution of transmission domains allows mobile operators to direct resources according to the data flow and end–users needs. However, the success of this application is highly dependent on commercial aspects and licensing issues between the primary operators and the future cognitive networks.

3.9 Network Modelling

In this section, the technologies used to create the coexistence models for the simulation procedures are described briefly. The aim is to maximally utilise radio resources of cognitive network in dynamic situations, offering mobile users an improved data rates using different technologies of LTE at the macrocell backbone and 802.11e at the microcells domains.

3.9.1 LTE Macrocell

The Release-10 LTE-Advanced (LTE-A) is a major enhancement of the Long Term Evolution (LTE) standard developed by the 3rd Generation Partnership Project (3GPP). LTE-A was ratified by the International Telecommunication Union (ITU) as an IMT-Advanced (fourth generation, 4G) technology in November 2010. The 4G objective is to meet challenges presented by the ever increasing use of "smart" wireless devices that require significantly higher spectral resources than conventional cell phones. LTE-A addresses those challenges by targeting peak data rates up to 1 Gb/s with up to 100 MHz supported spectrum bandwidth and by making use of high-order Multiple-Input Multiple-Output (MIMO) transmission with up to eight spatial layers on the downlink and four spatial layers on the uplink [23].

Proposals for CRoF aims at reduced delays, increased user data rates, increased cell-edge bit-rate and seamless mobility with deployed marco Evolved Node B (eNodeB) and micro WLAN. LTE-to-microcell networks enable local cell phone coverage and provide access to high speed wireless broadband services, which use smaller base station and existing fibre or other cable line as backhaul connectivity. It can diverse the load from LTE macrocell networks as well as reduce the operating and capital expenditure costs for operators.

LTE cell edge throughput maximisation is achieved mostly based on Link Adaptation optimisation and dense frequency planning strategies. The other solution is a smaller cell domain such as edge-microcellular system. These microcells come in a variety of sizes and flavours depending on how much traffic you want them to carry at a specific location. Classically WiFi hotspots are also small cells and WiFi offload is likely to form part of a mobile operator’s strategy in coping with network capacity demand. If traffic can be shifted onto WiFi, normally terminated onto a fixed line broadband connection it takes the strain off the mobile network.

3.9.2 IEEE802.11e for Microcell Cognitive Users

The 802.11b model is based on the application of the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) scheme known as the Distributed Coordination Function (DCF). The DCF is using a timing technique linking the Inter-Frame Space (IFS) and exponential backoff to avoid collisions and guarantee equal throughput to all stations. In this way, a station must first listen to the surrounding wireless environment before transmitting, or sense, the wireless medium to determine if it is busy. If the DCF Inter-Frame Space (DIFS) indicates an idle space then the station may transmit immediately. Otherwise, the station enters a contention period in which it will utilise the exponential backoff mechanism. The station selects a random backoff value from within the Contention Window (CW) and continues to monitor the state of the medium. When the medium remains free for a DIFS, the station starts to decrement its backoff timer once for each time slot the medium is free. Once the backoff timer reaches zero, the station will transmit. Otherwise, the station will freeze the timer at its current value and resume countdown when the medium has been free for a DIFS again.

The 802.11e is based on the original access mechanisms for 802.11b but has added functionality for QoS guarantees in which data transmissions that contain voice or video data can be very time-sensitive. QoS allows a lower delay to access the medium for this high priority traffic. This is incorporated on top of the 802.11b DCF in order to maintain backward compatibility. Priority of data is specified by an Access Category (AC). It is necessary that each data packet has an assigned AC. There are four ACs, in order from highest to lowest priority: Voice, Video, Best Effort, and Background. While Best Effort is the default set for any 802.11e station.

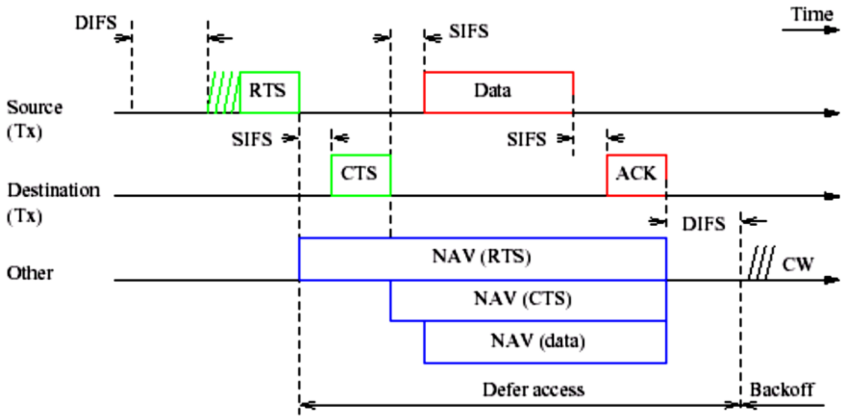

Figure 3.10: Relationships of key IFS times

The Enhanced Distributed Coordinated Access (EDCA) is the protocol that gives the 802.11e its distinguished features. It has a new parameter called the Arbitration Inter-Frame Space (AIFS) that replaces the DIFS used in 802.11b. The AIFS is determined by its AIFS Number (AIFSN) as specified in the standard for each AC. In this way, higher priority traffic is allowed to access the medium or resume backoff sooner than lower priority. The relationship between several IFS times is illustrated in Figure 3.10.

For 802.11e QoS application and in the event of a collision, the CW is doubled-up to a specified maximum value. In 802.11e, where two new minimum and maximum values are created, the lowest is used for high priority ACs. These ACs spend less time performing backoff after each collision or successful transmission. Higher priorities ACs are able to transmit more frequently, on average, than lower priorities since a backoff is always performed after a successful transmission [24, 25]. As a result, each station maintains a separate queue for each AC or traffic priority, this work is reported in [26].

These features ensures that the 802.11e do not interfere the other stations transmitting at anytime. It means that it is actually behaving as a secondary user for the unlicensed ISM band which matches the proposals for the cognitive radio functions. This allows us to deploy these stations in our simulation models and set the MANET transmission at different transmission intervals to simulate a dynamically access networks composed of primary and secondary networks.

3.10 Event Scheduling

There are a number of mechanisms that are used to generate the events driven by the simulation Kernel and the provided algorithm models. The Kernel scheduled events are a result of the configuration of object attributes of the different stations used in the Optimized Network Engineering Tool (OPNET) project. These are generated later to simulate scenarios according to certain specifications of traffic, application, and wireless environment. On the other hand, some interrupts are resulted from events relating to the new process models. These process models contain the developed call diversion algorithms. These code functions were modelled to allow call diversion Algorithms of 3.1, 3.2, and 3.3 to work collaboratively in order to examine the arrangements of RATs given in Section 3.8.

Figure 3.11 shows the generation of the call_div node model that connects the Opnet lte_as and ATM_sig node units. This arrangement allows re-diverting calls between the landline and wireless connections in the LTE macrocell BS.

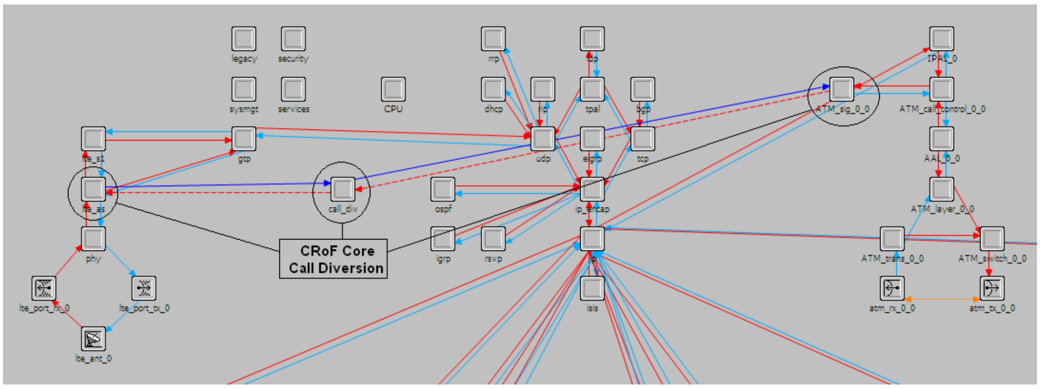

Figure 3.11: Call diversion algorithm 3.1 installation inside the LTE macrocell BS

The call_div unit contains the process model shown in Figure 3.12. The operation sequence starts with the initialisation of any interrupts and then to initialise the child process model. Then, idle process model unit judges the direction of packets between wireless and landline connections. This also includes the timing for decision making.

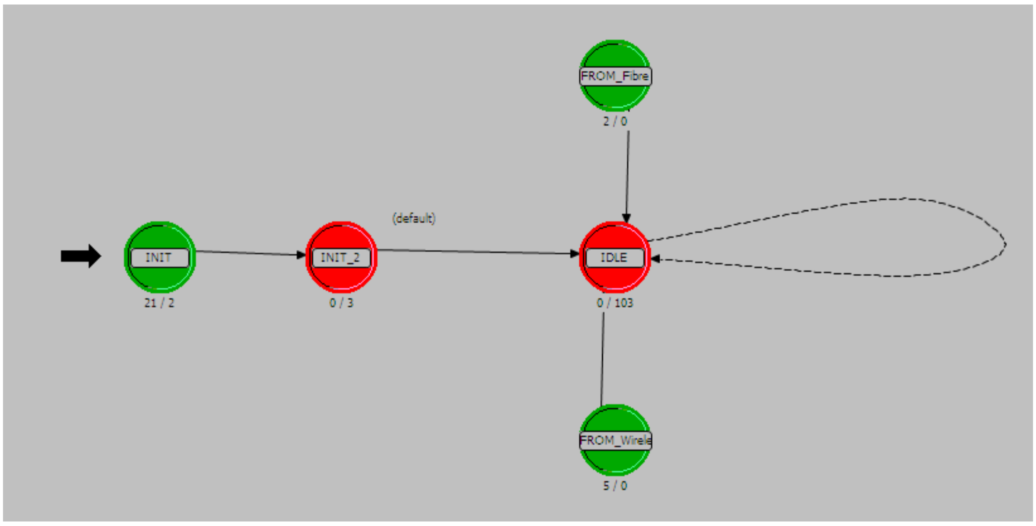

Figure 3.12: The process model for call_div node unit

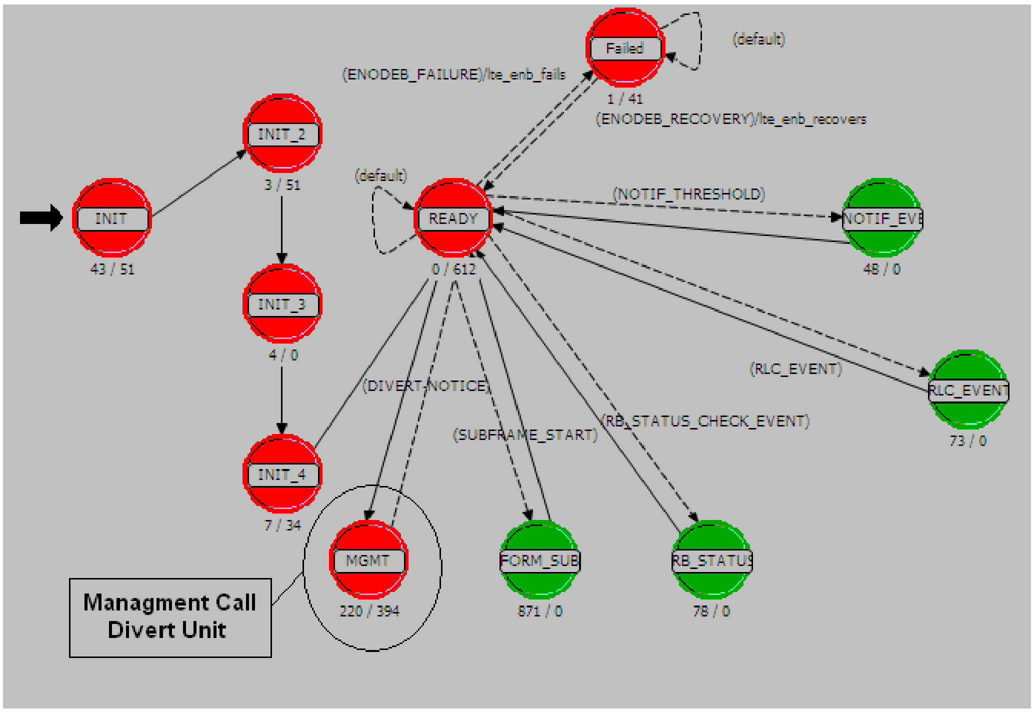

Figure 3.13: The MGMT process model for the macrocellular lte_as node unit

This developed model has added a new process state condition to the lte_as node model as shown in Figure 3.13. In this new arrangement, a management call divert unit named as MGMT is added to create the required interruption for re-diverting the calls to other sub-cells. In this new unit, target destinations are updated dynamically while assuming that all neighbour nodes are known and tracked. These data are used also to update the hash table with information about the positions of all User Equipment (UEs). This new model of LTE macrocell BS is combined to the algorithms installed at the APs and server attached bridges to enable efficient and immediate call diversions between CRoF terminal stations.

3.11 Simulations

The model settings and algorithms given earlier in this chapter were incorporated in the modules and settings of the simulated project with different scenarios to examine the performance of the CRoF microcells. These various corresponding RAT technologies of distributed and centralised managements were used to slice the available radio resources in coexistence with the primary network. The ultimate goals were to create heterogeneous network model were the LTE acts as the backbone macrocell base station, WiFi wireless routers as the microcell bases stations, and MANET stations as the primary users of the spectrum.

Together, these networks are set to operate simultaneously with their mobile end users. We study the performance of the cognitive WLAN end-to-end connections over wireless links, where transmitters are equipped with APs or bridges at the physical layer and finite-length buffers at the data link layer. The traditional probes in wireless links are used to derive the end-to-end time delays of packets delivery, medium access delays, retransmissions attempts, and throughput. The network parameters for the macrocell and microcell domains are given in Table 3.3.

The system performance was evaluated as a function for the load/demand. One of particular interest is end-to-end time delays: in this measure, the total time taken for a packet to be transmitted across a network from source to destination in order to evaluate the competence of the used RAT and the proposed diversion algorithm with respect to the traditional CR managements. The end-to-end time delay is compared for the five case study scenarios mentioned in the previous Section. Figure 3.14, shows the improvement in network performance due to the use of microcells.

Table 3.3: Network Settings for the simulation

Parameters	Values	Parameters	Values
Cell layout	Sectors: 1 macrocell, 1 user 2 microcells, 4 users 14 primary, 28 users	Target Beacon Transmission Time (TBTT)	0.02 sec
Propagation model	Hata-large city	Number of slot periods	2
Minimum distance to base station	35 meters	RTS thresholds	1024 bytes
Application Layer		Route request rate limit	10 pkts/sec
PCM Quality speech		Node Traversal Time	0.04 secs
encoder scheme	G 711	***Primary Network***	
signalling protocol	SIP	Physical characteristics	Direct sequence
Packet size	500 Bytes	Data rate	11Mbps
Macrocell	lte_enodeb	Channel bandwidth	22MHz
Transmission power	0.5W	Max. Receive lifetime	0.5 secs
Cognitive Microcell		TBTT	0.02 secs
HCF	Supported	***Fibre***	
Physical characteristics	OFDM (802.11a)	Model	1000BaseX
Data rate	48Mbps	Frame Bursting	Enabled
Transmission power	1 mW	Operation Mode	Full duplex
Transmission opportunity (TXOP) duration	1 MSDU	Delay	Distance based

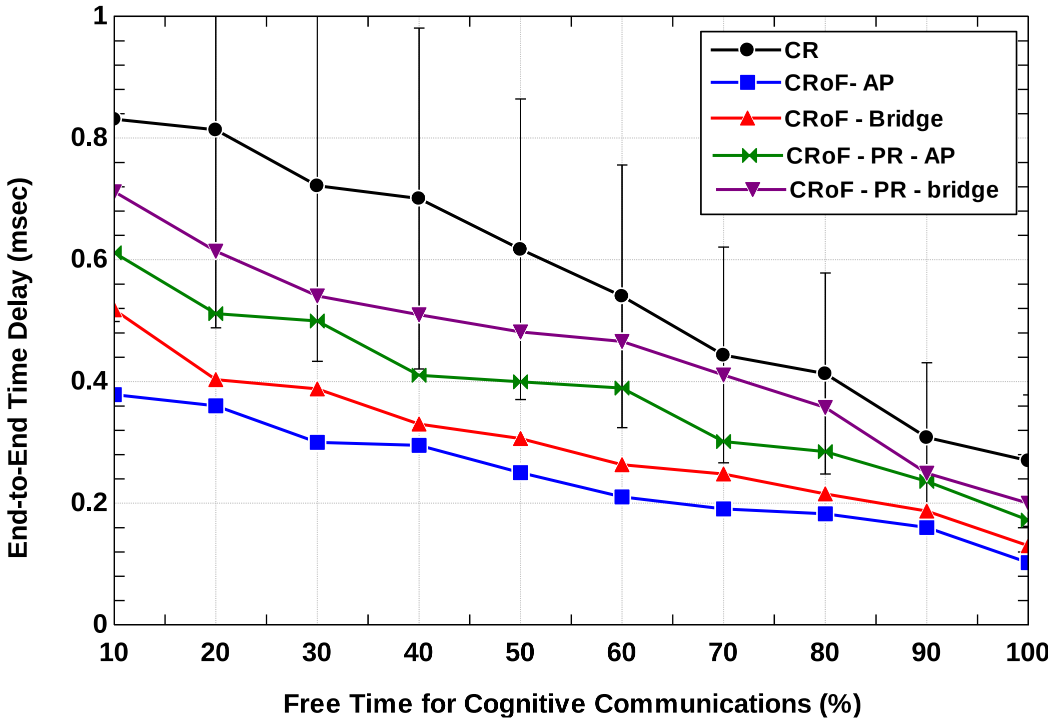

Figure 3.14: End-to-end time delay vs. free time available for cognitive communications

The CRoF_bridge can only relay the data to the main CRoF system. Therefore, the allocation of resources and the end-user registration and data delivery is actually performed by the macrocell headquarters of the cognitive system. This takes more time to make transmission decisions which in turn impacts the time for medium access as shown in Figure 3.15. The macrocell CRoF is the responsible for users linking outside microcells boundaries. In CRoF_PR_AP scenario the microcell AP is responsible for performing communications inside the microcell. The AP can exchange data wirelessly with macrocell BS directly on the primary channel if the primary end-users are off. These APs can communicate with their end-users and between each other independently from the CRoF core. The fibre is the medium used for transferring data to the CRoF core system. The CRoF_PR_bridge can deliver data to the microcells end users only and sxchange data with the main system core using the landline connections. Communications with the cognitive end-users off microcell are achieved using ad-hoc transmissions which are enabled in this scenario. The communication between microcells and the CRoF core system can be done only via fibre.

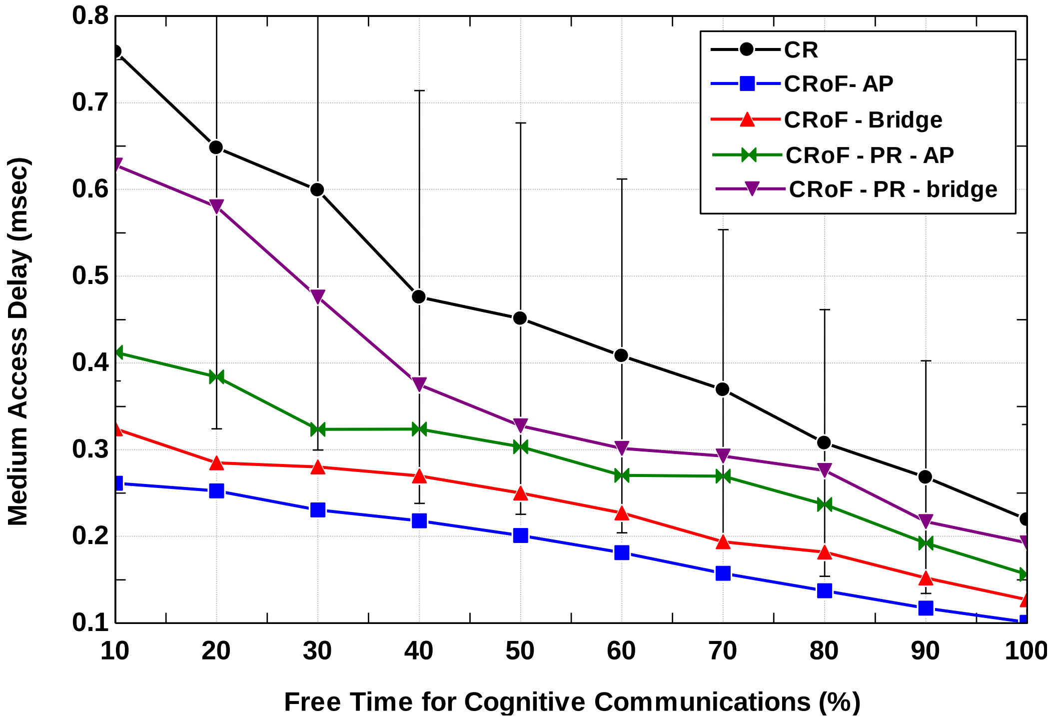

Figure 3.15: Medium Access Delay vs. free time available for cognitive communications

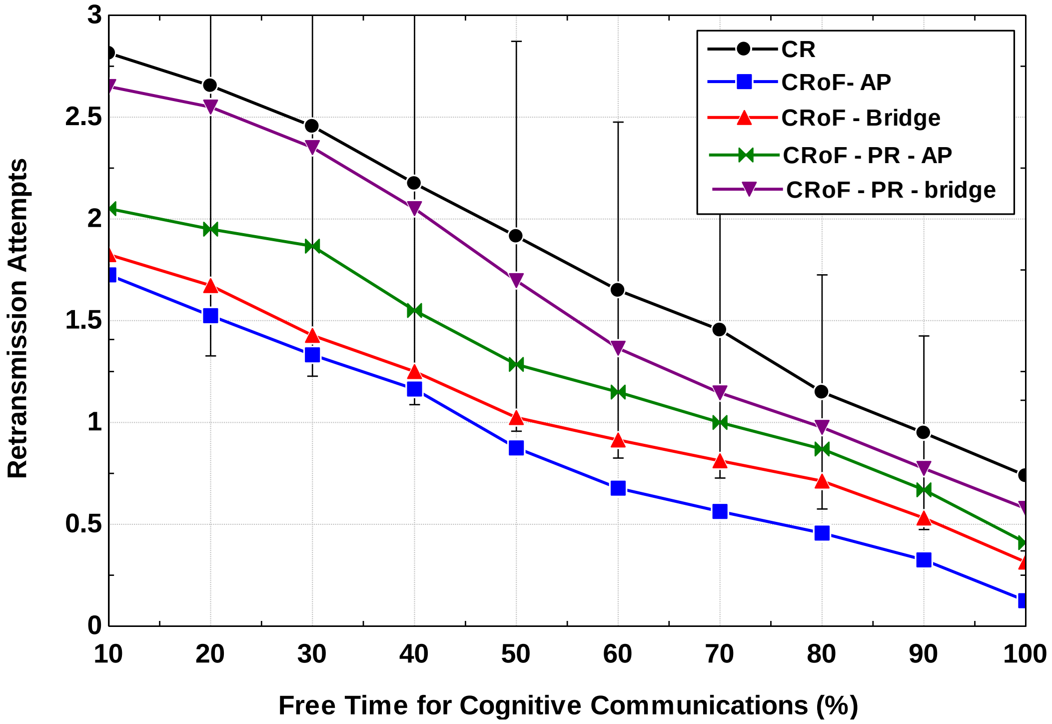

Figure 3.16: Retransmission Attempts vs. free time available for cognitive communications

Figure 3.16 depicts the retransmission attempts decreases as the time available for cognitive communications increasing in one pool of spectrum channels and different traffic occurrence times. Similarly, the performance has the same differences between different end-terminal radio technologies of transmission. This means that a normal cognitive mesh network has the highest values of accessing the spectrum due to the application of traditional producers of links establishment especially with short intervals of time availability for cognitive transmissions. The performance is gradually improved due to the growing of the transmission opportunities for the cognitive systems with the same differences between various RATs.

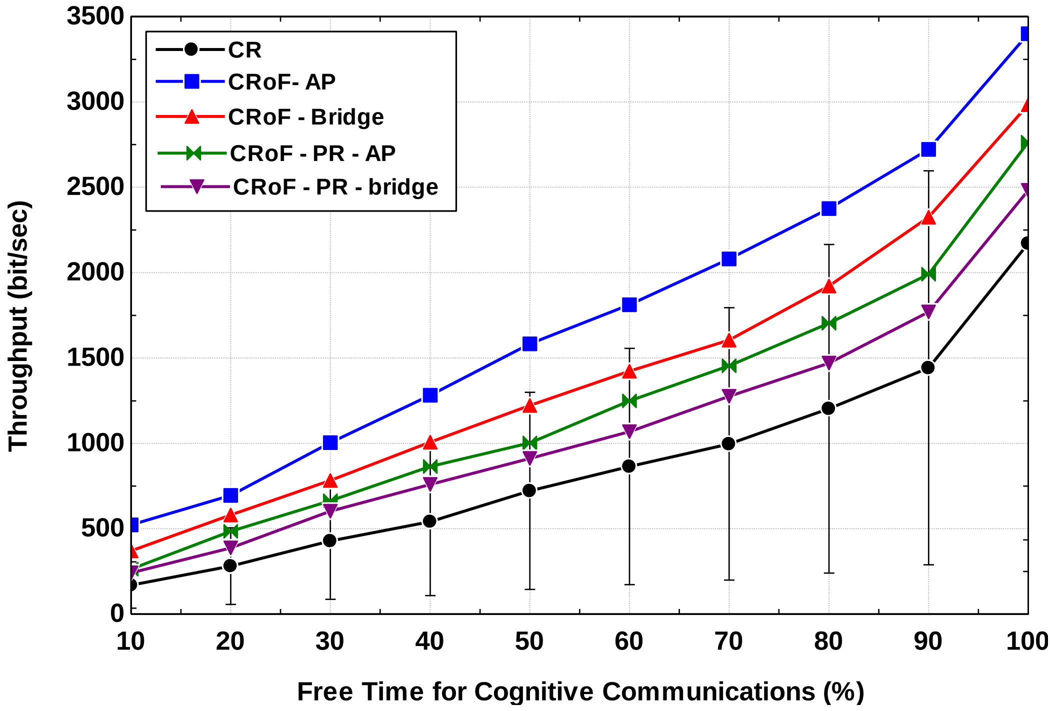

Figure 3.17: Cognitive throughput vs. free time available for cognitive communications

As traffic is not some steady-state phenomenon and the spectrum availability fluctuates dynamically in cognitive networks, the packets are diverted through fibre network. Therefore, the observation is that throughput is increasing for all CRoF-RATs whether wireless links are fully utilized in one moment or not over variable intervals of channels availability.

