Centralised Dynamic Spectrum Sharing in Wireless Networks

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Submitted for the Degree of Doctor of Philosophy from the University of Surrey

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May 2010

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Summary

The static method of allocating fixed blocks of spectrum, over a considerable period of time is gradually giving way to a more flexible method of using the spectrum. Dynamic spectrum access offers a new promising method of addressing the inefficient use of the spectrum. However, three main barriers still need to be addressed to reap the full benefit. These include the technical, economic and regulatory barriers. This thesis focuses on the technical challenges that will enhance the opportunistic use of the spectrum between two operators in a dynamic manner. The aim is to optimise the use of the scarce spectrum resource. A coordinated network based approach for spectrum allocation between two wireless operators is investigated, using the Universal Mobile Telecommunication Service (UMTS) as a case study.

This thesis proposes network centric algorithms to facilitate multi-operator spectrum sharing within the context of the cellular wireless network. The achievable gains in terms of the spectrum efficiency gain is compared with legacy Fixed Spectrum Allocation (FSA). The algorithms are investigated under uniform and non-uniform traffic conditions. The results show significant improvements in the spectrum efficiency gain of the network, up to thirty six percent for the non-pool algorithm (one primary carrier and two secondary carriers) and ten percent for the pool based algorithm (two carriers). The gain is as a result of the improved statistical multiplexing of mobile users. The results also reveal that additional gains up to four percent could be achieved depending on the connection queuing times.

Furthermore, the results show that the penalties associated with the proposed algorithms in the form of total call setup messages, can be minimised by sharing the radio resource management entity. Finally, the possible architectures to facilitate the improved spectrum sharing algorithm proposed in this thesis are also investigated.
Acknowledgments

I would like to express my profound appreciation and deepest thanks to my supervisor, Professor Rahim Tafazolli for his useful suggestions and contributions to this work, as well as his constant encouragement throughout the period of my PhD study.

I would also like to express my gratitude to Dr. Atta Quddus, Dr. Kamran Arshad, Dr. Shyamalie Thilakawardana for their constructive suggestions and valuable advice at different stages of my PhD programme.

I wish to express my sincere appreciation to all my research colleagues at the Centre for Communication Systems Research (CCSR), University of Surrey, for enriching my thoughts through our interactions. Furthermore, I would like to thank them for their unrelenting support in many diverse ways.

I wish to thank my parents Dr and Mrs Mudasirii Salami for their constant love, support and prayers. I would also wish to express my profound gratitude to Donald and Antonia Chittenden, for their deepest kindness and affection. Without you all, it would not have been possible.