Figure 3.17 shows that CRoF_AP scenario depicts higher throughput, followed by the CRoF_bridge, _PR_AP, PR_bridge and CR arrangements. The explanation for this is based on the technical descriptions for the APs and bridges' wireless systems. The wireless bridges relay data packets between wirelesses and wired systems, in this study, it works from WLAN 802.11e to IEEE 802.3. As mentioned before, the bridge has two layers only; therefore transmissions' actions and adaptations are hardly obtained by the CRoF core. Also, these bridges are able only to achieve point-to-point communications. On contrast, APs can relay packets between wireless and fibre and achieve point-to-multipoint wireless communications. Therefore, the communications are not interrupted at any time between the microcells' APs and the main CRoF core. Additionally, the AP is able to communicate with the next microcell AP without the requirement of relaying the data through the core CRoF system. This saves more time and enables to transmit more data to the end-users. This simplifies the procedures of route discovery and link formulation by choosing shorter communication distances.

Overall, the simulations show the superiority of the CRoF system equipped with diversion algorithm for microcell applications over the traditional CR management in achieving the goals of increasing the throughput and reducing the time delay. The final endeavour for the CRoF system is to become applicable as a subnet in the future CMNs

3.12 Conclusion

Combining microcell and macrocell cognitive domains to fibre give greater flexibility for the allocation and use of the bandwidth in the radio cells. This arrangement aims to maximise the capacity of limited radio resources in order to avoid local congestion or degradation of wireless link. In this regard, a mathematical model was developed and analytically evaluated to prove the concept of bandwidth savings due to the use of multi-access system equipped with fibre. Then, novel call diversion algorithms were developed to allow re-directing calls bewteen microcell and macrocell base stations through fibre connections. The microcell stations employs four different radio access technologies that have been used as the correspondence physical interfaces to the mobile end users. This system known as CRoF creates multi-domain of self-organised network that matches available resources to the delivered data based. The CRoF maintain secondary communications and creates new local access network based on network topology settings. The CRoF can be an independent secondary system or connected to the primary network. OPNET simulations were conducted to examine the performance of the anticipated CRoF management scenarios in comparison to the traditional CR system. Results show that a CRoF system employing the diversion algorithm supported by APs at microcells has improved performance compared to other microcells' technologies and no CRoF cases.

3.13 References

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Chapter 4

Optimising Cell Size and Power Consumption for LTE Networks

Optimised roadmap for the possible numbers of deployed microcells is proposed for cognitive networks. The studied system incorporates two tiers of cognitive coverage as macrocell and microcell domains with various local spectrum coexistence scenarios. The limitations of the free spectrum and the competition in accessing and sharing resources among secondary users are the main concerns while deploying cognitive microcells. This chapter proposes and analyses novel coexistence models for sharing the spectrum between cognitive microcells inside one typical LTE macrocell. The given algorithms and network architectural models solutions are validated by analysing the upload capacity for various numbers of microcells. Results show the dependence of the microcells' density on the number of free available channels, and that services start to decline at certain thresholds when microcells overlapping with each other in coverage areas and used channels. The models of study were further investigated using designed simulations to analyse the power consumption for the new two-tier cognitive heterogeneous networks. Results show that microcells can reduce the power consumed in comparison with the traditional macrocellular services models. A novel road map for deploying cognitive microcells with the optimum secondary users' density in coexistence with the primary networks is raised to the research and industry communities.

4.1 Motivation

The rapid adoption of mobile data services triggered by the availability of dongles, smartphones, and tablets is placing heavy traffic demands on cellular networks and making them congested. In order to supply these demands, operators will need to increase capacity with the three key ingredients of a wireless network: spectrum, spectral efficiency (a property of the technology) and cell density. Combining these three factors gives us capacity density, measured in (Mbps per km^2). Therefore, mobile operators will need to deploy dense networks of low-power small cells located near to users, in order to supply sufficient capacity density high-quality contiguous/ubiquitous coverage in order to meet the ever growing demands for mobile broadband services [1]. Long Term Evolution-Advanced (LTE-A) wireless networks are being designed to improve spectral efficiency per unit area by shrinking cell size via deployment of a diverse set of base-stations [2]. However, a heterogeneous network that integrates the optical and wireless systems into one access system is still the best solution for the evolution of a diverse mobile coexistence in future networks. The Cognitive Radio over Fibre is one of these solutions proposed for the future secondary networks [3 - 5].

The shorter transmission distance coupled with lower transmitted power that can be obtained through microcells, enhances both capacity as well as the SNR values that can be achieved within the macrocell. On the other hand, a designer or a system architect would have to answer questions such as: What is the optimum number of sub-cells that could be contained in a macrocell? What is the optimum cell size that maximises the throughput obtained due to the sub-cells installation? Does the receiver configuration matter? What is the implication of frequency reuse on the throughput achievable? [6].

The other question that can be raised here is how to make the cellular networks more power efficient in order to sustain high speed data-traffic is by decreasing the propagation distance between nodes, which leads to reduce the transmitted power. Cell partition and the deployment solutions based on smaller cells such as micro, pico and femtocells are very promising in this context. A typical microcell in a mobile phone network is served by a low power cellular BS that covers a small area with dense traffic such as a shopping mall, residential areas, a hotel, or a train station in the order of few hundred metres [7, 8]. As, the use of cognitive over fibre microcells to support cognitive mesh networks is a very new idea, therefore, none of the literature quantitatively addresses the impact of increasing the number of cognitive microcells on the practical capacity of the secondary multiple-access cognitive network and the quality of the proposed services. This chapter investigates the collision in services due to over the limits density of equipment. Along this line, this chapter characterises the optimal CRoF microcells network architecture by addressing the following questions:

- What is the optimal number of CRoF microcells that can be installed inside an LTE macrocell?
- How to arrange the spectrum coexistence of the newly installed cognitive microcells with primary users transmitting in the same existing band channels?
- What are the power implications of adding various numbers of microcells to LTE macrocells?

To answer these questions, CRoF microcells' coexistence was investigated using two different new approaches named: Space Filling and Time Filling. Firstly, the space is filled with cognitive microcells that are able to control and adapt their coverage areas from inter-lapping with each other. Practically, a cognitive macrocell is the home for cognitive microcells with different levels of awareness and independence, where any channel can be used by different non-adjacent microcells using the frequency reuse principles. Secondly, the microcells are installed randomly throughout the macrocell, where their coverage areas can overlap, and spectrum is used by all microcells as one common pool. In this regard, a novel scheduling for spectrum access is used as an approach for coexistence between many primary and secondary users along the same channels of the IEEE 802.11e. This allows the modelling of the spectrum access for the newly installed microcells as a Poisson Process. In this scenario, microcells access the holes in the spectrum based on the first come first served principle in their spatial locations. The main goal is to optimise the cell size design for the next generation networks.

4.2 Technical Contributions

By characterising the various CRoF techniques for microcells deployment, this chapter makes the following main contributions:

1. Investigating the coexistence of a cognitive microcell network for different CRoF architectural designs in coexistence with primary users for all used channels, jointly, considering the optimal number of microcells installed, and macrocell design policy for planning future cognitive mesh networks.
2. The most recent information-theoretic results on the IEEE 802.11af coexistence management are incorporated into this chapter to investigate the capacity of cognitive systems with adaptively sized microcells' coverage areas [9 - 12]. The analytical approach employed the probability that an end-user suddenly left off-connection due to the changes in microcells' transmission domains.
3. Comprehensive study of the different microcellular RATs, in order to further investigate the CRoF architecture proposed in [13]. This helps to set the fibre network installation requirements and to regulate coexistence between the future cognitive mesh networks and the primary networks.
4. Power optimisation of the macro-to-micro cellular system using a developed model for the LTE macro base station with realistic factors for heterogeneous cell deployments.

4.3 Dimensioning of Cognitive Networks

Mobile capacity is determined not by one single factor, but by three: the amount of spectrum; the efficiency of the technology; and the number of cells deployed. Unlike spectrum and technology, the number of cells is limited only by the economics of deploying more. Over the last few decades most of the gains in capacity have come from more cell sites. The likelihood that mobile operators would have the inclination and the resources to increase their network ten-fold, from around 15,000 cells in the UK to around 150,000, is remote. If the will exists on the part of mobile operators and other initiative leaders, however, there are alternative strategies that, arguably, could take advantage of an existing wireless infrastructure; one that would also make the most of the opportunities that access convergence can offer [14].

The main goals behind the development of the CRoF system are to utilise resources locally to attain more transmission opportunities for the secondary network. To do this, microcells are installed for small wireless enterprise objects. The main assumption in this proposal is that microcells' fibre connections can be provided through the accessible fibre connections, for instance the EU-Project FUTON which is designed for the 4G networks. This work is concentrated at the management of the hybrid optical-radio infrastructure existing between the fibre optic interface of the central unit and the RAUs architecture. [15]. Hence, there are no worries regarding the cost and availably of landline connections for the anticipated CRoF linking. The main outcomes of the cognitive microcells deployment are:

- Efficient access to short time holes in the spectrum on spatial basis. This helps in overcoming the spectrum unavailability problem through adaptive directed coverage beams of the cognitive microcells' stations. Obviously, more opportunities can be obtained for transmission with such an application [13].
- Increasing the overall throughput of the system through short and reliable communications. This means that less end-to-end time delays will occur during packet delivery all over the network as a result of the microcells and the landline applications. This reduces the complexity that the cognitive network is facing in sharing the spectrum with other users.
- Local coverage and access for the clients. This makes it much easier to track the subscribers and the delivery of huge-sized data.
- Lower cost of communications by saving power and spectrum leasing time. This is an important factor to be studied in order to understand the cost effectiveness of microcells' installation against the traditional macrocell costs of wireless broadcasting.
- Higher performance and lower network duty cycle. This is very important to achieve time-effective response to the dynamic changes of a cognitive wireless environment. This is achieved in this proposal through infrastructural modifications.

The starting point for the efficient analysis of the functionality of the management function proposed is the introduction of the components of the four CRoF implementation scenarios. This is illustrated in Table 4.1 which shows the set-up for each of the CRoF implementation scenarios.

Table 4.1: CRoF System Technologies

Model	**Scope**
CRoF-AP	This model specifies the 802.11e AP as the wireless interface of the CRoF system. Access points are then connected to the main macrocell CRoF core using RoF.
CRoF-bridge	This model specifies the 802.11e bridges as the wireless interface of the CRoF system. Bridges are then connected to the main macrocell CRoF core using RoF. These bridges are two layer transceivers.
CRoF-PR-AP	This model specifies the 802.11e access point as the wireless interface of the CRoF system. Access points are then connected to the macrocell CRoF core, which is connected to the primary macrocell BS.
CRoF-PR-bridge	This model specifies the 802.11e bridges as the wireless interface of the CRoF system. Bridges are then connected to the main macrocell CRoF core that is connected to the wireless terminals of the primary macrocell BS.

Each scenario proposes a certain RAT that has its own applications and usage according to the requested traffic and network management. Then, in order to study the coexistence modelling for microcells distribution, the optimal number of microcells that can be deployed within the boundary of a macrocell is analysed. In other words, this chapter is studying the balance between the number of microcells and the number of free channels available to cognitive users. As shown in Figure 4.1, microcells with access points are deployed to trade spectrum with the main CRoF core that serves the macrocell coverage area and the primary users.

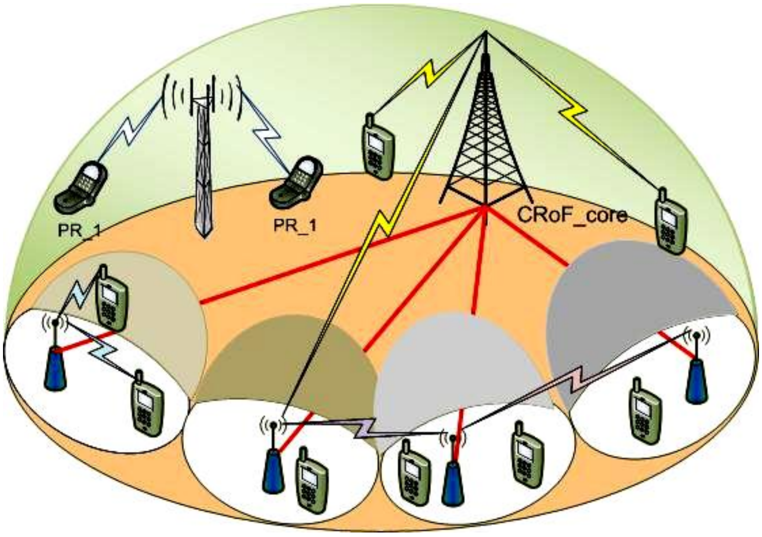


Figure 4.1: CRoF core and microcells coexistence with the primary users. At different locations, the microcells identify the free local opportunities for transmissions and use them

The aims are to optimise the most efficient equipment density and network planning for the cognitive networks that can collaborate efficiently to use the available spectrum. The ultimate goal of this study is to overcome possible disruption in services resulting from the competition of secondary systems in accessing limited resources. The case studies throughout this chapter use a dynamic wireless environment similar to real applications composed of primary and secondary networks.

4.4 Coexistence Modelling

Coexistence modelling has been extensively studied for conventional networks under fixed spectrum access. Tailoring to CRoF networks, this section analyses and compares five CRoF architectures for two spectrum access models of space and time filling modes.

4.4.1 Space Filling

For the CRoF network, the spectrum efficiency is fundamentally determined by identifying the exact location of the client and the choice of the nearest local access point for data delivery. This is strictly decided by the developments in the emerging CR technologies that can adapt transmission patterns for multi-shaped coverage areas.

A novel IEEE standard for cognitive radio has been developed by several groups at the end of 2009. However, the IEEE 802.11af working group has been created to present several modifications to both the 802.11 PHY layer and the 802.11 MAC layers, to link the channel access requirements and coexistence in the TV white spaces. In addition, the IEEE 802.19 group is working with regard to developing standards for allowing the coexistence between wireless standards for unlicensed devices [9 - 11]. It is expected that this work will build on IEEE 802.11y results, where an inherent key issue was addressed and resolved in a different context; the Dependent Station Enablement (DSE) mechanism defines how an operator extends and retracts permission for license exempt devices to use licensed radio spectrum; IEEE 802.19, on the other hand, works towards enabling the family of IEEE 802 Wireless Standards to most effectively use TV White Space by providing standard coexistence methods. Furthermore, IEEE SCC41 is developing standards related to dynamic spectrum access networks with a focus on improved spectrum usage. In this framework, the IEEE standard 1900.4, 2009 defines a management system supporting network terminal distributed optimisation of radio resource usage and improvement in QoS in heterogeneous wireless networks. Several CR standards are currently under development, mainly within the formworks of the IEEE and the European Telecommunications Standards Institute (ETSI). One of the first IEEE Working Groups (WG) to consider CR technology was IEEE 802.22, created in 2004, and developing a standard for Wireless Regional Area Networks (WRAN) using White Spaces in the TV frequency spectrum [12].

Therefore, it is assumed that there is always a chance to add more cognitive microcells to a fixed sized macrocell, as shown in Figure 4.2. Two scenarios are likely to occur:

1. Firstly, microcells do not overlap their coverage areas with each other. Thus, microcells squeeze their transmissions’ areas whenever a new microcell is positioned inside the macrocell. Obviously, such an adaption affects mainly the neighbouring microcells for the newly installed microcell unit. As a result, the macrocell may contain areas with different microcells’ densities. To ensure reliable coexistence and non-interfering sharing of the spectrum, the reuse frequency is vital for the success of this

implementation scenario. In other words, when a microcell uses a certain channel, its neighbouring microcells do not use the same channel for transmission at the same time. The reason for this is that competition on resources in a tiny coverage area may affect the rights of the primary user and increase the risk of the hidden point. The major task here is the management of the spectrum access in such a competitive, dynamic, wireless environment. This can be solved in two steps, firstly, through using the CRoF core entity to manage the channel sharing between the CRoF microcells. Then, CSCC [16] can be used to negotiate channels' sharing between neighbouring microcells in a distributed, localised manner. In this way, the microcells can accommodate newly installed microcells by adapting their coverage patterns and their used channels on a dynamic basis. The microcells are supposed to use sensing in order to perform the coexistence scenarios and have no advance knowledge of any future microcells' installations. Hence, accurate and efficient sensing is crucial for the success of such a system. Secondly, the CRoF core may act also as a spectrum broker to allocate the channels between the microcells in the macrocell boundaries. This requires the registration of the microcell IP with the CRoF core for any new installed microcell. The question *what is the time taken for issuing a request of spectrum access from a microcell to the macrocell and the time of approving that request with respect to the spectrum opportunity?* will remain always here, especially if the time taken for the CR to access and leave a certain channel opportunity does not exceed a few tens of microseconds [17]. This situation motivates the management of spectrum access even in an open access system like this one. Also, this is essential for operators to decide services and charge end-users for their spectrum usage.

2. In the second scenario for microcells installation, the microcells are assumed to be overlapped in their coverage areas as one nest. Thus, there will be shorter distances between microcells stations as shown in Figure 4.2. This makes the coexistence more challenging for service providers for allocating their subscribers, and to decide which microcells should be involved in performing transmissions and responding to the clients'

requests. Actually, this scenario of microcells overlapping can be proposed to serve buildings that are composed of many floors. Additionally, such scenario can be used for deploying microcells that belong to different cognitive operators in a heterogonous wireless environment. The negotiations for sharing the spectrum between microcells in such a situation can be done only through peer-to-peer microcells cooperation, or through operators' negotiations, which is unlikely to happen for reducing the complexity and time of processing orders. The spectrum reuse is the most appropriate solution for resources sharing and dynamic spectrum access management in this arrangement where no adjacent microcells can use the same channel at the same time. In fact, the spectrum reuse will reduce the interference risk that is raised dramatically due to the growing number of microcells. The accomplishment of this scenario is also dependent on the successful forecasting for any newly installed microcells. As for mesh networks, it is preferable that the operators exchange information about any newly installed microcells and their geographical locations. In fact, this job can be done by the spectrum management authorities that chart and sell temporary licenses to the cognitive operators. The OFCOM and FCC are examples of such regulating authorities in the UK and the USA, respectively.

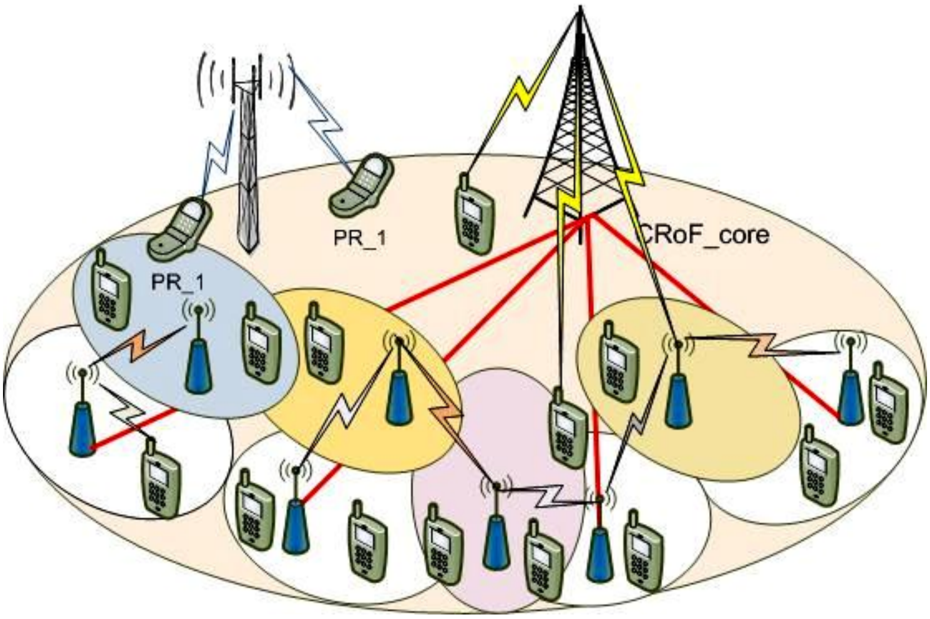


Figure 4.2: Adding more microcells to fixed sized LTE macrocell. The microcells can be side to side or overlapped in their coverage areas

To set a mathematical model for the adaptation in the coverage area of the cognitive microcells, a macrocell is located along the X-axis, covering a diameter of 2R, as shown in Figure 4.3. Then, a microcell of diameter 2r is placed along the macrocell axis. For the time t, the probability that the microcell will remain the same size is Prob $[Ms]$. Two cases are defined here: case (1) shown in Figure 4.3 where the microcell size is $0 \le s \le 2r$, and case (2) shown in Figure 4.4, where the microcell size is $0 \le s \le r$.

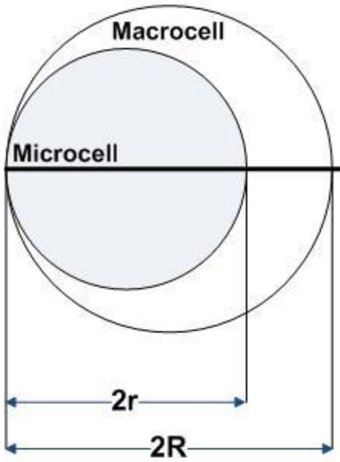


Figure 4.3: The adaptation of microcell coverage area when microcell diameter is 2r

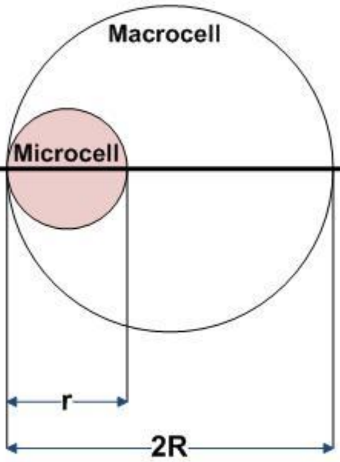


Figure 4.4: The adaptation of microcell coverage area when microcell diameter is r

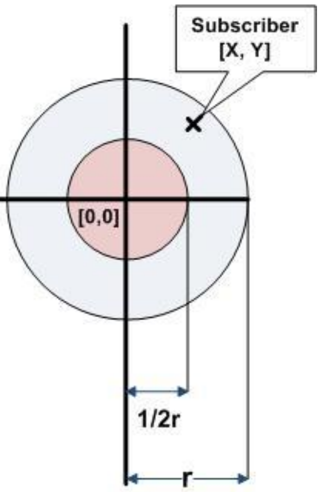


Figure 4.5: Subscriber coverage analysis

The reduction in the microcell size is the direct effect of the variation in the cognitive coverage area as a result for installing a new microcell in the macrocell zone. Hence:

$$\text{Prob}\ [M_s] = F\ [T \ge t \backslash s] \qquad (4.1)$$

where T is the time at which microcell coverage area is stable.Then, the coverage conditional probability Prob $[C]$ of the microcell for certain timed changes is:

$$\text{Prob}\ [C] = F[T \ge t] = \int k(s)\text{Prob}\ [Ms]ds \qquad (4.2)$$

where $k(s)$ is the probability density function for the number of microcells inside the macrocell and ds is the variation in the microcell size.

As the coverage area of the cognitive microcell adapts from time to time because of the newly installed microcells, there is a chance of losing communications with a certain subscriber that is registered with a microcell when the coverage area of the microcell is squeezed away from that client, as shown in Figure 4.5.

The probability that the microcell is covering a subscriber at point (X, Y) is actually the probability of microcell coverage identified by the function $\mathrm{F}\,[\mathrm{T} \geq \mathrm{t} \setminus \mathrm{X}, \mathrm{Y}]$. Then, the coverage probability for an adaptive timed microcell pattern is:

$$\mathrm{Prob}\;[\mathrm{C}] = \int\int \mathrm{k}(\mathrm{X},\mathrm{Y})\mathrm{Prob}\;[\mathrm{M}s]\mathrm{dXdY} \qquad (4.3)$$

where $\mathrm{k}(\mathrm{X},\mathrm{Y})$ is the probability density function for microcell coverage at X, Y locations. Increasing the number of microcells may impact user mobility and increase handovers, which is discussed in the next chapter.

4.4.2 Time Filling

In this section, the time holes in the spectrum are coordinated and accessed using SLS application. The implementation scenarios are proposed for the 802.11e multi-users’ microcells and LTE macrocell coexistence solution.

The 802.11 WLAN is being deployed widely and rapidly for many different environments, including enterprise, home, and public access networking [18]. The original 802.11 WLAN MAC sub-layer employs a DCF based on CSMA/CA for medium access, and is best known for its asynchronous best effort data transfer [19]. Consequently, a new standard IEEE 802.11e is specified [20]. IEEE 802.11e provides service differentiation by the priority based EDCF mechanism. This MAC layer introduces a priority re-allocation mechanism, which regulates flow priorities and prevents the aforementioned unbalanced case. With priority re-allocation, flow priorities will be used to not only provide service differentiation, but also minimise undesired collisions and improve the performance of real-time traffic [21].

The application of “waterfilling” from the information theory to the medium access of resource sharing wireless networks, enables a decentralised, coordinated, opportunistic usage of the spectrum, and is referred to as Spectrum Load Smoothing (SLS). In using SLS, the past usage of the radio resource by wireless networks is considered for redistribution and allocation for spectrum utilisation according to the individual quality of service requirements. Due to the principle of SLS these allocations are redistributed to less utilised or unallocated quantities of the transmission medium. Thereby, the individual quality of service requirements of the coexisting networks is considered. Further, the SLS allows an optimised usage of the available spectrum: the radio spectrum, which was originally licensed for other communication systems, is facilitated, as the SLS implies a search for unused spectrum as well as a release if it is needed again [22].

Consequently, two new applications are proposed for the SLS to host the growing number of newly installed microcells:

1. Many operators and new handsets are using a band of frequencies to perform communication with their clients in the technology known as “Quad-Band” [23, 24]. This means that multiple channels are used at different times and locations to transfer data between the base stations and the end-users according to the requested services, number of channel users, available technologies, and the geographical locations. Therefore, a new scheme can be developed to contain the wireless access for the new microcells by incorporating them into quad-channels in coexistence with primary operator, as shown in Figure 4.6. In this way, each microcell is assigned to share one frequency at any time with the primary network. This assumes that the CRoF system is actually the secondary user for a specific primary operator. The limitation of this application is that the number of microcells, which is decided by the number of channels, is owned by the primary network. In other words, the maximum number of CRoF microcells that can be installed using such a scenario should not exceed certain limits according to the available primary channels. Although there is an available choice for adding more microcells to this CRoF system, certain management methods have to be used. One assumption is to use the

principle of frequency reuse to avoid the existence of many neighbouring microcells on the same channel (even though [25] proposed a management for such a scenario) because it is unlikely to be implemented in small-sized network infrastructures like microcells. The main outcomes of this limitation are the simplification of the spectrum trading between primary and secondary users, the ease in monitoring services for charging entities, and the ability to connect all or most of the microcell to the fibre network. In contrast, this may limit the capabilities of the CR in accessing the spectrum dynamically, as needed for a fully adaptive and independent transceiver.

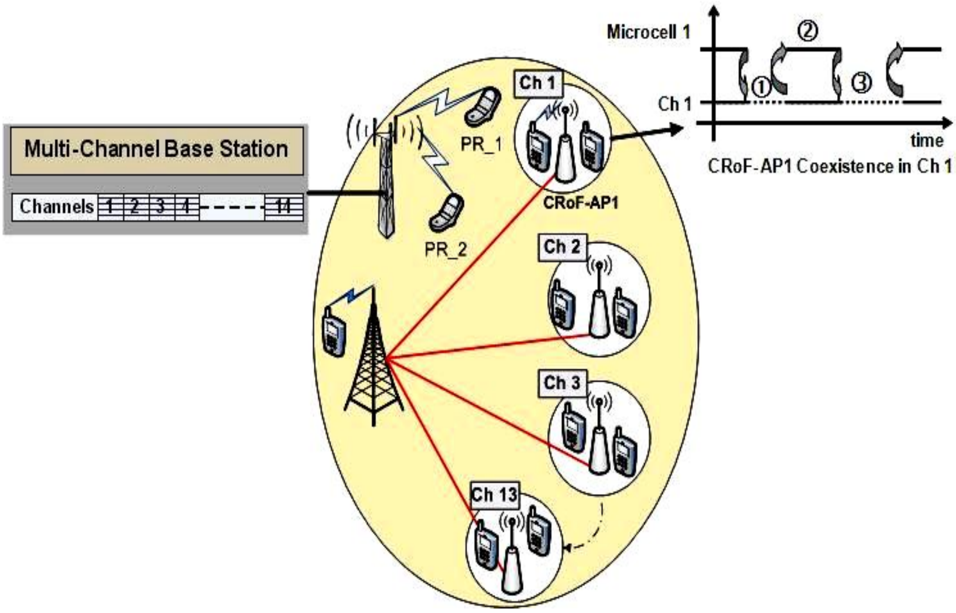


Figure 4.6: Time filling where each new microcell is assigned to one of the IEEE 802.11 5 GHz frequency band

To model the time filling scenario, the conditional probability Prob $[\mathrm{C}]$ for a microcell to transmit on slot time t of channel i is assumed to be:

$$\mathrm{Prob}\ [\mathrm{C}] = \int \mathrm{h(i)Prob}\ [\mathrm{M}i]\mathrm{dt} \tag{4.4}$$

where h(i) is the probability density function for the number of microcells that intend to transmit at the same time. Prob $[\mathrm{M}i]$ is identified as the probability that microcell is using channel i, as:

$$P[Mi]=F\ [T \leq X/i] \qquad (4.5)$$

To summarise, CRoF microcells are installed on the basis of filling the time gaps of the primary network transmissions.

2. The ideal application for the CR is to use all the spectrum channels as one pool [26]. Then, the CR is able to adapt and transmit using any channel in response to the timed availability of the various channels and the requested QoS. In this case, the cognitive transceivers' transmission decisions are taken on their own, according to their local wireless situation. For this massive independent spectrum access environment, microcells' installation rules are decided by the operators and end-users' requirements, rather than the technical or legal limitations. For the purposes of our study, there will be no cap at all on the number of microcells, excluding the cost of such a process, and the design of a powerful charging system. The SLS is the dominant solution for accessing the spectrum holes, reserving opportunities, and directing the usage between the microcells. Accordingly, microcells access the various channels to fill the gaps in transmission times of the primary users in either competitive or collaborative ways. This multi-access stations system provided with multi-access spectrum feature can provide more transmission opportunities. Therefore, CRoF is a promising supporting technology for cognitive mesh network as explained above. However, CRoF deployment is decided only when there is a landline network available for integration with the cognitive networks.

4.5 Coexistence Scheduling for LTE and WLAN

In this section, a comprehensive study is proposed on the coexistence of the LTE and WLAN systems. The enormous deployment of simultaneously active microcells can cause significant degradation in overall system performance. To avoid transmission related conflicts under such challenging wireless situations, new extensions are addressed to the LTE and WLAN medium access layers. Firstly, an extended scheduling architecture is proposed to the LTE protocol. Because of the expected irregularity in the transmission opportunities and transmitted traffic, the focus is on the data transmitted in the downlink (from the base station to the mobile user). The scheduling is performed according the channel-dependent scheduling mechanisms. Although, such scheduling have a tendency to be unfair due to the fact that receiving stations which are close to the sending station are served more often than others. This denotes that users with lower power and higher data rates are firstly scheduled for transmission. However, this allows sending at low power, reduced interference and as a result increases the overall system capacity.

Secondly, a new architecture for adaptive WLAN microcells is proposed based on the concept of updating the configurations of the physical layer. The solution starts with search for available surrounding BSs, position publish of new installed microcellular BSs, updating the PHY characteristics profile of each BS, and finally performing adaptation in response to the changes in wireless environment. Based on detailed MAC-level simulations, the proposed protocol extensions improve significantly the LTE/WLAN coexistence compared to the current state of the art. Later, the new schemes are used to capture the overall microcellular capacity to host new CRoF microcells using different techniques.

4.5.1 LTE Model Design

4.5.1.1 Channel-dependent Scheduling

At the core of the LTE transmission scheme is the use of shared-channel transmission, with the overall time-frequency resource dynamically shared between users. This approach, which is performed by the scheduler, assumes the realisation of a shared resource differs between the two: time and frequency, as shown in Figure 4.7. The use of shared-channel transmission is well matched to the rapidly varying resource requirements posed by packet data and also enables several of the other key technologies used by LTE [27].

The main task of a scheduler is to distribute resources to the users using time-frequency intervals consisting of a certain frequency and time amount. The Physical layers in the eNodeB and UE map the Transport Channels to the associated Physical Channels, which are combined to form the downlink Orthogonal Frequency-Division Multiple Access (OFDMA) and uplink Single-carrier Frequency-Division Multiple Access (SCFDMA) channels of the air interface. If the scheduling is performed in the time domain all resources are given to one user each scheduling time interval. A scheduling in frequency and time domain means that every scheduling time interval several users are allocated resources. A channel independent scheduler does not consider channel quality. A typical example is the Round Robin (RR) scheduler which every scheduling time interval assigns all resources to the user which has waited the largest amount of time to transmit [28, 29].

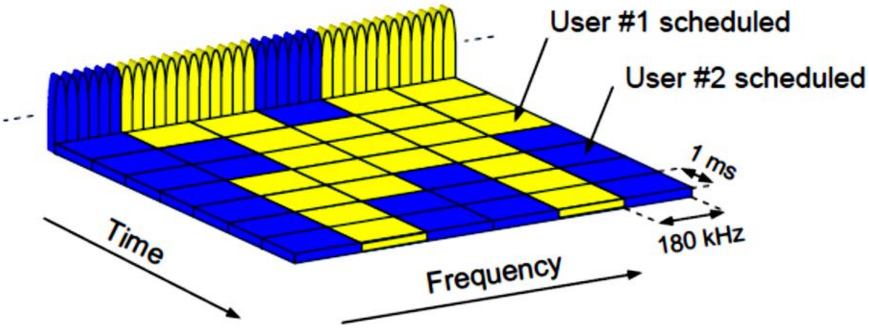


Figure 4.7: LTE channel-dependent scheduling in time and frequency domains

The LTE air interface uses OFDM together with advanced antenna techniques, adaptive modulation, and coding to achieve significant throughput and spectral efficiency improvements. Higher spectral efficiency enables operators to transfer more data per MHz of spectrum, resulting in a lower cost-per-bit. The scheduling is typically performed per cell when the base station receives the mobile request and starts assign resources. Plugging a MAC scheduler is a complex process involving a number of challenges [30]:

1. Optimising Uplink (UL) and Downlink (DL) challenges for capacity, throughput and cell edge performance.
2. Appropriate selection and implementation of QoS algorithms.
3. Utilising advanced RAT techniques in the DL.
4. Matching the real-time requirements with the available time and frequency slots in tight real-time constraints.
5. Minimising the amount of signalling used over the air interface.
6. Minimising power consumption.
7. Providing a framework for future improvements in areas such as cooperative scheduling for interference reduction.

The above limitations are considered when updating the scheduler with the new spectrum access changes due to the newly WLAN deployed microcells.

4.5.1.2 Uplink Control Channel Format for LTE Scheduler

The eNodeB allocates physical layer resources for the uplink and downlink shared channels (UL-SCH and DL-SCH). In each case, the aim of the shared channel scheduling algorithms is to allocate radio resources for the transmission of Transport Blocks (TBs) within a Transmission Time Interval (TTI). Resources are composed of Physical Resource Blocks (PRB) and Modulation Coding Scheme (MCS). The MCS determines the bit rate, and thus the capacity, of PRBs [31].

This section proposes a novel algorithm for invoking scheduling updates using the shared channels once a new microcell is installed. The goals is to updates the transmission profiles of the macrocell BS and its subscribers with the new changes in the spectrum users in order to allocate new frames/sub-frames for transmission between different users. This new scheme is given in Algorithm 4.1.

```
//***********Algorithm 4.1:  Spectrum Efficiency mode********** *//
/* Spectrum efficiency mode enabled when new BS installed */
/* Reset the frame allocation state variables */
lte_enb_as_frame_state_info_reset ();
/* Reset the PDCCH state to build a new DL MAP*/
lte_support_frame_pdcch_state_reset (frame_info_ptr);
/* Increase the current frame/subframe numbers */
lte_support_frame_count_increase (frame_info_ptr);
/* Block UEs that need measurement gaps  */
if (!spectrum_efficiency_enabled)
{
        lte_enb_as_ue_m_gap_setup ();
}
/* Schedule a self interrupt for the beginning of the next subframe */
 LteC_Subframe_Generate
```

4.5.2 WLAN Model Design in OPNET

As this chapter is analysing the capacity of the LTE macrocell, it is necessary to develop a new scheme for updating the microcells coverage domains with the new installed microcells. Therefore, this section proposes a novel scheme for updating the control plane of microcell BSs using OPNET wlan_mac_hcf function which is enabled with 11e functionality. The modules of the upgraded model are BS node model, mobile user node model, and universal MAC process model, as shown in Figure 4.8 for the OPNET process model functions.

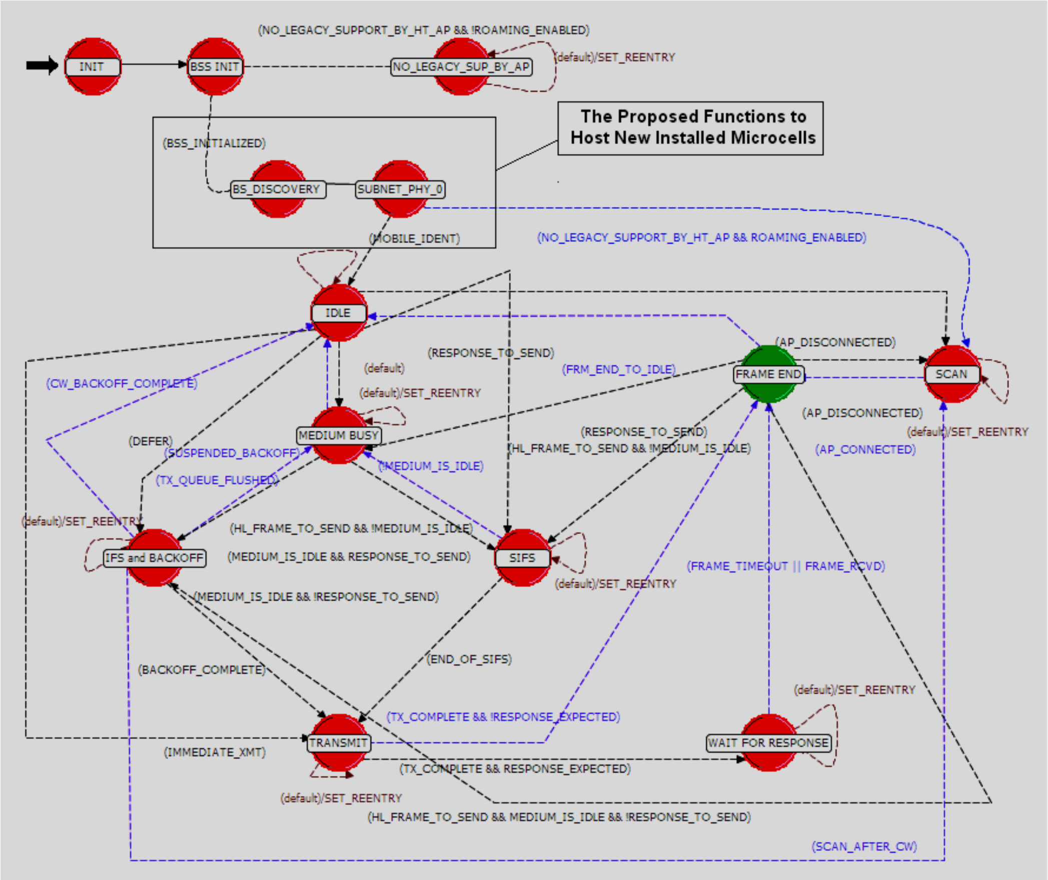


Figure 4.8: New 802.11e MAC layer model to update the control plane with new installed BSs

As the simulation starts, the microcell/UE starts searching for the nearest microcell BS. This is accomplished by the scanning the channels and performing backoff using CSMA/CA that has been discussed in Section 3.9.2. This happens while new installed microcell BSs starts to publish their new positions using the control plane. This information is used to extract nodes positions by checking the new BSs-IDs and to obtain their PHY features. Then, conclusions are returned to the UE with decisions if the new distance, after last microcell installation, is greater than acceptable threshold for connectivity. This is in comparison with previously cached position to decide to start a DSA request.

The Algorithm 4.2 is used by the newly arrived nodes to publish their positions for other nodes in the OPNET project and to update the control plane with their location information.

//*Algorithm 4.2: Publishing Locations for newly arrived Microcells*//

```
wlan_ap_position_publish (WlanT_AP_Position_Info* ap_pos_info_ptr)
{
  /*Inserting location of node into the global list of AP positions*/
  FIN (wlan_ap_position_publish (ap_pos_info_ptr));
  /* Inserting location information into the wireless linking list. */
  ap_pos_info_ptr->next_ptr = global_ap_pos_info_head;
  global_ap_pos_info_head = ap_pos_info_ptr;
  FOUT;
}
```

Once the global list of positions is updated, a DSA request can be issued by any UE/microcell whenever required to the BS/BSs for each service of uplink/downlink flows. The request contains the service flow parameters for the connection and source MAC address. Upon receiving request, the Admission control module at the BS starts processing it. The response sent back to the UE and contains acceptance status and accepted service flow parameters. If UE receives DSA response with an accepted state of connection, then it will configure the data plane data structures, containing Shaper, Classifier, data queue and segmentation buffer for the accepted connection. Algorithm 4.3 shows the procedure to identify new installed nodes and use the obtained position information to decide upon following actions of changing the PHY characteristics and data sharing algorithms.

//**************** Algorithm 4.3: BS Discovery *****************//**

```
/*Determine if there is any access point and start to collect information*/
for (i = 0; i < record_handle_list_size; i++ )
{
  /* Obtain a handle on the process record*/
  process_record_handle = (OmsT_Pr_Handle) op_prg_list_access (proc_record_handle_list_ptr, i);
  /* Get the station type*/
  oms_pr_attr_get (process_record_handle, "subprotocol", OMSC_PR_INT32, &statype);
  /* Obtain the MAC address of the STA and Read the value of the corresponding attribute*/
  oms_pr_attr_get (process_record_handle, "module objid", OMSC_PR_OBJID, &mac_objid);
  op_ima_obj_attr_get (mac_objid, "Address", &integer_mac_address);
  sta_addr = integer_mac_address;
  /* If the station is an Access Point then its station id will be a BSS id for all the station in its subnet*/
  If (statype == WlanC_QAP || statype == WlanC_AP)
      {
       /* Record the station address of the access point*/
       ap_mac_address = sta_addr;
       /* Save position information of the connected AP for "virtual" roaming*/
       oms_pr_attr_get (process_record_handle, "position record", OMSC_PR_POINTER, &conn_ap_pos_info_ptr);
      }
   /* Else if the station is an Mobile User then this station will be included in the subnet*/
  Else if (statype == WlanC_AP)
```

```
        {
          wlan_flags->nqsta_operation = OPC_TRUE;
          /* "best effort" is used to buffer the higher layer packets with DCF access parameters*/
          /* AIFS becomes DIFS, hence AIFSN becomes two slots to include the new mobile station in the services sequence*/
        }
    End if
}
```

Once the BS discovers a new node (BS/UE) in the area, it updates the physical characteristics of its transmission profile using Algorithm 4.4.The procedure starts by exploring PHY attributes and technology of the new AP. Next, the BS adjusts its PHY transmission features to overcome any clash in services and allow matched wireless characteristics for each individual domain. The BS may choose to terminate the transmission whenever there is a mismatch in the technologies used to establish wireless links to avoid confusion in services.

//*Algorithm 4.4: Updating the PHY characteristics for Microcells*//

```
/*Check the physical characteristic configuration for the new APs and obtain the values assigned to the various attributes */
op_ima_obj_attr_get (mac_objid, "Wireless LAN Parameters", &wlan_params_comp_attr_objid);
params_attr_objid = op_topo_child (wlan_params_comp_attr_objid, OPC_OBJTYPE_GENERIC, 0);
/* Adjust the physical layer characteristics for the new wireless environment*/
op_ima_obj_attr_get (params_attr_objid, "Physical Characteristics", &sta_phy_char_flag);
sta_phy_char_flag = (1 << (sta_phy_char_flag + WLANC_PHY_CHAR_BIT_SHIFT));
/*Store the physical layer technology used by the AP*/
if (statype == WlanC_QAP || statype == WlanC_AP)
```

```
{
        ap_phy_char_flag = sta_phy_char_flag;
        ap_ht_info_ptr   = sta_ht_info_ptr;
}
/* Mismatching physical layer technologies within the same BSS
are not allowed*/
if (sta_phy_char_flag != phy_char_flag)
{
if    (wlan_bss_phy_char_compatability_check    (phy_char_flag,
sta_phy_char_flag) == OPC_FALSE)
      {
        /*Terminate transmission*/
      }
  else
      {
        /*Start formulating wireless link*/
      }
```

The above algorithms are incorporated into the MAC layers of the LTE and WLAN nodes to perform the capacity studies given in the following sections.

4.6 Optimising Cognitive Network Architecture

In order to provide a vision for optimising the cognitive radio systems architectures using the above assumptions and scenarios, a big-sized network model was developed using Opnet simulator to examine the overall capacity of heterogeneous WLAN and LTE network environment. The ultimate goal is to create a threshold of performance for the numbers of newly installed microcells as given in Section 4.5.

4.6.1 System Setup

Mixed Opnet simulation environments were created from mobile ad-hoc network (MANET) and IEEE 802.11e, as the primary and secondary networks [1 - 3]. Two end-users were registered to each macrocell and microcell fixed station, as their terminal end-users. The various CRoF technologies were set according to Table 3.1 and using the algorithms developed in Chapter 3. In order to simulate various times intervals of spectrum availability for cognitive communications in different channels, a certain primary user is assigned for each of the 12 (5GHz) band channels band. The microcells were distributed at random distances from the cell border towards the LTE macrocell. The parameters of the simulated network are given in Table 4.2.

Table 4.2: Network Settings for Capacity Evaluations

Network Parameters	Values	Network Parameters	Values
Application Layer		Route request rate limit	10 pkts/sec
VoIP	IP telephony	Node Traversal Time	0.04 secs
VoIP encoder	G. 729 Silence	**Primary Systems**	
Type of voice service	Interactive voice	Physical characteristics	Direct sequence
Signalling	H.323	Data rate	11Mbps
Cognitive Systems		Bandwidth	22MHz
Macrocell		Max. Receive lifetime	0.5 secs
Transmission Power	0.5W	TBTT	0.02 secs
Microcells		**Fibre**	
Physical characteristics	OFDM (802.11a)	Model	1000BaseX
Data rate	48Mbps	Frame Bursting	Enabled
Transmission opportunity (TXOP) duration	1 MSDU	Operation Mode	Full duplex
Number of slot periods	2	Delay	Distance based

The primary users are set to transmit at various time intervals. This leaves the secondary network with very dynamic wireless changes that is similar to the real wireless environment. The time usage of the primary users was tuned by the starting time of the packet generation and the packet length, relative to the overall simulation time. On the other hand, cognitive stations are set to autoselect option to give them the opportunity to choose between the available channels and time holes.

Actually, this scenario is a mixture of space and time filling schemes where newly installed microcells have to coexist in the same network space and share the same transmission time spaces. Therefore, the number of stations is scalable but the channels available are the same. The main goal of the simulated models is to analyse the thresholds for the number of microcells that can be added to a certain macrocell where size and resources are predefined, and then to set a policy for future CRoF network planning.

4.6.2 Simulation Results

The various models of CRoF implementation technologies (described in Table 4.1) show a dissimilar performance in terms of the capacity of transmission. The reason for these differences is that the CRoF_AP scenario has the highest spectrum access adaptability compared to other CRoF implementation managements, followed by CRoF_bridge, CRoF_PR_AP, and CRoF_PR_bridge, in performance duties of higher throughput and time delay. The explanation for this is that APs have more capabilities in accessing the spectrum due to being self-adapted functionalities, compared to the bridges, which are actually two layered systems that act as gates to the fibre network and then to the CRoF core.

The throughput in Figure 4.9 is increasing as microcells numbers increase until the number of microcells is 76. Remembering that the number of channels used is 12, this means that the system is able to host this number of cognitive microcells before performance starts to decline as the number of microcells increases further. However, the throughput with the highest simulated number of 120 microcells remains better than the situation where there are no microcells or just a few microcells installed in the macrocell. This highlights the superiority of the CRoF microcells usage for high-demand cognitive networks. It should be mentioned that each microcell has two registered mobile end-users, this means that the optimum number of microcellular users stands at 228 at 80% area from the LTE cell border. This number is not a fixed number for all cases and it is subject to change as the number of spectrum users/channels changes.

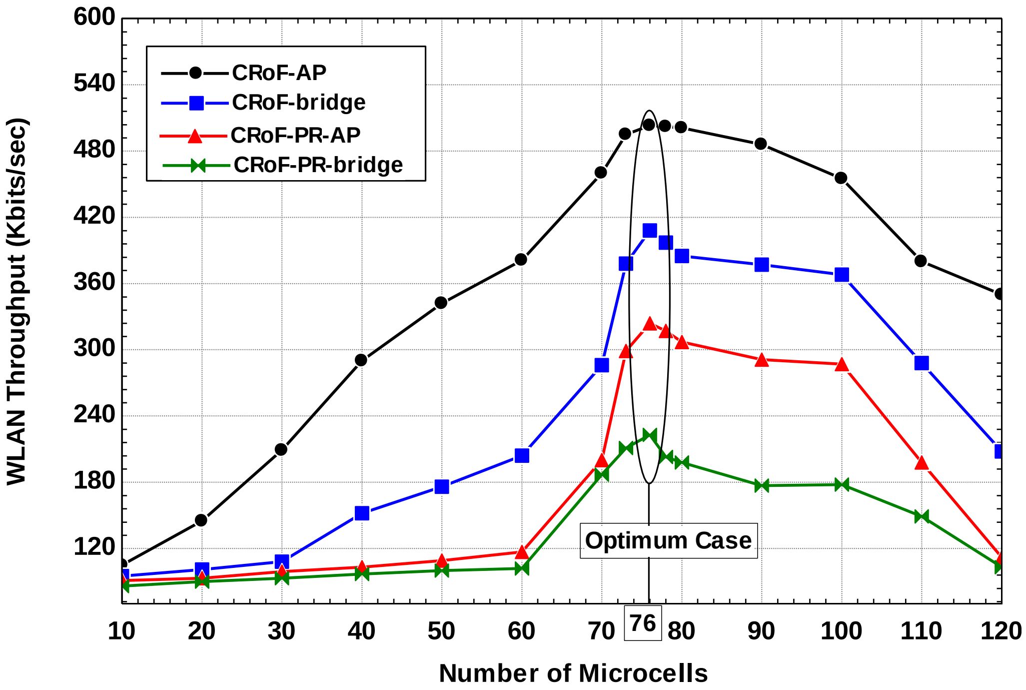


Figure 4.9: CRoF throughput vs. number of microcells

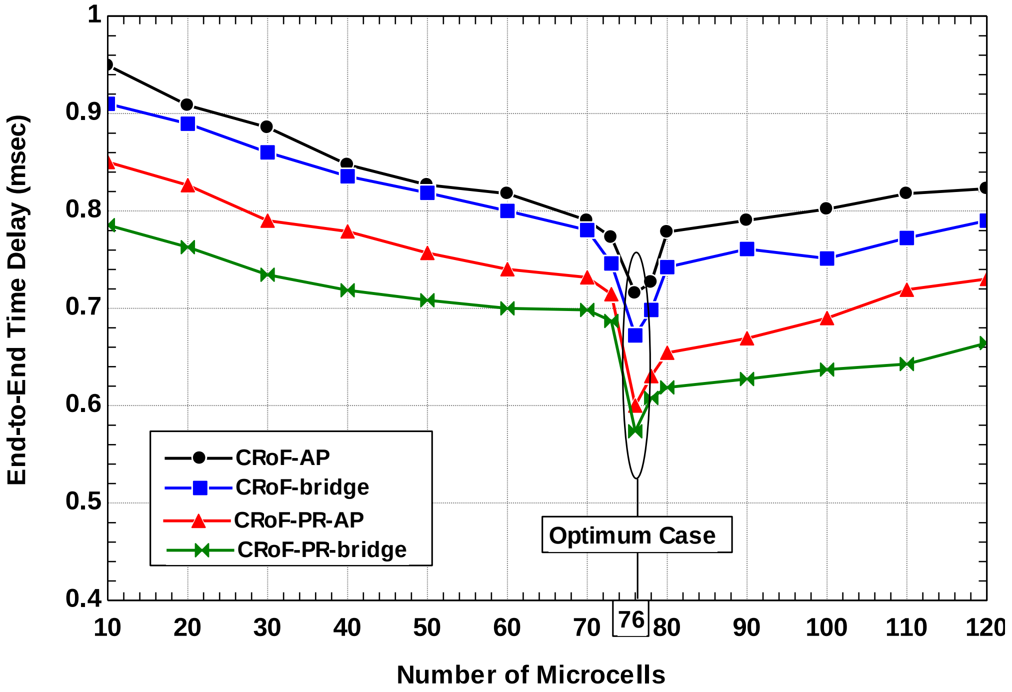


Figure 4.10: CRoF end-to-end time delay vs. number of microcells

Similarly, the end-to-end time delay in Figure 4.10 is decreasing as the number of microcells increases until certain limit. The explanation for this is that shorter communications provided by microcells saves more time for packet delivery to the end-users, and can identify end-users’ locations more readily and locally. However, the time delay is rising again as the number of microcells continues to increase, and especially when exceeding the 76 microcell threshold number. This can be justified by the unfair and rapid competition between microcells which increase the time required to access the channels and deliver the transmitted packets.

The medium access delay is increasing as the number of microcells increases, as shown is Figure 4.11. In fact, the figure shows that the access delays increase gradually as a numbers of microcells increase. This is a direct effect of increasing the transceivers in the channel band. Then, reasonably, the more microcells, the more recorded access delays. The reason for this is that reasonable filling of the space and time is a matter of successful installation of a suitable number of local wireless terminals in the suitable locations. For instance, microcells fill the nearest holes at the time of transmission, and approach users in a way that would make less impact on the traditional performance measurements. In other words, perfect selection of microcell numbers and locations can accomplish efficiently the goals of the CRoF system.

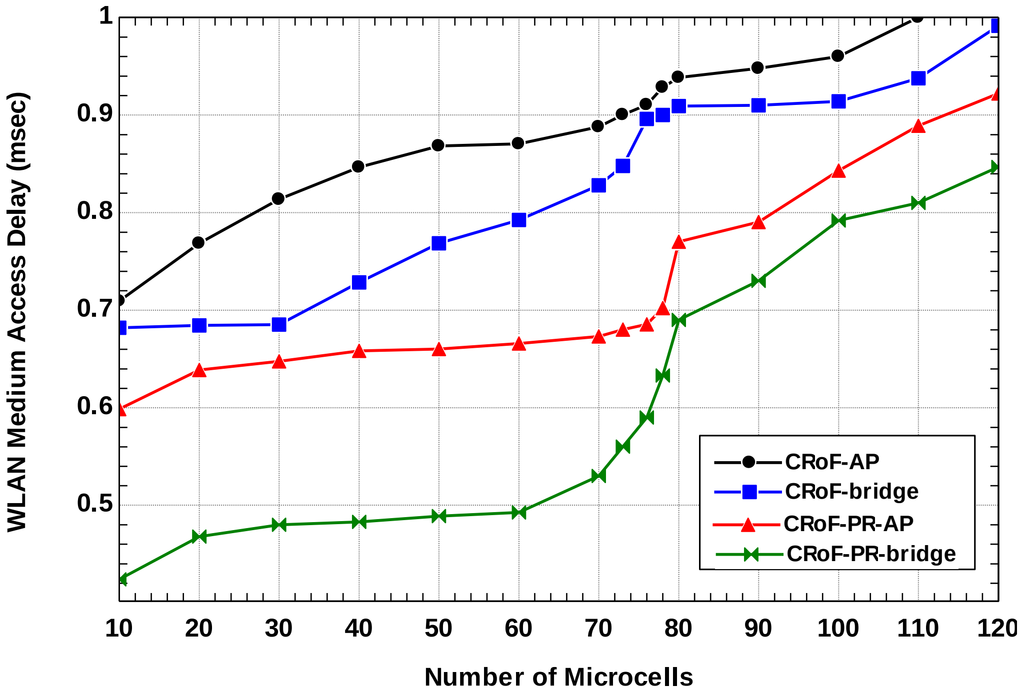


Figure 4.11: CRoF Medium Access Delay vs. number of microcells

The same above arguments are also applicable for Figure 4.12, which shows the number of packets dropped. It is clear that the packets dropped are lowest when only 76 microcells are installed inside the macrocell. The reason for the more packets dropped is due to fewer microcells, which results from the missing packets between microcells themselves in microcell-to-microcells cognitive communications. In fact, spaces between microcells and multiple channels used for communications are the main reasons for this drop. On the other hand, channel congestion and rejected in-transit packets are the main reasons for the higher number of packets dropped for scenarios where microcell numbers are higher than 76 microcells.

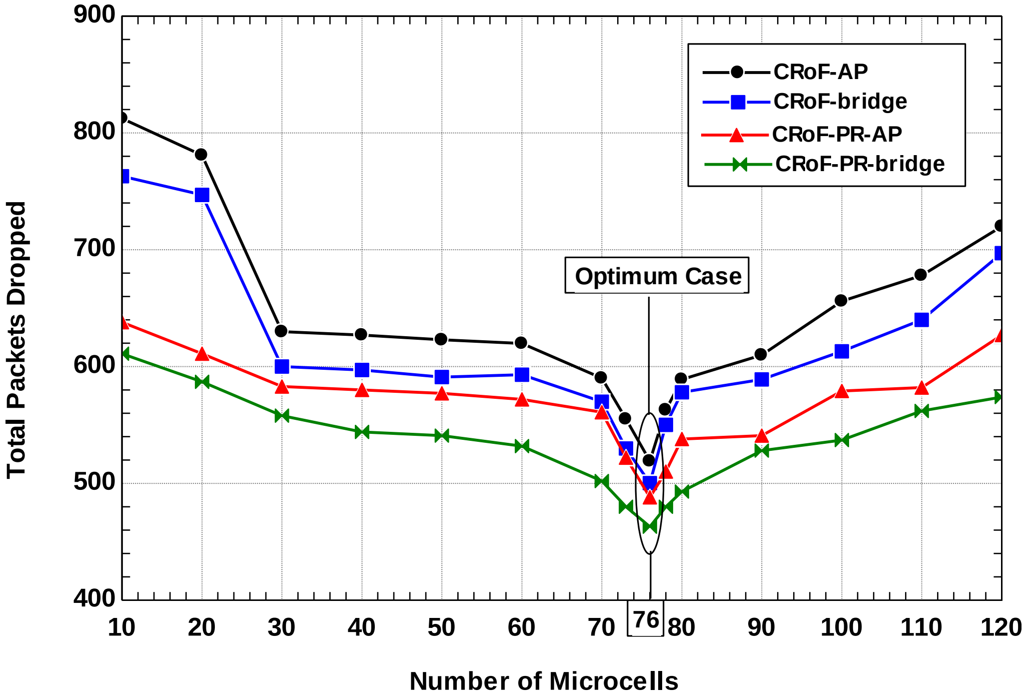


Figure 4.12: CRoF total packets dropped vs. number of microcells

In summary, the number of cognitive microcells installed in a macrocell is a function of the space and the number of channels available in the band. From this study, it is possible to add a limited number of cognitive microcells to the number of channels available for cognitive communications at a certain area space in order to reach a balance between the services and the resources offered to cognitive users. This should be accompanied by the necessary algorithms for updating the channel allocation of LTE macrocell scheduler and the transmission domains for the neighboured WLAN microcells. This will ensure the stability and continuity of services for cognitive users and prevent a collapse in cognitive mesh communications.

4.7 Power Consumption Planning

Power consumption planning is the first step in the process of dimensioning the cell size for any mobile network. It gives an evaluation of the system resources needed to provide service in the deployment zone with the specified system parameters, without any load concern. Therefore, it gives a clear idea about the allocation of the resources required to cover the area under consideration. This allows an efficient coverage that enables transmitters and receivers to communicate easily and cost-efficiently. One example of the coverage development consists of evaluation of radio link budgets. In this way, the maximum throughput is calculated based on the required SNR level at the receiver, taking into account the level of the interference caused by traffic [32]. This study covers LTE Coverage Planning with WLAN microcell deployment. Power consumption figures are investigated for deployments with increasing numbers of micro sites provided with simple models for the power consumption of different base station types in order to improve the overall energy consumption figures of cognitive network.

4.7.1 Case Study

To continue the optimisation of the macro-to-micro cellular system given in the previous sections, a power consumption model is proposed for the LTE/WLAN base station with realistic factors for heterogeneous cell deployments. This power consumption model has two parts, modelled simultaneously. The first part describes the static power consumption and gives a power figure for a macro base station with no users. Then, depending on the load situation, a dynamic power consumption part is added to the static power in order to calculate the overall consumed power. It is assumed that the optimum cell size is strongly affected by these changes.

Studies have identified the access network of cellular networks, more precisely the base stations, to be the major contributor to the total power consumption [33]. Although, there are other methods to reduce power consumption of a cellular system using more efficient base stations, the focus is on evaluating the possible energy saving in OFDM networks through low power micro BS deployment alongside macrocell BSs. In OFDM networks, offloading from macrocells to microcell results is decreasing the macrocell loads which in turn can be used in adjusting the cell size. This happens by increasing the Inter-Site Distance (ISD) as a result of the decrease in the overall energy consumption of the LTE system. Nevertheless, the reduced energy consumption by LTE infrastructure will be offset by the increase of the energy consumption by the dense micro deployment.

4.7.2 Area Spectral Efficiency

In this section, the concept of Area Spectral Efficiency (ASE) is studied for fully loaded systems in which the cells' resources (service channels) are randomly distributed between different users, as in Figure 4.13. To simplify, the ASE is assumed to be applicable in partially loaded systems.

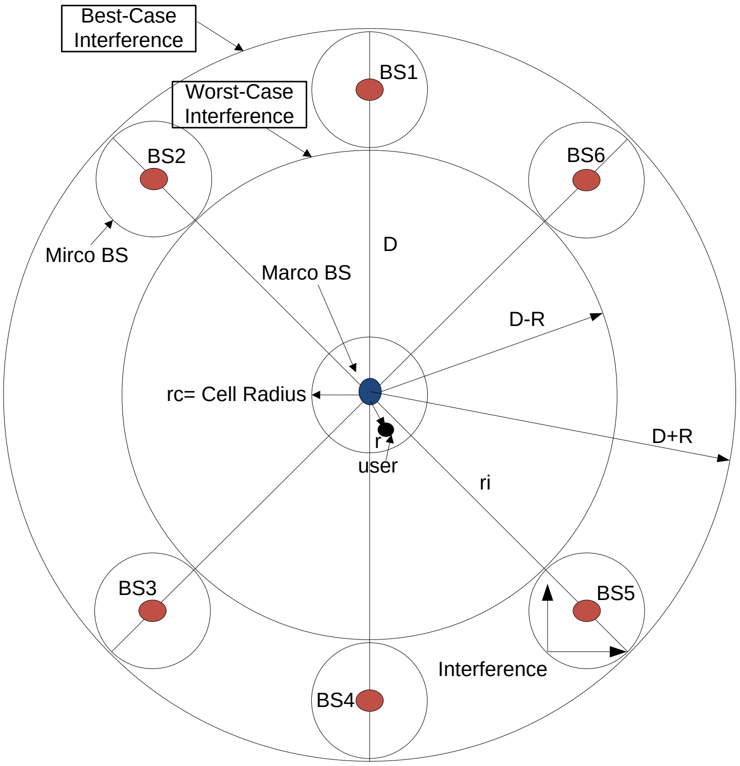


Figure 4.13: Cells resources allocated in fully loaded non-divided system

Define the *Reuse Distance D* [m] to be the distance between two BSs using the same set of frequencies. The ASE of a cell is defined as the sum of the maximum bit rates/Hz/unit area supported by a cells BS. Since frequencies are reused at a distance D, the area covered by one of these partitions is given by [34]:

$$A = \pi \left(\frac{D}{2}\right)^2 [\mathrm{m}^2] \tag{4.6}$$

The ASE, A_e [b/s/Hz/m^2] is therefore calculated by [34]:

$$A_e = \frac{\sum_{k=1}^{N_s} C_k}{\pi \, . W . \left(\frac{D}{2}\right)^2} \tag{4.7}$$

where N_s is the total number of active serviced channels per cell, C_k [b/s] is the maximum data rate of the k_{th} user, and W [Hz] is the total allocated bandwidth per cell. We define C_k as the maximum rate to be the Shannon capacity of the k_{th} user in the cell, and W_k the bandwidth allocated to that user.

4.7.3 Area Power Consumption

In general, observing the simple power consumption per site is inappropriate for comparing networks of differing site densities, since increasing distances generate larger coverage areas. Therefore it might be more reasonable to identify the power consumption for each tier of stations individually. Therefore we identify the following:

Area power consumption of one macro cell APC$_{macro}$ is given as [35]:

$$\text{APC}_{macro} = \frac{P_{ma}}{A_{cell}} \left(\frac{watt}{km^2}\right) \tag{4.8}$$

Area power consumption of one microcell APC$_{micro}$ is given as [35]:

$$\text{APC}_{micro} = \frac{P_{mi}}{A_{cell}} \left(\frac{watt}{km^2}\right) \tag{4.9}$$

where P_{ma} and P_{mi} are the average power consumed by macro and micro sites, respectively.

In order to assess that the power consumption of the network is relative to its size, we propose the notion of area power consumption as the average power consumed in a reference cell divided by the corresponding cell size measured in Watts per square kilometre. With an average of N micro sites in a reference cell of size A, the total area power consumption APC is defined as [35]

$$\text{APC} = \frac{P_{ma}+N.P_{mi}}{A} \tag{4.10}$$

4.7.4 Deployment Scenarios

In this work, the LTE network is modelled as an intersection network design consisting of 7-sectored macro base stations as shown in Figure 4.14. The design is characterized by an arbitrary Macrocell ISD fluctuating in a certain range.

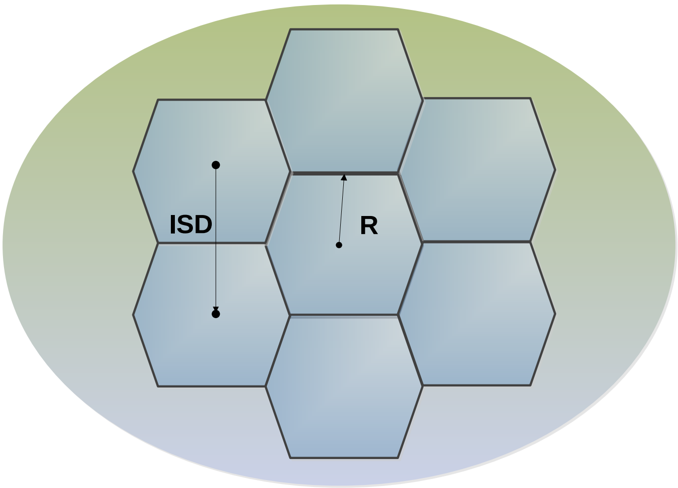
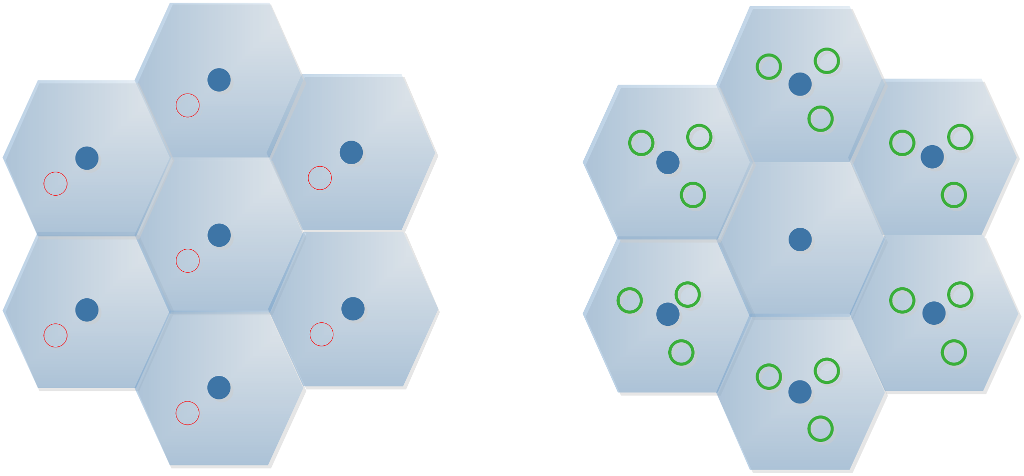


Figure 4.14: Hexagonal macrocell network

Each macrocell serves an area denoted by A_{cell} with area size $|A_{cell}|$. In WLAN microcell networks the area A is pointed to the cell, whereas the structural location of a base station is denoted as the cell site. Therefore, a LTE site serves a cell consisting of 7-sectors. The power consumption model is based on the downlink of an LTE system with the parameters provided in [36]. The users are uniformly distributed in the area and that there are no hotspot locations. The intensity of the network is given by the number of active users per unit area, where different user densities reflecting low load and high load scenarios are considered. In these scenarios, the simulated LTE-ISD is not fixed, ranging between 500m up to 2000m, and micro sites ranges from 200m-500m. The studied scenarios are considered in the busy hour which is the time of the day with peak traffic. Since part of the traffic is offloaded to the microcell, then the required number of macrocell BSs is decreasing due to cell breathing. The number of users in each cell is fixed to 50 users and it is the same among all cells. So the total number of active users is:

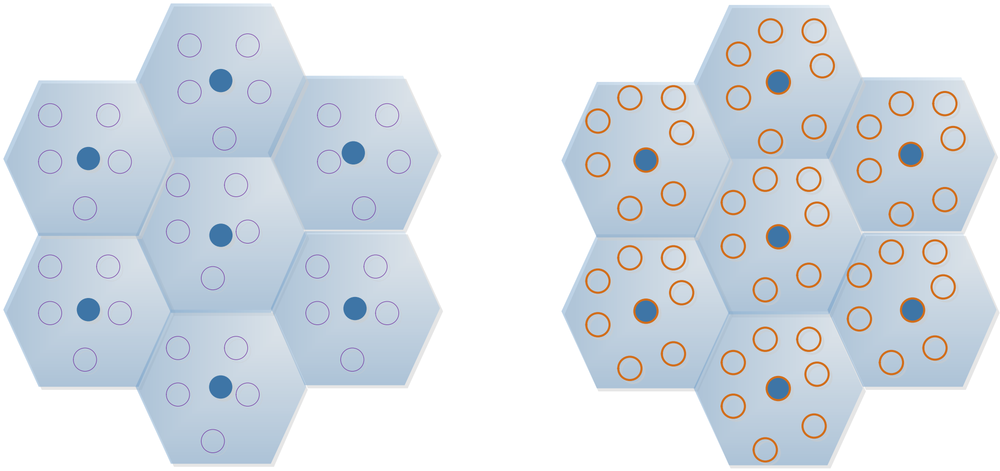
$$\text{Total number of active users} = 50\,\frac{\text{user}}{\text{cell}} * 9\ \text{cell} = \ 450 \qquad (4.11)$$

The target load in macrocell is specified to the services required for 450 active users. Also, all the active users are distributed randomly in the cells. The gradual increase of microcells within the LTE macrocell is shown in Figure 4.15.



Scenario 1: (1) microcell per LTE site

Scenario 2: (3) microcell per LTE site



Scenario 3: (5) microcell per LTE site

Scenario 4: (7) microcell per LTE site

Figure 4.15: Different scenarios of micro with LTE macrocell at the centre

4.7.5 Results

In this section, simulation results are given to show how the power consumption varies for macro and micro deployment scenarios. Simulation parameters used are given in Table 4.3. In order to simplify the analysis, the end-users are assumed to be fixed and therefore the handover impacts are not considered during this model system. The model network architecture is generated using equally sized hexagonal cell structures of side length [34]:

Table 4.3: Simulation Parameters for Power Calculations

Parameters	Specifications
Power (Watt) Macro and Micro	40W, and 6.3W
Bandwidth of Macro and Micro	10 MHz and 5MHz
ASE of Macro	4bits/sec/Hz/$\mathbf{km^2}$
ASE of Micro	6bits/sec/Hz/$\mathbf{km^2}$

In the simulation scenarios, a network dimensioning of LTE/WLAN base stations with fixed maximum transmit power are considered. The goal is to identify the best ISD for the LTE site with the above simulation settings. This is realised by evaluating the transmitting power necessary to deliver a predefined traffic with certain numbers of the active users.

In order to evaluate the area power consumption of different deployments we compute the average power of different models while increasing the site distance ISD. Since increasing cell sizes require increasing power for fixed coverage, there exists a fundamental tradeoff between an increase of the covered area and an increase in power consumption as shown in Figure 4.16. The results show that power consumption is decreasing for scenarios employ more deployed microcells compared to fewer/non microcells models. This shows that there is a significant savings in power due to the use of microcells rather than having a single macrocell BS unit. Additionally, there is a certain value for the ISD where the power consumption shows the minimum values for all scenarios and is named as the optimum case for the ISD. From network planning view point, the optimum ISD for a BS is value that provides the desired performance with the predefined network features. The most energy efficient ISD significantly depends on the type of macro/micro BSs and the power consumption of each domain.

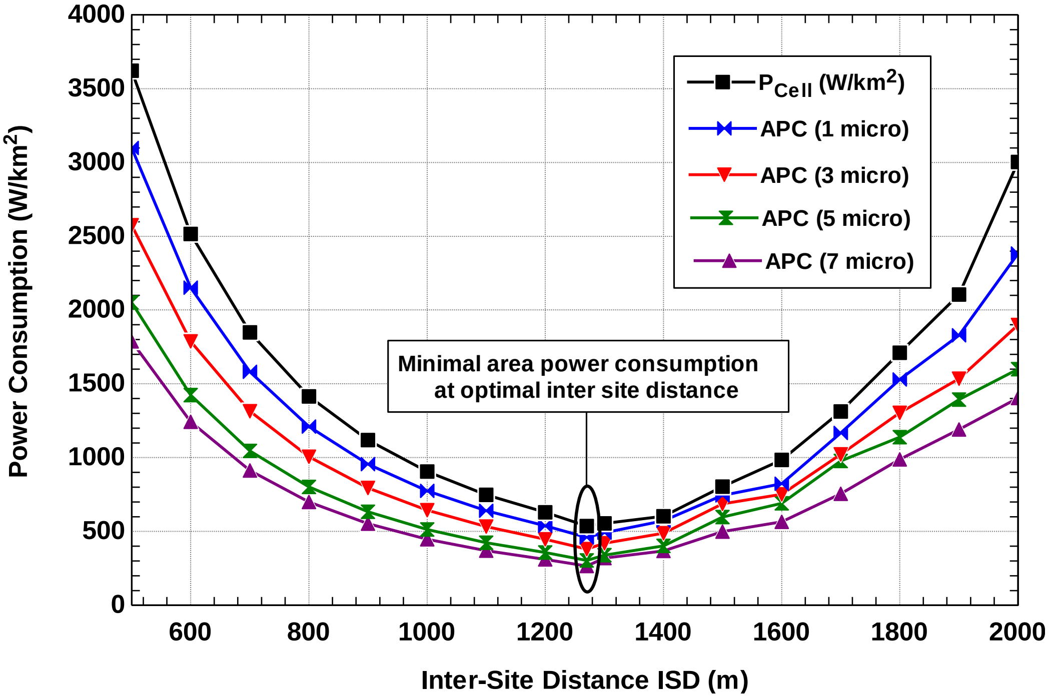


Figure 4.16: Area power consumption vs. inter site distance for different micro/macro deployments

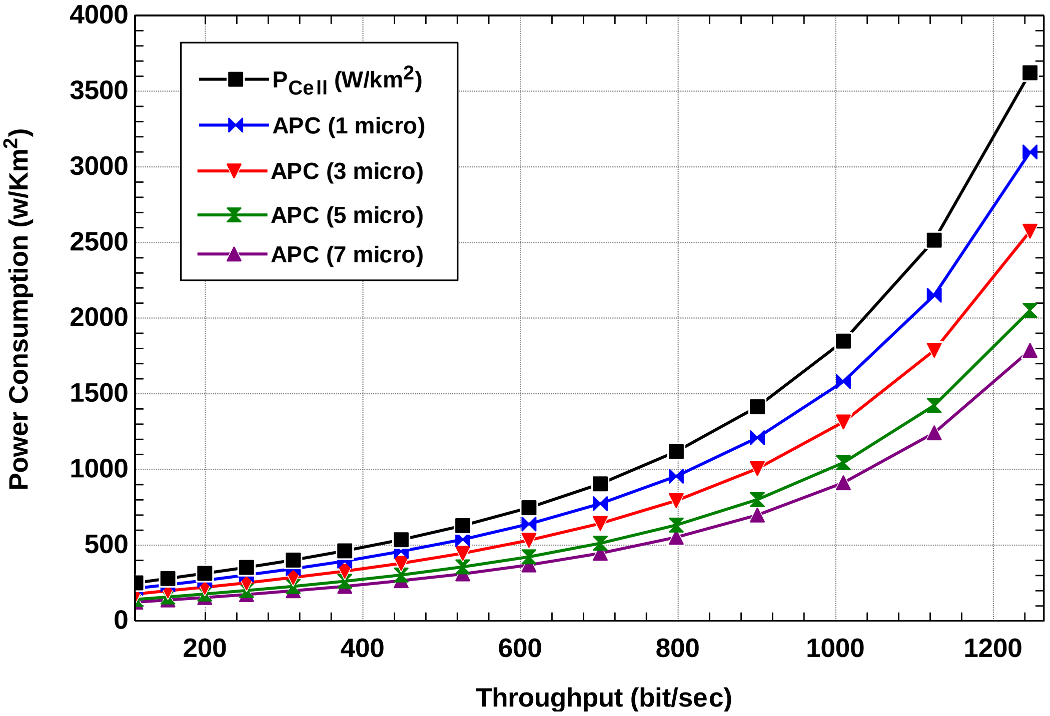


Figure 4.17: Area power consumption vs. throughput for different micro/macro deployments

The deployment of micro sites lead to a reduction in power consumption by relaxing the coverage requirements as it provides significant gains in spectral efficiency in high load scenarios. Obviously, small base stations are intended to increase throughput locally by exploiting good propagation and transmission opportunities. This effect is shown in Figure 4.17 where the power consumed is increasing as a function of the increase in the area throughput. Similar to the previous system performance, scenarios that employ higher number of microcells show lower values of power consumption for the same throughput values as the lower-microcells/macro scenarios.

In this section we analysed the optimum cellular network deployments with respect to the average number of micro sites per macro cell as well as the macro cell size. The area power consumption was calculated for different deployment scenarios as well as the throughput.

4.8 Conclusion

This Chapter proposes thresholds for installing microcells in cognitive mesh planning of the CRoF system. In this regard, the scenarios for adding cognitive microcells are studied for two main coexistence methods: Space Filling and Time Filling. Cognitive microcells' adapted coverage areas are presented through Space Filling with the new standard 802.11af. The Spectrum Load Smoothing principle is used for time utilisation and/or adding more microcells to the available band channels in the Time Filling method. A capacity model for subcarrier allocation in multiple access OFDM systems is proposed using novel algorithms for hosting new arrived microcells. The goals were to explore the total density constraints of users at pre-identified cell zones and numbers of channels. The subcarrier allocation algorithms are combined with previous chapter solutions for cognitive microcellular systems to present simulation results for wireless multi-access microcells in LTE cells. At the end, tis chapter shows that the deployment of micro sites allows to significantly decreasing the area power consumption in the network while still achieving certain area throughput targets and efficient services delivery. The chapter combines the network architecture density equipments to the available recourses in the field in order to attain an efficient architecture for the future cognitive networks.

4.9 References

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Chapter 5

Mobility Management in Cognitive Networks

Cognitive networks are accepted as a facilitator of the quest to offer seamless mobility to users, considering their ever-increasing service demand. This is done by adopting their operation (proactively or reactively) in responding to external stimuli. However, the dynamic adaptation between channels known as *Spectrum Handover* raises many questions about the validity of the cognitive network solution in the 4G systems. The handover here is not just a registration with a new operator station, but it is also a negotiation to get access to the available channels locally in coexistence with the primary users. Therefore, it is necessary to develop a novel method for roaming new mobiles moving between microcells and macrocell coverage areas to reduce unnecessary channel adaptations. This chapter proposes new entity namely *Channel Assigning Agent* for managing spectrum handover, channel allocation, and operator database. The proposed mechanism retains the same channel used by mobile phone while moving between different cognitive domains in order to improve network operation by reducing the unnecessary spectrum handovers. Also, network division into many zones of services is proposed for which CRoF-BS acts as the core of the zones. Therefore, a new paradigm for local resources sharing emerges through these architectural network modifications. This multi-zoned structure formulates new models of cell handover between the CRoF zones and the traditional cognitive networks.

5.1 Introduction

The key enabling technology of dynamic spectrum access techniques is CR technology, which provides the capability to share the wireless channel with licensed users in an opportunistic manner. Cognitive networks are envisioned to provide high bandwidth to mobile users via heterogeneous wireless architectures and dynamic spectrum access techniques [1]. However, the need for CRs is motivated by many factors. Principally, though, the need for cognition is driven by the complexity of the radio systems themselves. The existence of SDRs capable of implementing a near endless number of different waveforms with different modulation schemes, power levels, error control codes, carrier frequencies, etc., means that controlling the radio becomes a problem of combinatorial optimisation [2].

There are two major approaches in cognitive radio: dynamic spectrum allocation and opportunistic spectrum access. For dynamic spectrum allocation, information on spectrum occupation is used for channel allocation and planning on a long-term basis. On the other hand, with opportunistic spectrum access, instantaneous information of channel usage by a primary user is observed and utilised to grant access to secondary users to increase utilisation on a short term basis [3]. Earlier research done by [4] shows that wireless cognitive networks are able to coexist with primary networks, and operate at the same time and location without harmful interference. Similar goals have been formulated of the coexistence between decentralised cognitive radio and primary radio systems is specified [5] by introducing two benchmarks, the network performance with and without cognitive radio technology, with the function of detecting radio signals to avoid the primary radio system is studied. A different cooperative transmission has been investigated in [6], where the cognitive cooperative diversity is a strong technique which can provide the maximum throughputs. Cooperative opportunistic large array algorithms can improve the reliability as well as the energy efficiency of the communication.

The first significant radio-domain application for such smarter radios was the autonomous sharing of pooled spectrum, which the US-FCC endorsed relatively soon thereafter, to encourage the development of secondary spectrum markets [7]. In a cognitive network, autonomous and adaptive radios select their operating parameters to achieve individual and network-wide goals. The effectiveness of these adaptations depends on the amount of knowledge about the state of the network that is available to the radios [8]. In [9], the authors present an effective centralised decision approach to deal with the problem regarding how a spectrum manager should periodically re-allocate the spectrum between two networks in a single cell, while maintaining both the call blocking and dropping probabilities in their acceptable levels, and improving the spectrum efficiency simultaneously.

Additionally, [10] take up the idea of the dynamic allocation of spectrum among multiple wireless network systems, first discussed and investigated from a general perspective, including its major advantages and technical issues. On the other hand, resource allocation is a fundamental problem in cognitive radio networks and has been discussed a lot in the recent works [11 - 13].

In microcellular networks, handover management exerts considerable impact on the system performance. Handover can occur in the time interval during which the ratio of the power levels received from the current cell site and the mobile user destination cell site is within two appropriate thresholds (handover based on link quality measurements). A handover procedure results in a call termination in the current cell jointly with a simultaneous call arrival in the destination cell. The focus here is on achieving an efficient dynamic channel allocation technique that can increase the utilisation of available channels and the quality of service [14].

A channel allocation mechanism for CRs aims to enable maximum throughput and minimum forced termination probability for CR users that are not capable of SH. Spectrum handover is an optimal collision-avoidance scheme used by CR users to evacuate from time-slots that will be used by primary users based on time-slot assignment information obtained in advance [15]. At the start of the spectrum handover procedure, CR informs the current cognitive network regarding the handover execution process. In a situation when the CR wants to change to a particular network/cell operating in a different spectrum, it sends information about the preferred network/cell to the current network. The current network may inform the CR that it will assist in the handover procedure (recommended in case of ongoing call/packet data transfer/reception) or it may leave the radio to execute handover by itself [16].

The contribution of this chapter is to propose a seamless spectrum handover scheme that can reduce the number of handovers. The proposed spectrum handover procedure allocates the same channel to the cognitive user in order to guarantee QoS and overcome service interruption during channel re-configuration. This new scheme is an efficient solution to avoid redundant intercell handovers in cognitive macro-to-micro systems. Further investigations are performed to show the fairness of the proposed scheme while considering the new arrived calls from cognitive users. In addition, new concepts are studied for multi-zoned secondary network in heterogeneous cognitive networks.

5.2 Challenges of Dynamic Resources Allocation

The cognitive networks that use cognitive radio applications are posing new requirements for the resource allocation schemes and the network’s technical capabilities. Hence, new models are essential for carrying out network communication and the way that the network responds to the data delivery requests. All these changes are fully dependent on the agility of the cognitive network in sensing the spectrum, advanced recognition, and adaption competences. Therefore, the attainment of a powerful cognitive network is a matter of cooperation between individual stations, and selfishness reduction more than anything else. The reason for this is that resources are available on temporary basis and any monopoly can cause the collapse of the whole secondary system. Such cases of failure in the cognitive network can only solved by moving away the communication trajectories from the infected cells/zones. Later, these network cells/zones can be reconnected as soon as congestion problems eased.

Developing strategies for network management are based on the network architecture, size, and autonomy of the network subscribers. One important thing to remember is that no user can be shielded from dynamic changes in the cognitive network. This is due to the changes in the surrounding wireless environment and activity of the primary users. These changes can take part in protocols, routing maps, and network distribution. In fact, this dynamic nature of the cognitive network impacts the continuity of services and the flow of data, and increases the complexity of the entire system, especially for huge sized networks.

5.2.1 Channel Access Management

The management of the mobile networks architecture is set to achieve highly adaptive end-user service and efficient access to the spectrum. As a secondary user for the spectrum, it is necessary for cognitive networks to have their models for accessing the spectrum. This is a matter of successful internetworking and interoperability between free channels available at different locations. The research in [17] focused on the dynamic allocation of wireless links using the new models of DSA. In this way, channels are allocated using spectrum-aware operations that are able to predict the availability of channels. The operation of mobility management can be divided into two parts, location management and handover management.

5.2.1.1 Location Management

This involves two actions; location registration and call delivery as shown in Figure 5.1. Location registration involves the UE periodically updating the network about its new location through socialising with local access point. This allows the network to keep a track of the UE and match this to its map of the free channels in service. In the second operation the network is analysing the user location profile and the current and future positions of the mobile host are retrieved [18].

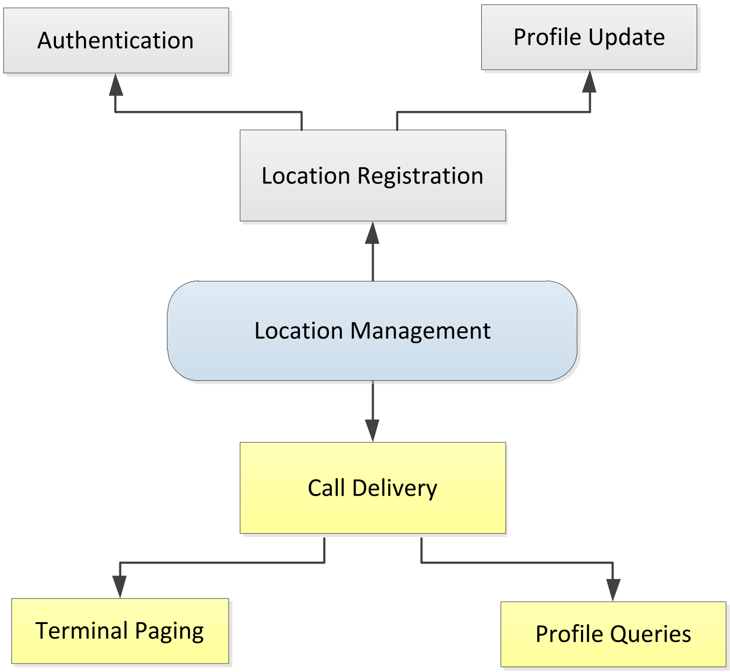

Figure 5.1: Location management schemes

The location of the mobile phone can be predicated if the trajectory of movement has been set already. This could be a result of long/mid-term monitoring of the mobile movement routes and times. In this way, the site's position is directly updated during regular data exchanges and socialisation with the mobile unit. The mobile site's x- and y-positions specify its location in its parent sub-network. A mobile site's altitude attribute specifies its elevation in relative to sea level, the underlying terrain, or the parent sub-network. A change to one of these attributes will cause an immediate change in the location of the mobile site. Typically, there are two techniques employed to dynamically change the location of a mobile site [19]:

- *Centralised approach*, in which one process is responsible for updating the positions of all of the mobile sites in a network model. Often this method requires a central control site to which all locations updates are directed.
- *Decentralised approach*, in the sense that each mobile site has a process executing within it that updates only its own position. The key difference between a centralised management system and a decentralised management system, is that the above runs a management operation as a centralised process, while this runs as a distributed process. This approach is more suitable to perform efficiently in large networks such as our model for cognitive microcells. Also, this approach is more flexible in dynamically adapting to network failures and any other changes in state and network configuration.

5.2.1.2 Handover Management

Handover management is a fundamental operation for any mobile network. Although its functionality and implementation differs among the various technologies, some basic characteristics are common. Handover management enables the network to keep active connections during mobile user movement or even balance the network load evenly among different areas [20].

The operations of handover management are shown in Figure 5.2 and include

[18]:

- *Handover Triggering*, i.e. the handover process is initiated due to some conditions that may include e.g. fall in signal strength, workload overload, bandwidth insufficiency, new better connection becomes available, cost and quality tradeoff, flow stream characteristic, change in network topology, etc. Triggering may even happen according to a user's explicit control or heuristic advice from local monitor software.
- *Connection Re-establishing*, i.e. the process to generate new connection between the UE and the new access point and/or link channel. The main task of the operation relates to the discovery and assignment of new connection resource. This behaviour may be based on either network-active or mobile-active procedure, depending on which is needed to locate the new resource essential to the new establishment of connection.
- *Packet Routing*, i.e. to change the delivering route of the subsequent data to the new connection path after the new connection has been successfully established.

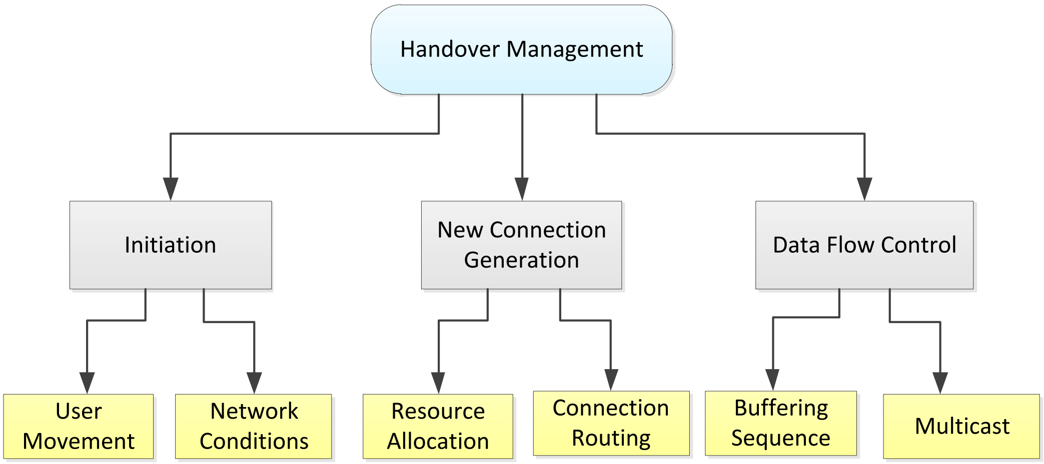

Figure 5.2: Handover management operations

Wireless networks show different performance in delivering services and technical features; therefore no single wireless network technology can be used to optimise different requirements on latency, coverage, data rate, and cost. This raises discussions on having an efficient strategy for managing the potential wireless overlay architecture and mobility within the any framework for online communications. In homogeneous networks, traditional horizontal handover can be employed for intra-technology mobility. In heterogeneous networks, vertical handover should be used for inter-technology mobility. Vertical handover may occur either upward (i.e. to a larger cell size and lower bandwidth) or downward (i.e. to a smaller cell size and higher bandwidth); and the UE does not necessarily move out of the coverage area of the original cell. Some packet-level QoS parameters become more important to real-time multimedia services, including packet latency, packet loss rate, throughput, signalling bandwidth overhead, and device power consumption [21, 22].

5.2.2 Handover in Cognitive Networks

The main reason for this intensive interest in handover over cognitive networks is that there is no concise description for the changes that cognitive radio would bring to the current mesh networks. This problem is growing with the absence of a standard cognitive radio system definition. For example, the cognitive radio suggested by [23] can adapt its transmission signals to efficiently utilise and respond to the spectrum changes. Therefore, cognitive mesh networks face many serious challenges in order to establish successful online communication links. One of these challenges is that CMNs has many cell nodes that need to be connected wirelessly together during the establishment of any link. This means that a high numbers of handovers are likely to occur in certain cognitive node due to the primary users' activities. Such a situation can block success of the future CMN in achieving real time communications between subscribers. In addition, it raises many questions about the expected numbers of handovers in such a network. The setback factors in CMN can result also from the absence of any guarantee for stability of wireless links in a dynamic wireless spectrum access models. Hence, cognitive wireless links can be interrupted at any time due to the transmissions of the primary networks. In this way, the more interrupted cognitive services, the less time online for cognitive communications and more handovers iterations occurrence. These bring forward the challenge of reducing the spectrum handover while reducing the complexity of running such networks. Besides the basic functions of handover management, there are additional requirements for performance and packet-level QoS that should be taken into account when trying to design a new handover management scheme, including

[18 - 20]:

- *Fast Handover*, i.e. this ensures that UE can receive data packets at its new location/channel within a reasonable time interval (at certain time counter) in order to reduce the packet delay as much as possible. This is extremely important in real-time services.
- *Seamless Handover*, i.e. any handover algorithm should minimise the packet loss rate into zero or near zero.
- *Routing Efficiency*, i.e. the routing path between corresponding access point and MU should be optimised in order to exclude possible redundant transfer. This is proposed to be performed by the CRoF-core management unit.

Therefore, it is necessary to analyse the expected free resources in different areas prior to any domain-based mobility management actions. This allows deciding the mobile handover that could happen within one domain or between different domains. This future analysis for spectrum usage is known as the *Spectrum Forecasting.*

5.2.3 Spectrum Forecasting

Spectrum Forecasting is an emerging topic for the 4G networks. This expectation for spectrum availability resulted from spatio long-term monitoring of the spectrum usage. Initially, these analyses motivated the development of the cognitive radio, and it may also motivate the selection criteria for CMN installation positions. The measurement of channels availability as a function of time and place may lead to a new category of spectrum forecasting namely: *Global and Local Spectrum Forecasting*.

For global forecasting, the charts for spectrum channels availability can be produced by the main spectrum governing entities, such as the FCC and the Ofcom. This is supported by the fact that these institutes have all information about the spectrum users' licenses and the occurrence time of their activities. The spectrum management entities are likely to monitor the licensed users to assess the possibility to offering licensed channels to cognitive services. In this way, spectrum reports may be generated on hourly, daily and annually basis in order to be used to predict future spectrum usage. These reports and expectations cover big cities and wide sites of the states at overlay networks services.

The other kind of spectrum forecasting is the local determination for the available resources. Here, the free spectrum holes are tracked for small sized cell and sub-cell domains where some channels could be accessible in some areas but they are not in others. Obviously, these measurements can be done by local cognitive radio units. Therefore, efficient sensing, and the collaborative distribution of sensing data are crucial for obtaining comprehensive spectrum usage reports. Actually, there are two main challenges in this kind of spectrum assessment:

- Firstly, new sensing schemes should be developed to intelligently track the free channel spaces and also the angle of arrival. This leads to slice the coverage domains and help to solve the problem of the hidden point.
- Secondly, local spectrum management entities role emerge to distribute the obtained spectrum reports between local users. The proposals for *Local Spectrum Brokers* find a strong inspiration for implementation here where the broker can contact all users in its area. However, the question here is how to accomplish the necessary awareness to analyse these data on a real time basis. Then, how to assign the requested evaluations to certain users? In fact, all these dynamic computational and geographical data will increase considerably the complexity of the cognitive network.

The spectrum forecasting reports are delivered to the cognitive nodes according to the level they intend to access in the spectrum. Therefore, global reports are provided if a link establishment is needed over multi-cell hops. While, local reports would be provided for users at intracell domains. The other scenario suggests that both reports are provided to all stations, and hence, a wireless link can be created from many short connections using local channels. This is the most useful setup, especially in a very dynamic wireless environment with an increasing number of cognitive users.

5.3 IP Modelling

Research and technological development on handovers in macrocell network has been going extensively to provide better Radio Resource Management (RRM). Most of the researches focused on network-controlled horizontal handover where handover is executed between adjacent cells of the same network. In order to achieve the optimise procedure, a new handover decision policy based on mobility prediction is introduced and proposed to mitigate the frequent and unnecessary handover. This is based on IP wireless network where handover is done typically in LTE networks. The development in both L1 (physical layer) and L2 (MAC layer) is undergoing in order to realise the most efficient handover and reduce the handover overhead [24].

Mobile IPv6 (MIPv6) [5] has been proposed by Internet Engineering Task Force (IETF) to support mobility for nodes in IPv6 networks. Though MIPv6 proposes many solutions to provide mobility, it also poses many challenges to the network world, mainly delay, packet loss and signalling overhead caused during the movement of the node. These factors result in the disturbance or disconnection of real-time applications such as Voice over Internet Protocol (VoIP). When a UE changes its point of attachment, the node moves from one network to another; this process is called a handoff or handover. Handover latency is one factor that makes most mobility protocols lose sessions during movement. Many Transmission Control Protocol (TCP) [6] applications can request retransmission in case of loss of packets, but real-time applications cannot do so because they rely mostly on User Datagram Protocol (UDP) [7] transmission. Real-time applications are time sensitive and rely on timely controlled packets that cannot be recovered once lost during the handover process. Many methods have been proposed by researchers to solve handoff latency problems, which include reduction in movement detection [8], packet loss [9], creating new IPv6 address, exchanging fast signals between old networks and performing fast signalling [10] in the new network. An extension to the MIPv6 original protocol called Fast Handover in MIPv6 (FMIPv6) [11] and Hierarchical Mobile IPv6 [12] has also been standardized to reduce the handoff latency. This section identifies the new IP integrated model for the LTE nodes and explains the possible scenario of application in the CRoF network.

5.3.1 Introducing the CAA

In order to reduce the interruption time resulted from the frequent spectrum handover of the UE moving between different accesses points, the CAA is proposed as a new modification for the IP network layer. The current known infrastructure does not include the dynamic spectrum allocation; therefore it is necessary to add such modelling especially with CRoF multi sub-cell domains that demands many spectrum handovers. The modification is proposed to be implemented in the IPv6. As a result, IP-Dynamic Host Configuration Protocol (DHCP) is used to create the global interface for the CR clients in motion. Firstly, the UE is allowed to communicate directly with its Correspondent Nodes (CN) instead of tunnelling the traffic via Home Agent (HA) node whenever they can do so especially inside microcells. This utilises efficiently local transmission opportunities in short range communications which is the main goal for the secondary systems. Additionally, two-way handshake (Solicit/Reply) is used instead of the usual four-way handshake (Solicit/Advertise, Request/Reply) to reduce the time of response while adapting between various channels. This is a major requirement for UEs that are moving at high speeds.

As mentioned earlier, the framework solution introduces the CAA at the IP network layer to assign the available channels prior to any handover actions. This assumes that the CAA knows the channel used by a certain MU and it checks the availability of the same channel at the new access point sub-cell domain prior to any new registration request. This should be combined by a pre-knowledge of the MU route of movement. The CAA is connected to the Access Router (AR) and from there to the main network entity named Mobility Management Entity (MME) as shown in Figure 5.3. This model is valid for the LTE systems and to roam UEs between various network domains.

The main functions of the CAA for the mobility management inside a macrocell are: Firstly, informing the corresponding node to assign a certain channel at the time of arrival of any new UE to interface communications immediately. Secondly, the CAA is responsible to manage the allocation of the same channel for the same mobile along its journey route whenever this is possible to avoid unnecessary SHs. The last scenario is very likely to occur when mobile moves between macrocell and microcell transmission domains in the

CRoF networks. This improves the roaming of the cognitive users that represents a major task with their numerous numbers of SHs.

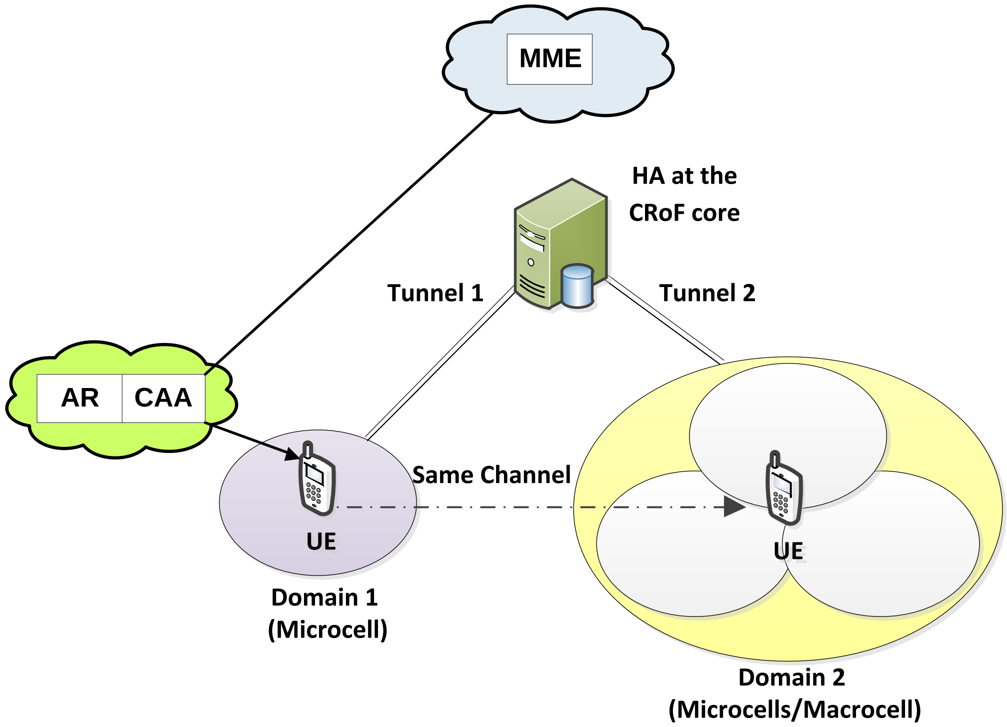

Figure 5.3: The CAA entity as part of IP protocol

It can be seen that the CAA is actually tries to keep the handover of the UE as horizontal-handover of sequence of connections to the APs along the way rather than vertical-handover where UE jumps between channels [25]. When the UE movies from Domain #1 to Domain #2 in Figure 5.3, tunnel 1 is terminated at the time of the UE registered with the AP at Domain #2. The reduction in time delay of packets delivery using this scheme is resulted from the cancellation of the SH.

5.3.2 Model Formulation

In the spectrum handover model given in Figure 5.4 [26], UEs sense the spectrum periodically in order to detect the appearance of any primary users. If any primary user is detected, the source BS decides to adapt to a new frequency and the availability of the new frequency will be negotiated with neighbour BSs. If it was decided to adapt to a new frequency there will be a distribution in the services at the time of frequency adaptation. These disrupted UEs needs to carry out additional intercell handover to maintain a connection. In the worst case, the

UEs must carry out network entry procedure due to connection loss.

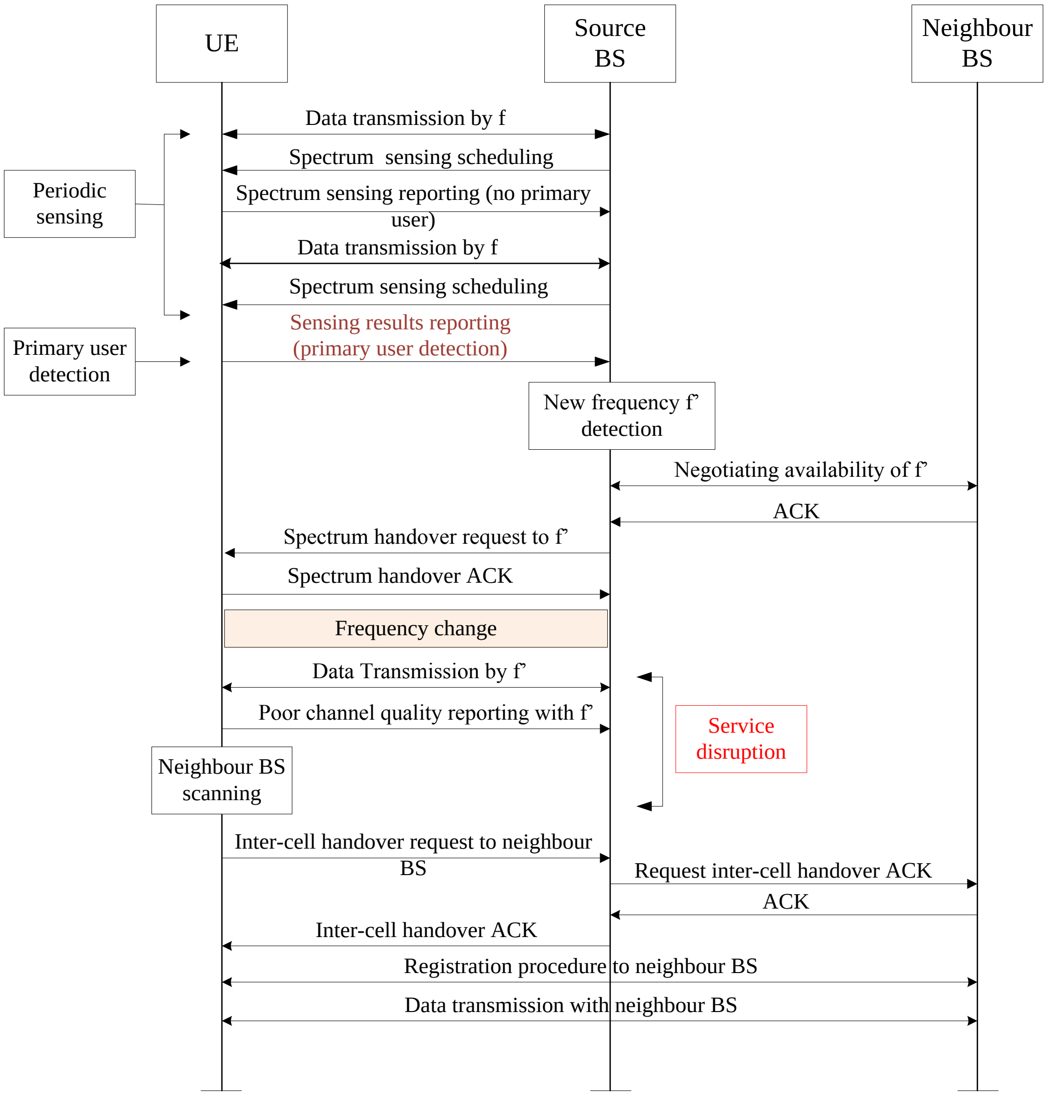

Figure 5.4 Operation of intercell spectrum handover

Considering the interruption loss, a seamless spectrum handover scheme is proposed to reduce the probability of service interruption by reducing the numbers of spectrum handovers. The proposed mechanism is applicable in two cases as shown in Figure 5.5: spectrum handover within the cell, and spectrum handover within the sub-cell. This is under the assumption of one pool for spectrum channels that are available and accessible to any cognitive user. Therefore, frequency adaptations can be reduced for mobile user moving between different domains when the same user channel is allocated to avoid unnecessary handovers. In sub-cell case, this is an efficient scheme to reduce signalling overhead by avoiding redundant intercell handovers.

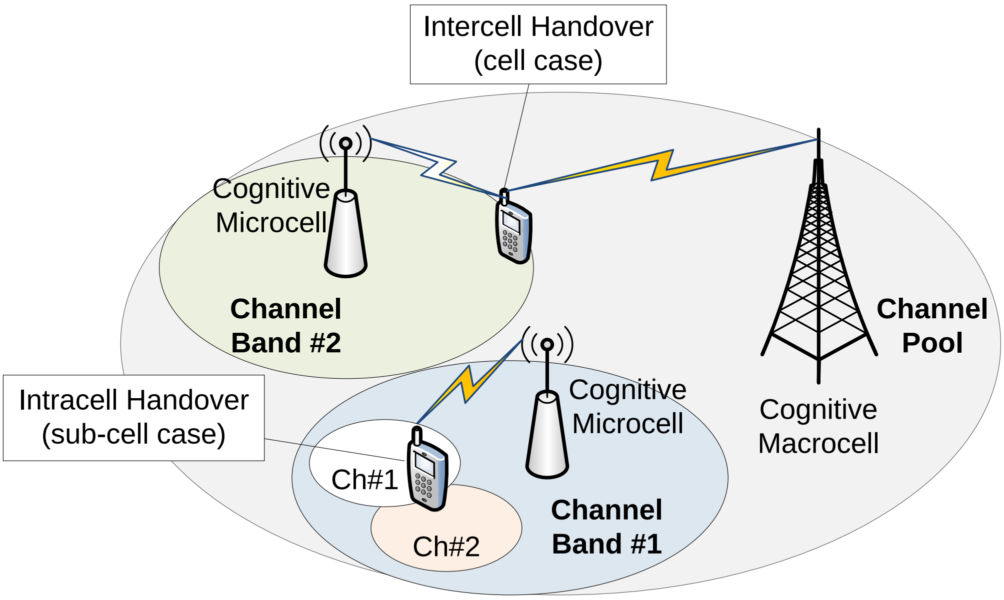

Figure 5.5: Inter/Intra cell spectrum handover

Using the proposed spectrum handover scheme, an intercell handover can be enforced before changing the frequency in case that same frequency channel is not available. In addition, the suspension of the intercell handover of a UE at the edge of a cell can be enforced to reduce signalling overhead if UE has changed his course of movement backwards or if the same channel can be secured to the UE in the new domain. Then, two conditions are defined in related to spectrum handover: the enforcing condition of spectrum handover and the stopping condition of spectrum handover.

Condition 1: Enforcing spectrum handover:

$$\{\, \text{ϙ}(f') < \delta_{th1}\} \cap \{\, i, s.t. \text{ϙ}(f_i\,) > \ \delta_{th2}\} \tag{5.1}$$

Condition 2: Stopping of spectrum handover:

$$\{\, \text{ϙ}(f\,) < \delta_{th1}\,\} \cap \{\, \text{ϙ}(f') > \ \delta_{th2}\} \tag{5.2}$$

where f is the original frequency of serving BS, f' is the new frequency of the serving BS after spectrum handover, f_i is the frequency of the next BS indexed by i, δ_{th1} is the threshold for triggering spectrum handover, δ_{th2} is the threshold for determining spectrum handover, and ϙ is defined as the received SINR for each frequency.

5.3.3 The New Handover Scheme

The proposed handover scheme when the macrocell BS determines the availability of the frequency (f) for the new arrival UE that is using the same channel at its former registration domain is shown in Figure 5.6.

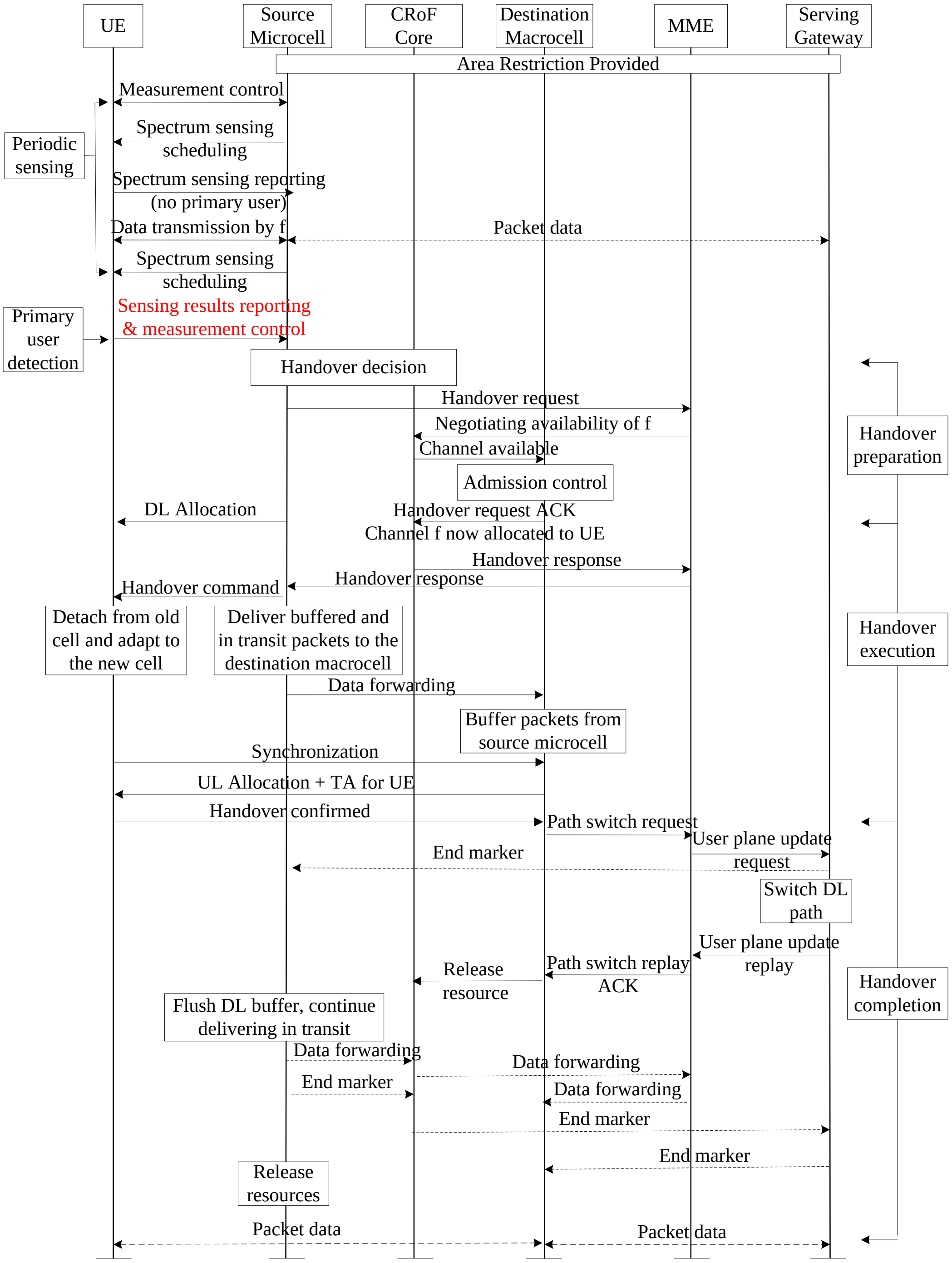

Figure 5.6: Scheme for spectrum handover using same channel (f)

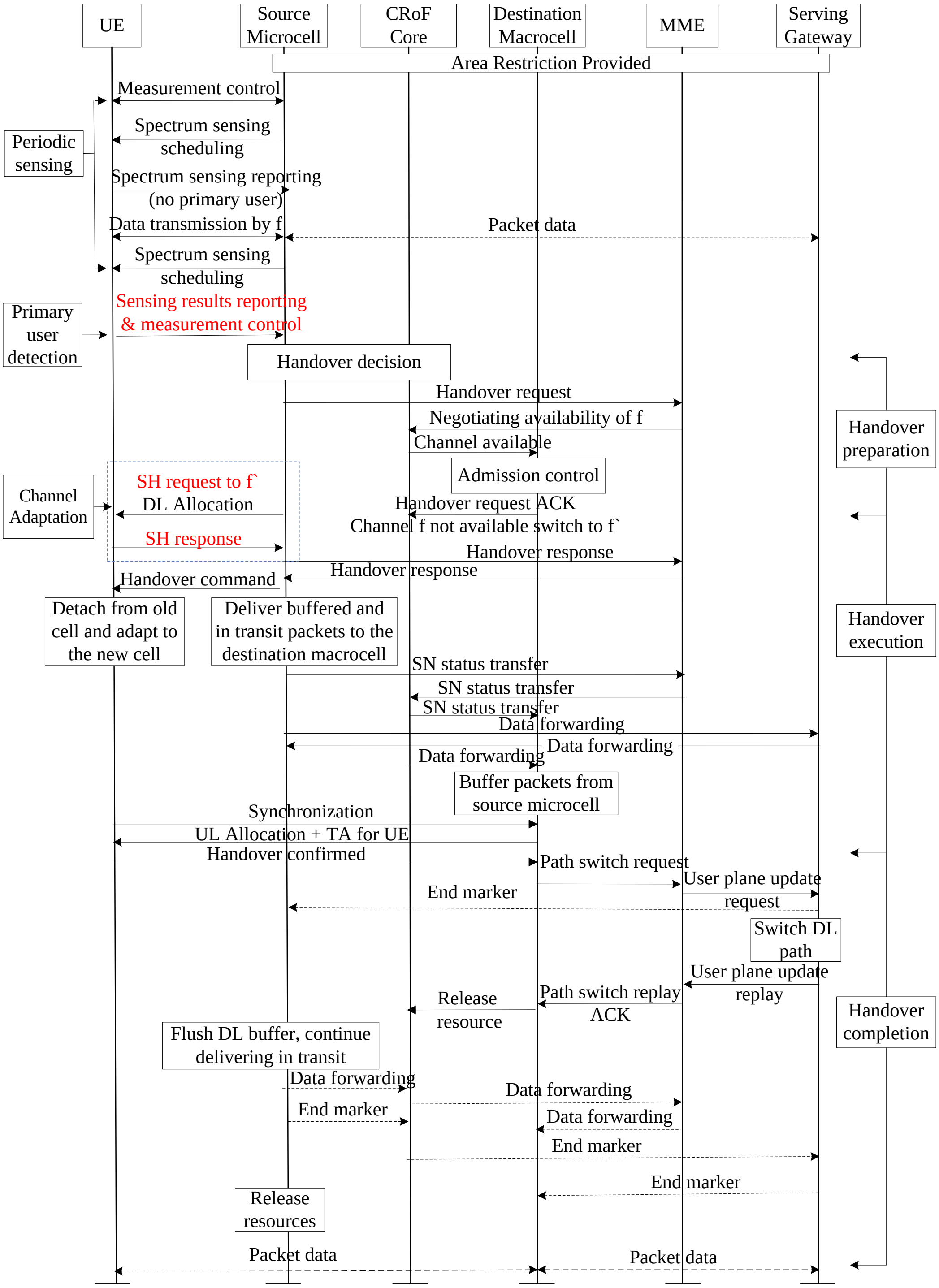

Figure 5.7: Scheme for spectrum handover while changing to (f′)

If the enforcing condition of intercell spectrum handover given in Equation 5.1 is satisfied, the detailed procedure shown in Figure 5.7 is carried out. When a primary user is moving towards macrocell domain, a control message is reported with the latest updates of the periodic spectrum sensing. Then, a handover request is made to the next BS provided by the frequency of operation (f) to negotiate the availability of this channel at the new domain. Then, if the frequency is not available at the new destination BS, a channel scanning is performed to look for a new available channel namely (f'). Then a channel adaption request is sent back to the UE to change to (f'). Here and before changing the frequency, the UE buffer the data and halt transmission while packets at the microcell are also buffered and directed to the macrocell BS. When the BS adapts to a new frequency, all the other transmission conditions are maintained except the centre frequency. A path switch request is issued to the CRoF core that acts as the serving gateway and the user plane profile is updated with the new location and frequency. In the proposed scheme, some UEs that satisfy the enforcing condition of intercell handover may not immediately change to a new frequency due to the limitation of resources available and the time required for performing spectrum scanning and assigning new channels.

The handover scheme when the macrocell BS determines the availability of the frequency (f) for the new arrival UE is shown in Figure 5.7. It can be seen clearly the differences in time spent while adapting the frequency between the two scenarios of Figures 5.6 and 5.7. In the next section we will show the installation scheme for the CAA functioning channel holding between various BSs.

5.4 Spectrum Handover Mechanism

5.4.1 Channel Availability Algorithm

When the cognitive user issues a request for handover, it sends its location data and its current used frequency channel. These are typed into the packets attributes exchanged with the BS during the handover process. The MME starts making predictions of the channel availability before the current transmission frame ends. Based on the prediction, the MME decides whether to allocate the same channel to the UE or to allocate a new channel or stop the ongoing transmission. This model is proposing two conditions for determining whether a spectrum handover should occur: (1) the forecast probability that the current candidate channel (i.e., a channel that can be selected for continuing the current data transmission) is busy or idle and (2) the expected length of the channel idle period. Based on these measures, spectrum handover actions are performed as given in the following section.

In this section, a novel protocol is proposed to conduct spectrum handover based on the spectrum utilisation assumptions given in the previous section. It consists of two parts. The first part, namely Algorithm 5.1 (highlights the signal flow diagram in Figure 5.6) describes how a cognitive user initiates a handover request. Regardless of the transmission domain, if a handover request arrives at the BS, the BS predicts the availability of the channel used by the UE at the beginning of the next slot. Based on the prediction results, the transmitter sends Acknowledgement (ACK) that frequency channel f is available to the receiver at the beginning of the next time slot. Upon allocating the channel the UE is detached from the old BS and performs the normal handover and start the data transmission on the same channel.

```
//** Algorithm 5.1:  Starting A Handover Request: f is available  **//
Register initiation
Hanover request received: $Ch_i=f$, HO request=0
Predicting the availability of (f): frequency and time duration
{
If (f) is available
    HO request=1
    Else switch to Algorithm 5.2
End if
If HO request=1
    Sending ACK
End if
Upon receiving ACK
Performing handover
If handover completed
    Transmitting data
    HO request =0 when transmission ends
End if
}
```

5.4.2 Channel Adaptation Algorithm

The second part, namely Algorithm 5.2 (the pseudo-code highlights the signal flow diagram in Figure 5.7, is a spectrum handover when channel f is not available for UE transmission. This scheme is used to determine the process for UE to carry out a spectrum handover and then switch to a new channel by the time the current frame in transmission ends. This is likely to happen due to the primary user activities or due to the limitations of the channel characteristics.

Based on the observed channel usage information, a cognitive UE checks the current mobile user channel by predicting the channel availability at the end of the frame. If the condition is not fulfilled, then the used channel will be available for the next frame transmission. At this stage, the UE will not carry out any spectrum handovers and keeps staying on the same channel. However, if the condition is fulfilled, the *Channel-Adaptation* (CAP) function is set and the current channel is considered to be busy during the next frame time. The UE performs a spectrum handover by the end of the frame to avoid any interference to the primary user. After the CAP is set, the connection is maintained between the UE and the serving BS.

```
//***** Algorithm 5.2: Spectrum Handover: $f$ is not available *****//
Register initiation
CAR=0, CAP=0, NUC=0, LSC=∅
{
For $(i = 0, i \le M)$ do
    Predicting the availability of $Ch_i$ (channels other than ($f$)): frequency and time duration
End for
If $(Ch_i, 0 \le i \le M)$ is available: frequency and time duration acceptable
    CAP = 1
    NUC = NUC + 1
    LSC(NUC) = i
End if
If LSC=∅
```

```
13          Transmission stops
14          Go to step 4
15      End if
16      Upon receiving CAR then
        Send ACK
17      Switch to the selected channel
18      Start scanning the channel
19      If channel get busy
20          Transmission stops
21          Go to step 4
22          Else HO request = 1, CAP = 0
23      End if
24      If HO request =1
25          Transmitting data
26          HO request = 0 when transmission ends
27      End if
28      }
29      Go to Algorithm 5.1
```

The BS checks for other candidate channels in the band to perform handover. If no channel is available, then any ongoing transmission will be stopped immediately at the end of the frame. Then, the BS checks the channel availability at the beginning of the next time slot. The BS then sends a *Channel-Adaptation-Request* (CAR) packet containing the updated chosen channel information in the next time slot. Upon receiving the CAP packet, the cognitive UE replies with a *Channel-Adaptation-acKnowledgement* (CAK) packet. If the CAK packet is successfully received by the BS this means that a new frequency channel is now allocated. Then, a new link is established and data transmission proceeds onto the next frame. The algorithm proposes two functions of NUC and LSC as the number and the list of the candidate channels for cognitive transmissions, respectively.

The handover time delay occurs because of the spectrum handover is defined as the interval from the time a cognitive user leaves its used channel to the time it resumes the transmission. There is also a possibility that the allocation is not correct and that there is a primary user in operation over the new channel. Therefore, it is necessary to the cognitive UE to scan the channel and make sure that it is idle at the beginning of any frame transmission. If the channel is sensed busy, the Algorithm 5.2 is launched again to investigate for another channel.

5.5 Mobility Performance Evaluation

5.5.1 Simulation Scenario

Spectrum handover is another source besides traditional handover for providing mobility in cognitive network architecture. Considering SH, this dynamic process of adaptation between channels may happen to fixed and moving mobiles at the same time. However, splitting the effects of traditional handover schemes from the new SH is a very new topic for discussion in secondary networks. The main aim is to reduce the time of interruption in services resulted during the adaptation of the cognitive UE between channels. The evaluation setup of the proposed soft-spectrum handover method is performed by allowing the UE shown in Figure 5.8 to use the same channel when moving between positions #1 to #2, #3, #4 and then back to #1.

This was compared to the traditional model where UE may be forced by the primary user to adapt to another frequency.

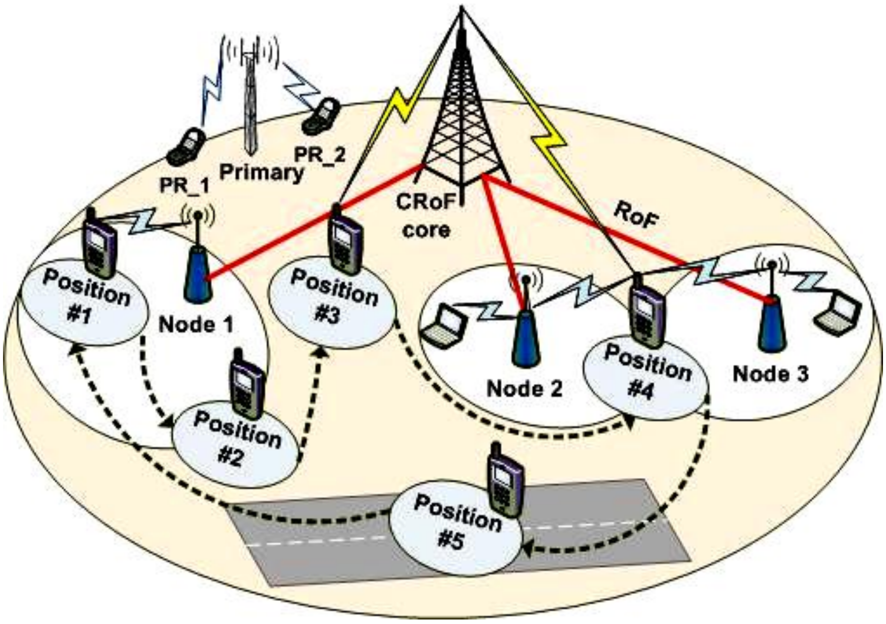

Figure 5.8: Spectrum handovers events for a cognitive mobile station move between different microcellular and macrocellular domains

Considering the system in Figure 5.8, for a cognitive MU using this movement route *the lazier the more comfortable while the more active is the more exhausted*. Hence, the UE experiences five different events of handover as it moves along the trajectory shown in the figure, these handovers occurs when:

1. The UE moves into the microcell coverage area (position#1) where service capacity is much higher because of the stable and short range communications.
2. The UE leaves the microcell coverage area (position#2) to the macrocellular services area.
3. The UE heads directly near to the macrocell base station (position#3).
4. The UE moves to the fully covered area by three transmissions sources: the macrocell and two microcells (position#4).
5. The UE moves along the motorway (position#5) returning to its initial point (position#1).

To examine the performance of the new SH schemes using the scenario above, the UE is set to use different speeds of movement along the route shown in the figure. These speeds were set according to the Table 5.1 which presents the vehicular speed limits in the UK as follows:

Table 5.1: Simulated Mobile Station Speeds

Speed Kilometre/hour (km/h)	**Description**
4.63	Pedestrian
32.18	Cars speed in urban areas
48.28	Cars speed in urban areas & villages
64.37	Cars speed in non-built areas
80.46	Cars speed in non-built areas
112.65	National speed limit

An IP telephony, silence suppressed signals are generated to test the system performance. The reason to choose this kind of application is that normal phone calls are actually composed of different times of activity where the user is either talking or silent. The IP networks transmit packets only when the data and control information are in action. Therefore there is no usage for the channel if the clients are not sending anything. Thus, such an application is very useful in analysing the cognitive networks and the dynamic spectrum access models. The reason for this is that transmissions occur temporarily and only when it is needed which is the same principles of the cognitive radio systems.

The simulation setup includes two networks primary and secondary networks that coexist with each other. Primary users are transmitting along all channels while secondary systems are accessing the available band on temporarily basis whenever there are no primary activities. In order to simulate the performance of the new model at precisely, the number of the UEs moving around is set to 1, 3 and 7 respectively. In each case study, an evaluation for the system improvement with no SH using algorithm 5.1 is compared to the traditional case where the SH is happening along the movement route algorithm 5.2.

5.5.2 Results

In this section, the simulation results are presented to validate the proposed scheme. In Figure 5.9, end-to-end time delay is shown for all the simulated numbers of UEs as function for the mobile speed.

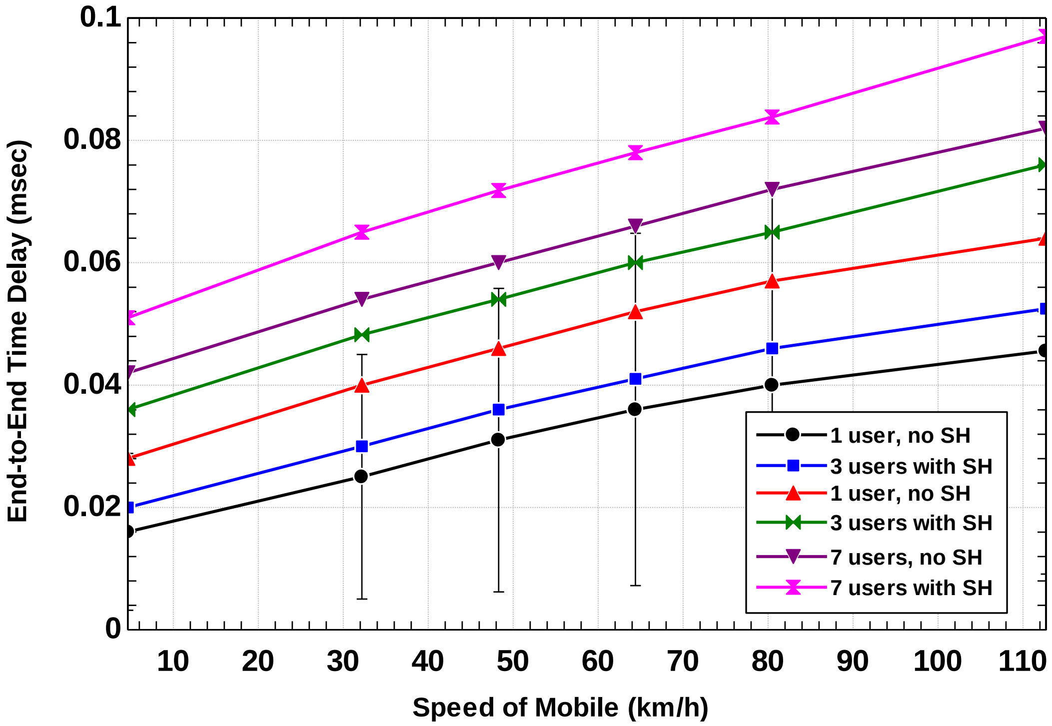

Figure 5.9: End-to end time delays as a function for the mobile speed

The figure depicts that there is a considerable time delay savings using the new scheme of CAA as compared to the traditional models where the mobile phones conduct a SH while registering with the new base stations. In this way, we can see the time savings gained from the CAA installation. The reason for this is that limited available resources blocks the continuity of performance improvement in the system for non SH case because there is no channels to host growing number of UEs.

The throughput in Figure 5.10 shows also a major improvement with the application of CAA and no SH events. For all simulated cases, the throughput is higher than the case for the traditional spectrum handover. The explanation for this is that the time spent in the adaptation between various channels reduces the performance of the system. This interruption time impacts the time delay in Figure 5.9 and the throughput in Figure 5.10 with the values shown in both drawings. It can be noticed also that the performance of the simulated system is declining slowly with the increment of the UEs speed. A speedy UE loses some local transmission opportunities that are available at scattered locations in the macrocellular and microcellular domains. Therefore, the faster the UEs become the lower their ability to attain white-time spaces.

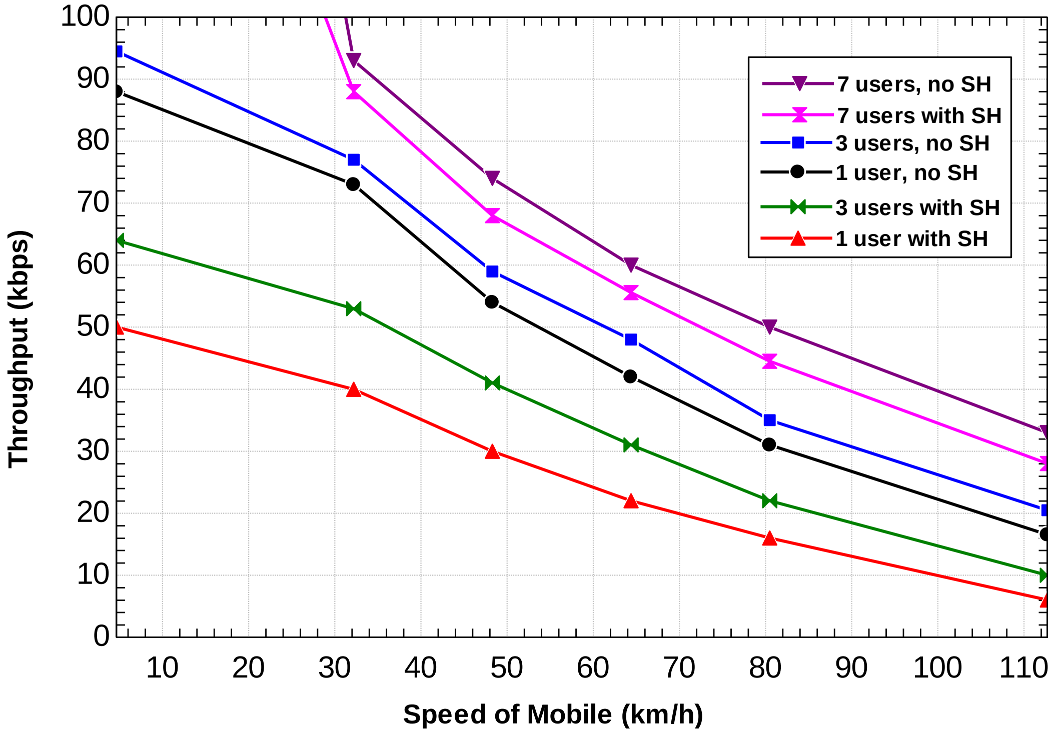

Figure 5.10: Throughput as a function for the mobile speed

To understand further the performance of the cognitive UEs at different positions using the simulated speeds, the connectivity to the APs in Figure 5.11 is analysed as a function for the measurement points illustrated in Figure 5.8. This means that a mobile phone can detect the next station easier on its channel rather than waiting for normal adaptation before conducting the search and registration with the next base station.

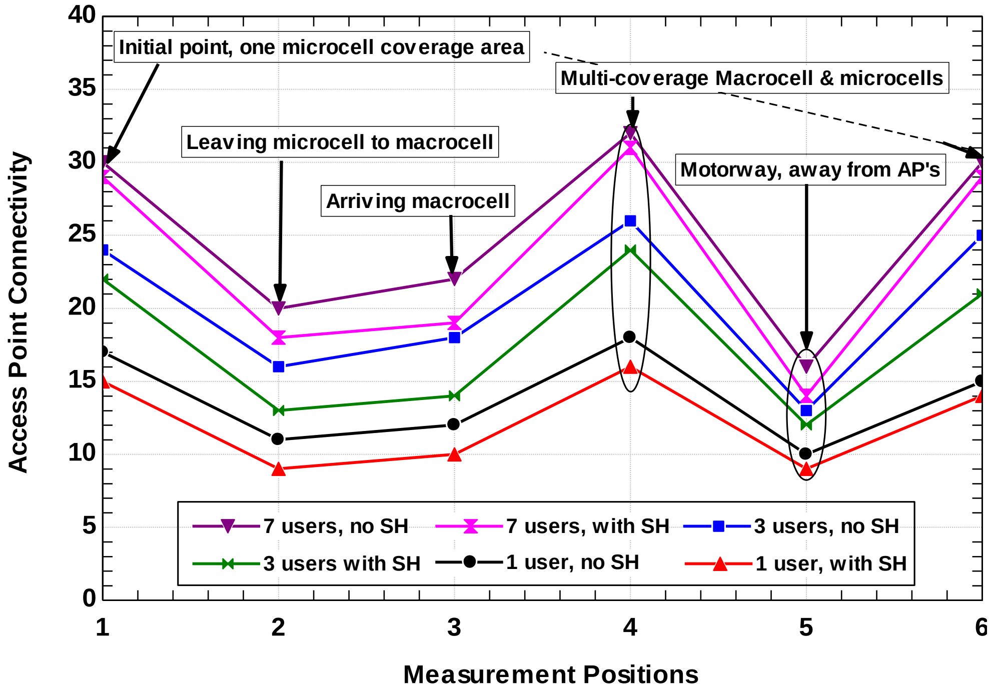

Figure 5.11: AP connectivity vs. mobile locations as shown in Figure 5.9

Firstly, the studied cases shows a similar performance for no SH and with SH scenarios. Secondly, there is an obvious improvement in the performance due to the CAA application. However, it can be seen that the connectivity levels between the UEs and the APs are declining as the mobile movies from the main coverage area of the microcell leaving to the macrocell (positions#1 to #2). It can be noticed that the connectivity levels to the AP is increasing as the MU moves towards the macrocell base station (position#2 to #3). Then, reaching the maximum value under the coverage of three sources: macrocell and two microcells at position#4. Afterwards, connectivity shows the lowest values as the UE travels along the motorway away from the APs at position#5. At the end, the connectivity values raises again as the UE returns home to the initial point of their journey (position#1).

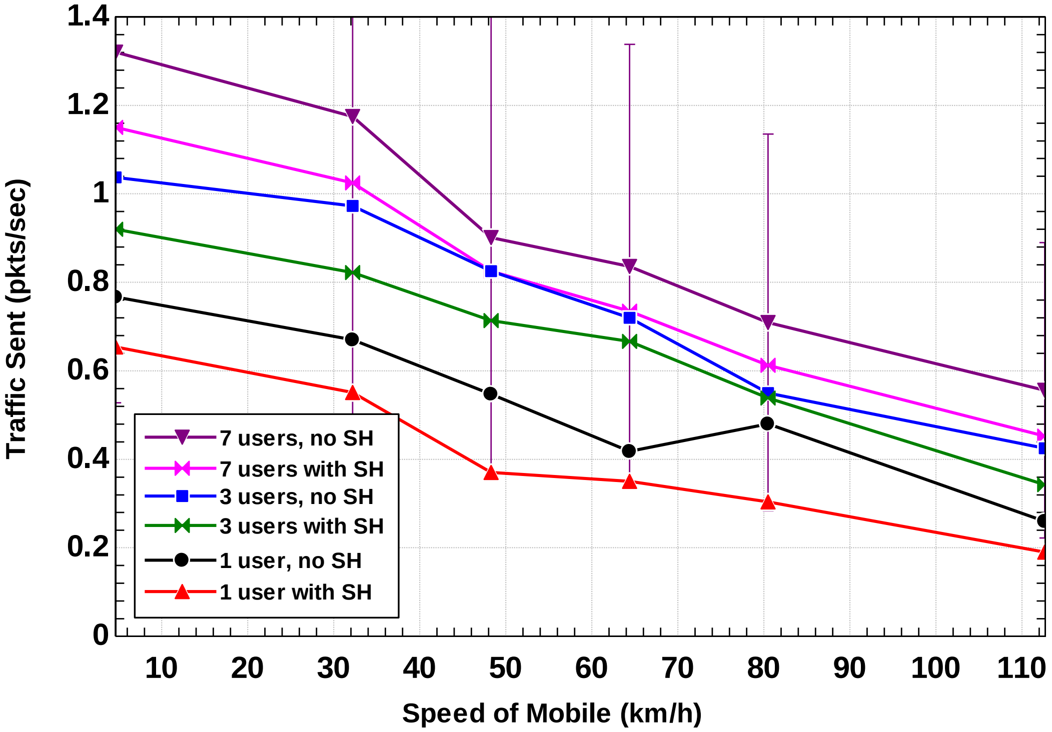

Figure 5.12: Traffic sent as a function for the mobile speed

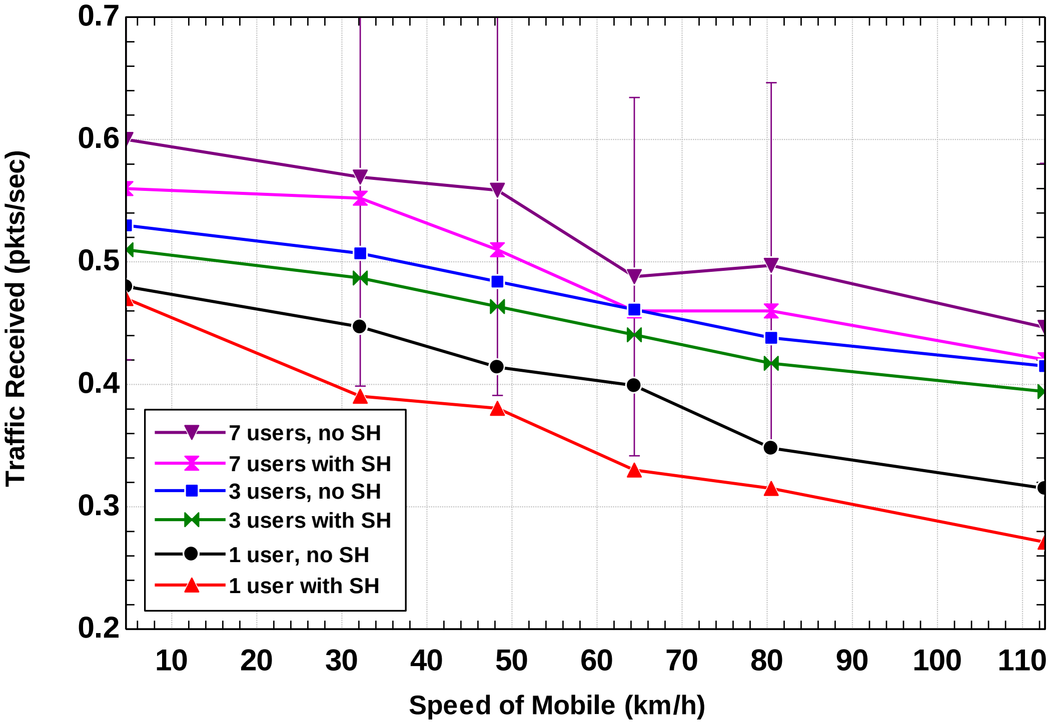

Figure 5.13: Traffic received as a function for the mobile speed

The traffic figures show similar performance for both traffic sent and the traffic received as shown in Figures 5.12 & 5.13 respectively. In both cases, the scenarios for UEs without any SH that are using the new proposed scheme of keeping the same channel of transmission along the movement trajectory show a better performance than traditional SH scenarios. In addition, the traffic in both cases is declining as the speed of the UEs is increasing.

In summary, the CAA application for reserving channels to the cognitive UE improves the performance in accessing the spectrum and interfacing to the new APs.

5.6 Fairness of the Channel Assigning Scheme

5.6.1 Background

Mobile IP allows a mobile station to maintain connectivity while changing its point of attachment. The aim is to ensure that the user is “always-connected” or better still “always-best-connected” to the access networks [27]. This can be matched to the way that TCP reacts to the loss where it reduces its transmission window size before retransmitting lost packets. This reduction in window size eases the load on intermediate links, hence controlling congestion in the network. The subsequent increase in window size depends on whether TCP is in slow start phase or congestion avoidance phase. In the slow start phase the window size grows linearly in response to every acknowledged packet, while the window size grows sublinearly in the congestion avoidance phase. In general, the essential functionality of TCP remains the same, despite the modifications to improve its performance [28].

The above discussion shows that our proposed channel allocation scheme can avoid unnecessary frequency adaptations and improve performance among cognitive users and it is a fully distributed algorithm. In addition, from the above discussion, obviously the most important feature of the proposed distributed channel allocation scheme is the priority in choosing channels during spectrum access. Therefore, it is necessary to understand and analyse the fairness of our proposed model and the equal distribution among new placed call admissions. In this section, the fairness is defined here as the opportunity for equal handover access for every cognitive UE. This is because from the network performance viewpoint, handover delay is the most significant metric to evaluate a spectrum handover protocol. Thus, allocating the channels for certain users may impact the equal average handover delay. The spectrum handover delay describes the duration from the moment a UE starts to perform a spectrum handover to the moment it resumes the data transmission. However, this prior forecasting for the mobile transition actions help to improve traffic planning and minimise the spectral congestion by redirecting the new users away from the allocated channels. In this section, the fairness of a system that employs CAA is evaluated to examine the TCP/IP interface performance and capacity utilisation.

5.6.2 Performance Evaluation

5.6.2.1 Network Settings

The examined network environment was created to allow the coexistence of the two networks, namely: cognitive and primary. The cognitive mobile users were set to randomly arrive at different time intervals throughout the simulation time to register with the access points. The traffic was generated using VoIP generators and the proposed CAA model was installed at the Mobile IP units. The network consists of 130 mobile users and four access points that connected via fibre, as shown in Figure 5.14.

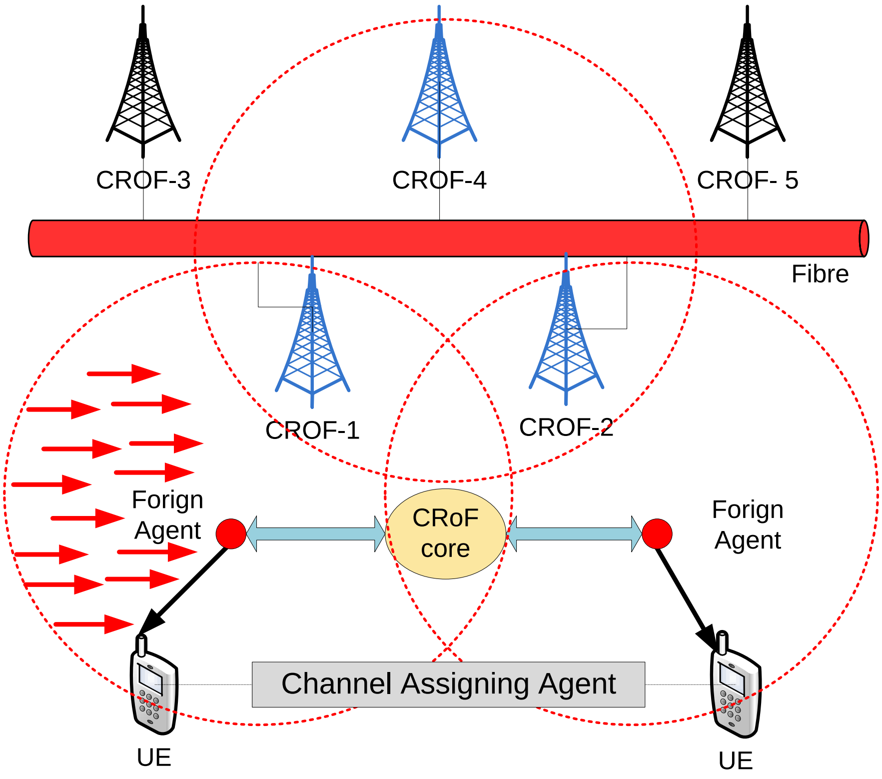

Figure 5.14: Connection performance study model

The specifications of the simulated network are shown in Table 5.2:

Table 5.2: Network Settings for Simulating CAA

NETWORK PARAMETERS	VALUES	NETWORK PARAMETERS	VALUES
Application Layer		**Cognitive Microcell**	
Encoder Scheme	G.711 (silence)	HCF	Supported
Voice Frames Per Packet	1	Physical characteristics	OFDM (802.11a)
Type of Service	Best Effort (0)	Data rate	48Mbps
Signalling	SIP	Transmission opportunity (TXOP) duration	1 MSDU
TCP parameters		RTS thresholds	1024 bytes
ACK Mechanism	Segment/Clock Based	Route request rate limit	10 pkts/sec
Max. ACK Delay	0.2 sec	Node Traversal Time	0.04 secs
Max. ACK Segments	2	**Primary Gateway**	
Fast Recovery	Reno	Physical characteristics	Direct sequence
Fibre		Data rate	11Mbps
Model	1000BaseX	Bandwidth	22MHz
Frame Bursting	Enabled	Max. Receive lifetime	0.5 secs
Operation Mode	Full duplex	TBTT	0.02 secs
Delay	Distance based		

The maximum segment size is set to "Auto-Assigned", so that TCP can calculate this parameter based on the Maximum Transmission Unit (MTU) size of the first IP interface of the surrounding node.

5.6.2.2 Results

The simulation was conducted for one hour; results show impressive performance with the CAA installation in congestion control at the TCP layer. In Figure 5.15, the number of connections aborted using the CAA application is less than the same number with no CAA. This means that it is more reliable to use the new proposed scheme for the connections in operation and connections in place. Packets are transferred over a smooth and faster link until they reach even beyond the maximum allowed connections at the mobile base station. On the other side, connections aborted are considerably higher for the traditional cognitive communications schemes. The connections aborted in this case show higher values and they are not able to utilise the permitted numbers of connections at any of the access points.

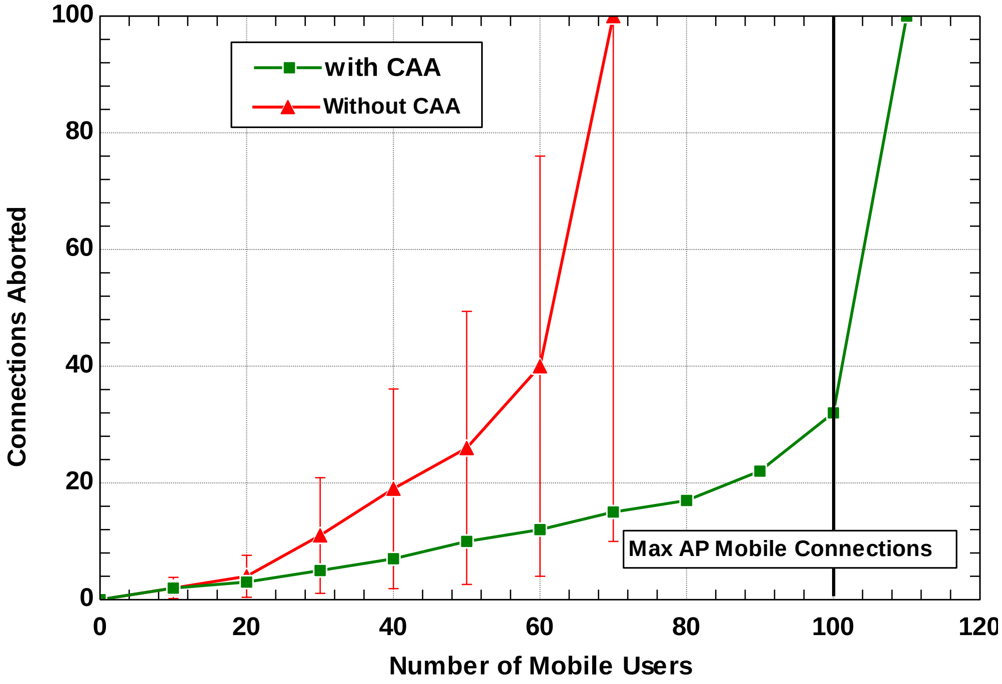

Figure 5.15: Connections aborted with/without CAA

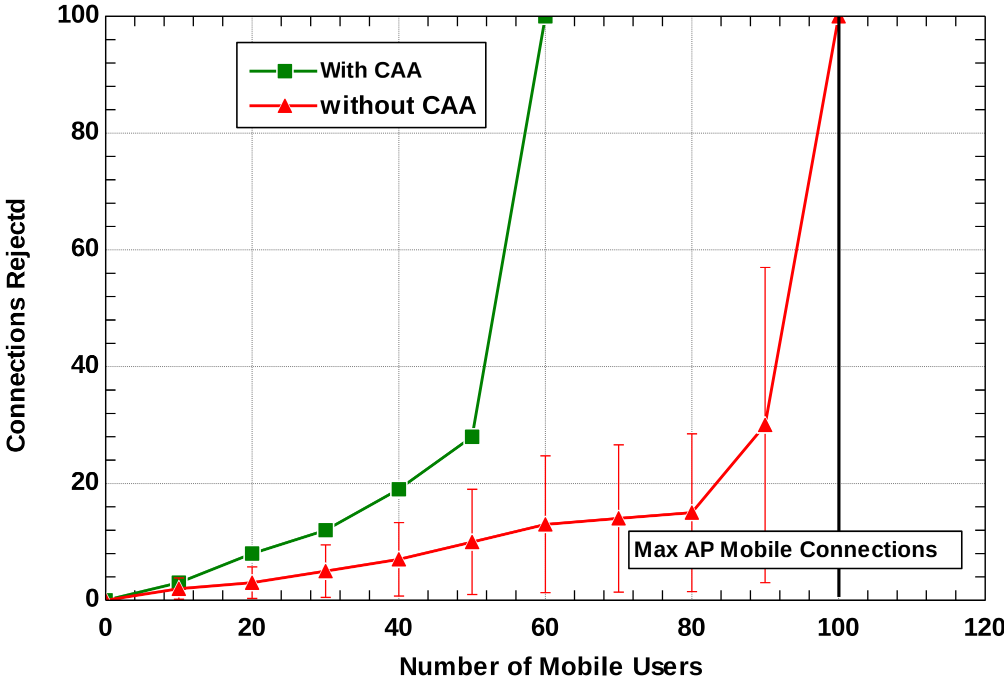

Figure 5.16: Connections rejected with/without CAA

Figure 5.16 shows the connections rejected with and without CAA. The numbers of the rejected connections with the CAA is much higher than the numbers without CAA. The is due to the fact that the CAA reserves channels for longer times compared to the traditional calling schemes causing more connections to be rejected while give longer time and preference in accessing the spectrum to the successful connections in operation. This might be a defect in this application and an indicator of unfairness especially when the available bandwidth is small. On the other hand, this increases the need for a congestion control scheme based on inline network measurement for any deteriorates resulted from unexpected loads.

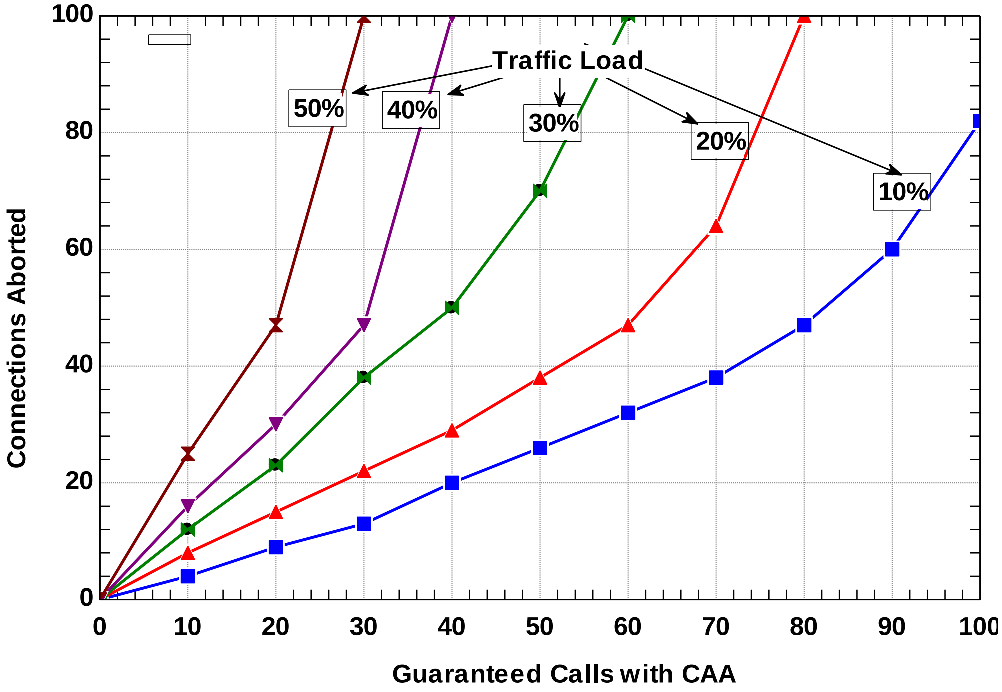

Figure 5.17: Connections aborted vs. guaranteed calls with CAA as a function for traffic applied loading

In Figure 5.17, we evaluate the behaviour of the proposed channel allocation scheme against the changes in the amount of cross traffic. In this way, the results are compared for various traffic loads with the guaranteed connections available by the CAA. Obviously, the number of calls aborted for the guaranteed users increase as the loads increases. When the load becomes high the queue length becomes large with fixed bandwidth availability causing more calls to be dropped.

In summary, it is clear that CAA can optimally utilise available resources to provide allocated service applications to the users in connection. However, the system is not fear to the new arrival mobile units or the ones who are performing frequency adaptations.

5.7 Multi-Zoned Spectrum Sharing

The future cognitive mesh network is to be deployed in coexistence with the other primary networks. Therefore, the positions of the cognitive BSs are decided by many factors such as the transmission power, coverage range, used channels and number of expected end-users, in order to avoid interfering with primary networks. Thus, it is presumed that not all BSs would have the accessibility to fibre connections for many reasons:

1. CRoF-BSs are to be connected to the backbone fibre networks and not fibre terminal edges or copper connection. This will assure the highest speed for data transfers across the fibre network. In addition, this prevents the decline in services, which may result from the time taken for downloading and uploading data frames.
2. The fibre connections are not as replacement for the wireless links between cognitive BSs. Fibre is used to support the network as an alternative for wireless links only when there is no way to formulate an efficient and reliable wireless link.
3. The cost of connecting fibre to the cognitive network and the modified CRoF stations should be taken into consideration when choosing the installation positions and the number of CRoF-BSs.

For all these reasons, only some selected BSs are connected to the fibre network as CRoF gates. The best strategy for installing the cognitive BSs is to place them within the known boundaries of the primary bases stations. This is to simplify the spectrum trading between the primary and secondary networks and also to make it easier in dealing with temporary licenses issued from local spectrum entities. Thus, a new network system of multi-access cognitive networks emerges to improve the cognitive communications performance and reliability. Figure 5.18 shows a big sized cognitive network with only selected cells as CRoF areas.

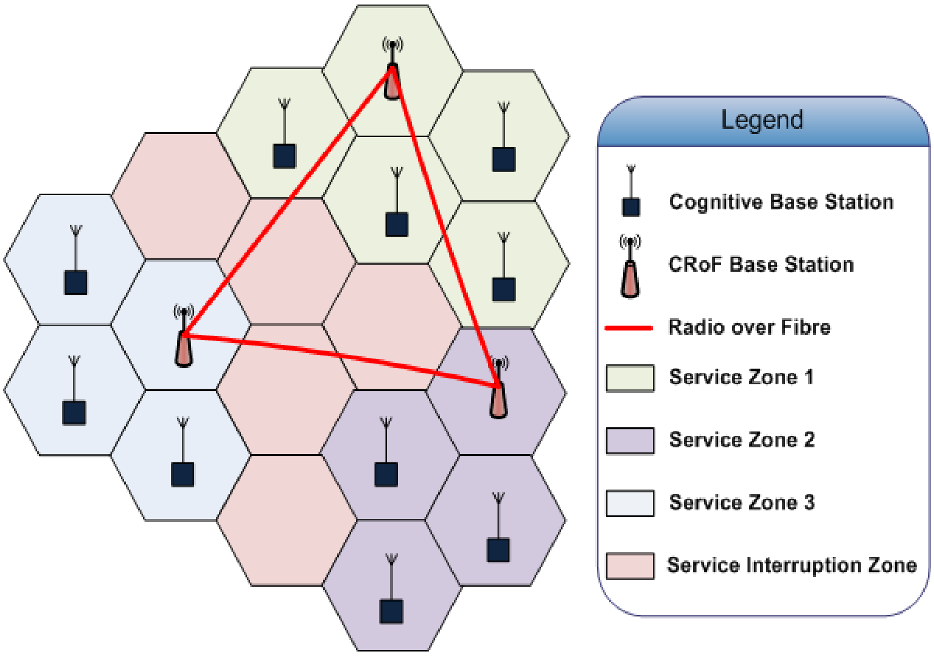

Figure 5.18: Multi-access cellular network of CRoF and CR base stations

The CRoF cells will attract neighbouring cognitive cells to use CRoFs fibre connections for data exchanges in severe wireless situations. This is likely to happen whenever a cognitive BS fails to establish a link with remote sites of the network [29, 30]. These groups of CRoF and cognitive cells that share the same wireless environment conditions split the network into different zones of services. In each zone, CRoF acts as the master for all other cognitive cells. This division makes it easier to achieve local resources sharing between each zone cells while CRoF cell as a main hub of communications. The spectrum channels are shared in a distributed way between the zone cells and using the same proposals in this chapter. In fact, the CRoF acts as a subnet that is quite similar to what neurons do in the human's body. The CRoF exchanges data, information, transmission requests with other zone sites using its landline connection and via the other sites CRoF cells. The new network architecture can be defined as a new hybrid system for dynamic spectrum access using local, central-to-local, and global network resources management. The advantages of multi-zoned application to future cognitive networks can be summarised as:

1. Novel Base Stations that is integrated to landline access. These are chosen based to long-term monitoring for the traffic loads and availability of free spectrum at local areas.

2. More independent cells that are able to reconfigure and adapt to various wireless spectral situations and network interfacing managements. This requires an extended cognition engine designs for the cognitive Base Stations and new protocols for transferring knowledge between different network stations as in [31].
3. Establishing temporal, local, flexible zones of neighboured cognitive cells. These formulations may ease the access procedure and mobility managements in smaller areas of one pool of spectrum channels.
4. New mobility schemes that can deal with cells rather than individual mobile stations. The main goal is to create a system that can respond and act to unpredicted wireless spectral changes and various numbers of users.
5. Reducing complexity of dealing with main spectrum entities by establishing local governing units supported by protocols. The cooperation between various cells is necessary for the success of the proposed models.

The following sections will investigate the criterion for the formulation of these zones, changes in the zones’ sizes and boundaries, and the possible scenarios for cognitive cell migration between these zones. This new paradigm of local resources sharing through architectural adaptation between the secondary systems is a subject for evaluation using route optimised cellular MIP protocol [32].

5.8 Cell Migration between Zones of Service

The zoned cell groups are proposed to be dynamically changeable formulations to host and release new cognitive cells. In other words, cognitive cells may join or leave zones at any time as their wireless spectral situation change. These changes in wireless environment may result from the dynamic activities of the primary users. Such changes may affect local wireless environment at certain cells and make them different to the other cells inside a definite zone. Consequently, a cell may decide to leave a certain zone and join another one or even stay as an independent cell, according to the negotiations between the cell BS and other neighboured zones. This section analyses briefly the possible scenarios of coexistence between various zones and the migrated cell. The objectives of this cell migration are to attain the most efficient spectrum utilisation and the highest quality of service. The main assumption is that the coexistence is done in a cooperative way and based on dynamic network management that can adapt to any real-time adaptation requirements.

In order to be able to formulate the proposed zones, there should be arrangements to share the necessary awareness on the wireless spectral and resource changes at the cellular and network levels. The best scenario is to supply information in two levels, *Global Network* and *Local Zone*. In the global network, information is spread between zones and independent cells, and vice-versa, to make them aware of the general wireless situation inside each area. This information may be provided by each zone to its cells. On the other hand, a local zone (x for example) may provide regulating data, changes inside a zone, and neighboured zones change to the cells grouped by zone(x). An IP address may be given to different zones on a temporary basis to simplify the way of providing services throughout the network. One suggestion is to use the CRoF-BS IP address as the zone address. Therefore, a new and fully dynamic network is created to various wireless events.

The possible events for cell migration are explained in the following cases:

5.8.1 *Case 1:* Cell moving between zones

The disengagement process for a cell leaving from one zone to another can be performed through informing the neighboured cells in the area. The cell takes the decision to leave a zone whenever it recognises that spectrum availability has changed and it is not possible to establish links with other cells as before. This can be performed by setting a linkage threshold for the number of link request iterations before making the leaving decision. This might happen also when the reports received from local spectrum governing entities show a major change in the forecasted and presently accessible channels for cognitive communications. However, it is necessary to set regulations that prevent cells from leaving zones just because they are turning selfish and they want to keep more resources for themselves. Whenever a cell is intending to leave the zone, all other zone cells are advised about this decision. Then all other zone cells may terminate their special *Local Zone Connections* with the leaving cell and re-direct their transmission routes using other stations. The migrating cell becomes free and can immediately join any other zone, as shown in Figure 5.19.

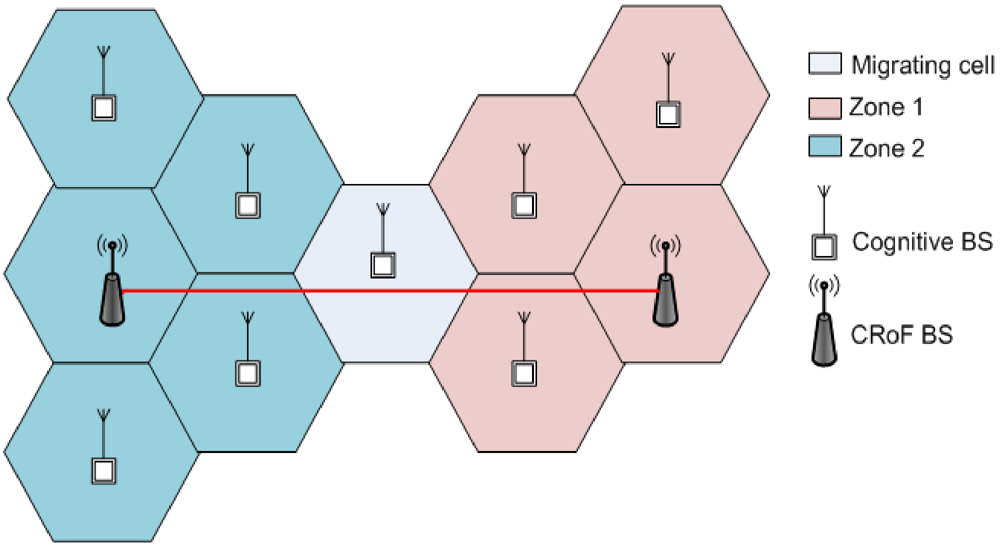

Figure 5.19: Cell migrations between two zones

Here, there are two methods for joining the new zone, either the cell had negotiate this with the target zone prior to its decision to leave the home zone, or it makes this decision after it becomes free. In both cases the cell will be able to attend the new zone only if it had the same wireless spectral and resources situations and there are no more obligations any more with the old zone.

Normally, a zone accepts the request issued by an individual cell to join its cells as long as this application follows the above procedures and gets more resources. The time taken for cell migration should be quick enough to prevent any interruptions in communications for the migrated cell and to prevent being trapped between two zones of services. At all times, the cell is still part of a bigger network infrastructure and operator services. This in case the cell did not identified itself as an independent service zone. The local communications and re-directing of the services throughout the zone is changed as soon as the new cell is unified with the service area. The time that is spent by a cell during migration between two zones is named as *Cell Migration Time (CMT)*. The cell inner services to its end-users should not be affected during the CMT.

5.8.2 *Case 2:* Independent cell between zones

As the formulation of zones is based on unifying cells that have similar wireless conditions, a certain cell may choose to stay out of these zones due to the fact that it has different resources availability, as shown in Figure 5.20. This independent cell emerges as a new small-sized zone of service that may or may not have fibre access connection. While it is acceptable to have smaller zones without landline access, it is unlikely but possible to have bigger zones with no fibre connections.

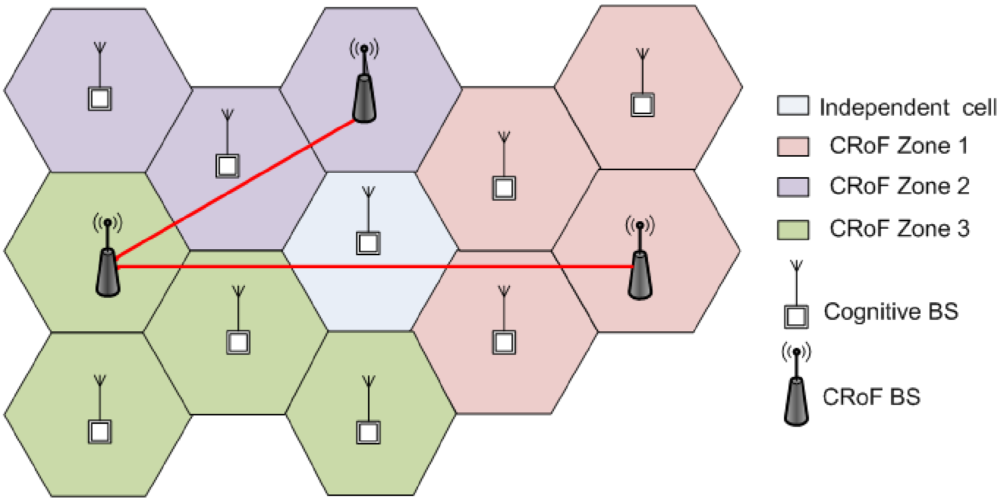

Figure 5.20: Independent cell coexistences with zones

The main concern for having many independent cells is the time taken for negotiations during link formulation between the neighboured zones and this independent cell. The complexity in such a system comes from two sources: firstly, the time taken to decide to connect large zones' services and small sized zones (cells) in a very dynamic wireless environment where transmission opportunities may be lost anytime. Secondly, the identification of end-users' locations and high risk of adjacent channels interference, in case the cells on both sides turn selfish. All this shows that the choice of a certain cognitive cell to work independently from CRoF zones may impact network performance. However, it is still acceptable for the zones to coexist with a different cell that chose to become independent. However, this independence should not affect at any time the overall network performance and the network duty life cycle. This can be achieved through fully cooperative management which is guaranteed by the local spectrum governing entities and the operating protocols.

5.8.3 *Case 3:* Cell trapped by one zone

The unification of different cognitive cells having the same resources may lead to the isolation of a certain cell with different wireless situations, as shown in Figure 5.21. This cell is actually trapped by the same zone cells from all sides. This may happen if the cell leaves the zone after being part of it. In fact, this situation can happen when two neighboured zones choose to bond together as one zone leaving one cell in the middle. Suddenly, this cell finds itself trapped between the boundaries of this new establishment with no other choices to take.

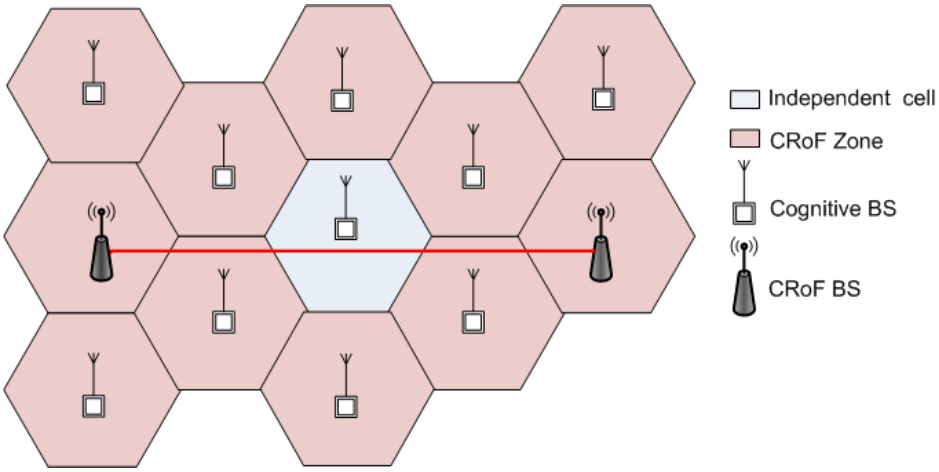

Figure 5.21: Independent cell trapped by one zone

Practically, this is a critical situation for the trapped cell in achieving high levels of cooperation with other zone stations. To maintain seamless communications in this specific scenario, the zone has to give its cells that surround the trapped cell the authority to communicate directly with this free cell without central approval. In this way, a distributed access is approved to overcome the delay resulted from requests to communicate with a small coverage area as this. There is an expected increase in the complexity of running such a network because of the long procedures of having one cell standalone between zone boundaries. However, the complexity may increase further in case the cell is forced to join a zone of unmatched wireless situations. Therefore, it is preferable to oblige with the general rules of balancing services by reunifying only similar cells rather than adding one more different cell.

As for being dynamic sets, the zone sizes, places, cell members, and shared resources may change at any time due to the activities of the primary users and the technical difficulties/differences in adjusting transmission functions. Therefore, negotiations are undergoing between all cells at all times to achieve the highest QoS in responding to clients' requests and spectrum developments.

5.9 Conclusion

A novel scheme is proposed to reduce the spectrum handover in the future cognitive networks that employ sectored macrocells. A new entity named as Channel Assigning Agent is introduced at the mobile IP to allocate the same channel used by the cognitive mobile station to it whenever it moves inside the macrocellular sub-areas. The main goal of this design is to reduce the interruption time during frequency adaptation and the redundant unnecessary spectrum handovers for a UE travelling at various speeds. The solution involved the design of algorithms that scans the available band for the channel in operation before any decision of shifting to other frequencies. Results show considerable improvement in throughput, AP connectivity and major savings in time delay. The fairness of the proposed scheme was evaluated to show the connections aborted and rejected as a function for allocating certain channels to certain users. The work has been developed further by partitioning the cognitive networks into different zones to ease the management and access of resources, using both wireless and fibre connections. These zones are composed of a group of cognitive cells mastered by the CRoF cell, with optional attendance. The boundaries and size of any of these zones can change at any time due to the dynamical wireless changes. Various scenarios for cells leaving and joining zones are surveyed and discussed. The aim of this proposal is to identify a new local resources sharing scheme through topology adjustments. New topics are raised to the research community by analysing new IPv6 models for the cognitive networks.

5.10 References

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Chapter 6

Conclusions and Future Work

6.1 Conclusions

There is no predictable paradigm for expanding the cognitive network capacity or dealing with the dynamic spectrum access challenges through architectural solutions. However, it is acceptable that installing ever increasing numbers of macrocell BS towers with improved techniques can increase the network competence. The key problem with adding more macrocell (or microcell) BSs is a) they may not be able to communicate between each other or even formulate a wireless link due to the spectrum availability, and b) these deployments do not scale well with the ever increasing demand for data rates for reasons of mobility and scarce availability of spectrum.

In contrast, supplementary landline infrastructure in the form of fibre connected to distributed microcells restructure wireless capacity by exploiting the relative proximity of users to their AP (thereby reducing the average transmit–receive communication distance). This results in a greater number of local transmission opportunities and power consumption models. Because these technologies potentially require integration between many networks, cellular and fibre operators can recoup their initial investments into one powerful wireless–to–fibre access network and offer better service, while consuming less spectrum.

This thesis has addressed the key technical challenges confronting tiered cellular wireless systems when macro and micro users either share radio spectrum or operate over orthogonal spectrum. Our main goals are that tiered networks with one spectrum pool will be significantly encumbered by the terminal radio technologies and the distribution of microcells over the cellular networks. Specifically, there is a fundamental tradeoff between providing finding the mobile user location and providing reliable diverted call. This is performed with high level of coordination between the macrocell and microcells BSs transmissions using the fibre as part of the backbone network. The net consequence is that accommodating greater numbers of microcells (or providing higher microcell data rates) reduces the number of cellular users that can reliably operate in the same spectrum beyond certain levels. Without resources management, adding microcells will likely be self-defeating, because of the potentially likely disruption in reliable coverage of the cognitive cellular infrastructure under the assumption of no impacts on the primary network.

The focus of this work has been to address decentralised radio management in microcell-aided cellular architectures, encompassing a variety of physical layer technologies, through a combination of resources filling and sharing, power control and mobility management for alleviating spectrum scarcity and improving system capacity. With interference avoidance, the new heterogeneous network users attempt to avoid causing mutual collisions (through landline connections and dividing the coverage zones).

Improving capacity is achieved by forcing microcells to choose their end–users (and hence their transmit powers) for minimising the unnecessary spectrum usage. This thesis has developed an algorithm to divert calls between the new combined cognitive BS through fibre network rather than establishing wireless connections, a road map for the deployment capacities of cognitive users and power control analysation for the power gained from diverting calls across the microcellular system. The efficacy of these resources filling and power control schemes has been evaluated in typical coexistence scenarios with large number of microcells deployed. Finally, novel mobility schemes are suggested in this thesis to reduce the unnecessary spectrum handovers in two-tier networks using developed IP algorithms, this is done by allocating the same channel in operation for a mobile user that travels between different domains while guaranteeing a minimum desirable service to new users in either tier.

6.2 Future Work

Adaptive and open–access microcell operation will cause the cellular users experiencing radio interference at both the macrocell and microcell BSs. It is reasonable to assume that a practical system would assign weighted priorities to serviced users with high competition on valuable resources and consumers receiving higher priority of higher biddings. Because the microcells transport their traffic over the fibre network, it is important to understand the impacts of diverting calls over the landline on the fibre capacity, power consumption, time delays of signals conversion, and the Quality-of-Service for the whole system technical design.

An open research problem is to analyse which mode of operation (one pool or frequency re-use) is preferable either from the perspective of avoiding inference and efficient sharing of resources (as an instance, which operation yields a higher average throughput), or from the perspective of the entire network (a centralised entity could maximise the network-wide spatial reuse by determining two classes of wireless domains: one would provide one core for each macrocell domain, and the other set would operate cross connections between microcells). The implication is that microcells would adaptively configure their access mode depending on their location, the prevailing levels of co-channel interference, the channel conditions between users to their BSs, the number of already serviced users in each microcell and their prevailing target data rates.

In multi–zoned network operation, the dynamic changes of the network combinations overhead arising the need to dynamically update the routing tables of the available links and stations locations. These dynamically updated routing tables contain information about the topology of the network immediately around it. These routes should be an entries made in a routing table by automatic means and as a result of instant network topology “discovery” procedure. This information is delivered latter to the macrocells nodes to enable them to adjust their position within and between zones. This is a serious challenge for the practical deployments of large numbers of microcells in such divided networks. One method of minimising frequent handover events is that microcells dynamically adapt their coverage radius depending on the changes in the backbone network zone connections, channel conditions, number of users served by each microcell, and the numbers of newly installed microcells. This will generate new unidirectional shared trees of routes per group, and optionally creates shortest-path trees per source. The problem of determining the “optimal" network coverage, as a function of the available bandwidth and user mobility, is an open avenue for further research.