I will like to thank my wife and son, Lola Habiba and Muhammad Fawaz Olaitan, for their constant words of encouragement and patience during the period of my PhD study. Finally, my deepest gratitude goes to God Almighty for bestowing me with good health, wisdom, inspiration, and the strength to complete my academic studies.
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<td>3GPP</td>
<td>Third Generation Partnership Project</td>
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<tr>
<td>AAA</td>
<td>Accounting, Authorisation and Authentication</td>
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<tr>
<td>AM</td>
<td>Amplitude Modulation</td>
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<td>ACIR</td>
<td>Adjacent Channel Interference Ratio</td>
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<td>B3G</td>
<td>Beyond Third Generation</td>
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<td>BTS</td>
<td>Base-station Transceiver System</td>
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<td>BSC</td>
<td>Base station Controller</td>
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<td>CAC</td>
<td>Call Admission Control</td>
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<td>CDMA</td>
<td>Code Division Multiple Access</td>
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<td>CHT</td>
<td>Call Holding Time</td>
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<td>CN</td>
<td>Core Node</td>
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<td>CR</td>
<td>Cognitive Radio</td>
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<td>CSM</td>
<td>Centralised Spectrum Management</td>
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<td>DAB</td>
<td>Digital Audio Broadcast</td>
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<td>DARPA</td>
<td>Defence Advanced Research Projects Agency</td>
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<td>DRiVE</td>
<td>Dynamic Radio for IP Services in Vehicular Environment</td>
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<tr>
<td>DRA</td>
<td>Dynamic Resource Allocation</td>
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<td>DSA</td>
<td>Dynamic Spectrum Allocation</td>
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<td>DSM</td>
<td>Distributed Spectrum Management</td>
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<td>DSS</td>
<td>Dynamic Spectrum Sharing</td>
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<td>DVB-T</td>
<td>Digital Video Broadcast Terrestrial</td>
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<td>DYSPAN</td>
<td>Dynamic Spectrum Access Networks</td>
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<tr>
<td>FCC</td>
<td>Federal Communication Commission</td>
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<td>FDD</td>
<td>Frequency Division Duplex</td>
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<td>FDMA</td>
<td>Frequency Division Multiple Access</td>
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<td>FM</td>
<td>Frequency Modulation</td>
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<td>FRS</td>
<td>Family Radio Service</td>
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<td>FSA</td>
<td>Fixed Spectrum Allocation</td>
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<td>FSU</td>
<td>Flexible Spectrum Use</td>
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<td>E2R</td>
<td>End to End Reconfigurability</td>
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<td>E3</td>
<td>End to End Efficiency</td>
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<td>Term</td>
<td>Definition</td>
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<tr>
<td>ETSI</td>
<td>European Telecommunications Standards Institute</td>
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<td>GMRS</td>
<td>General Mobile Radio Service</td>
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<td>GPRS</td>
<td>General Packet Radio Service</td>
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<tr>
<td>GPS</td>
<td>Global Positioning System</td>
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<tr>
<td>GSM</td>
<td>Global System for Mobile Communication</td>
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<td>GUI</td>
<td>Graphic User Interface</td>
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<tr>
<td>HLSM</td>
<td>High Level Spectrum Management</td>
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<tr>
<td>IEEE</td>
<td>Institution of Electrical and Electronic Engineers</td>
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<tr>
<td>IMT-A</td>
<td>International Mobile Telecommunication Advanced</td>
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<tr>
<td>ISM</td>
<td>Industrial Scientific and Medical band</td>
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<tr>
<td>IT</td>
<td>Interference Temperature</td>
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<tr>
<td>ITU</td>
<td>International Telecommunication Union</td>
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<tr>
<td>JRRM</td>
<td>Joint Radio Resource Management</td>
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<tr>
<td>LB</td>
<td>Load Balancing</td>
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<tr>
<td>LBT</td>
<td>Listen Before Talk</td>
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<tr>
<td>LLSM</td>
<td>Low Level Spectrum Management</td>
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<tr>
<td>LTE</td>
<td>Long Term Evolution</td>
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<tr>
<td>MAC</td>
<td>Medium Access Control</td>
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<tr>
<td>MLSM</td>
<td>Medium Level Spectrum Management</td>
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<tr>
<td>MS</td>
<td>Mobile Station</td>
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<tr>
<td>NGN</td>
<td>Next Generation Networks</td>
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<tr>
<td>OFCOM</td>
<td>Office of Communication</td>
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<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
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<td>OFDMA</td>
<td>Orthogonal Frequency Division Multiple Access</td>
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<tr>
<td>OVERDRIVE</td>
<td>Spectrum Efficient Uni- and Multicast over Dynamic Radio Networks in Vehicular Environments</td>
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<tr>
<td>PO</td>
<td>Primary Operator</td>
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<tr>
<td>QoS</td>
<td>Quality of Service</td>
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<td>RAN</td>
<td>Radio Access Network</td>
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<td>RAT</td>
<td>Radio Access Technology</td>
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<td>RF</td>
<td>Radio Frequency</td>
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<td>RFID</td>
<td>Radio Frequency Identification</td>
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<td>RNC</td>
<td>Radio Network Controller</td>
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<td>RRC</td>
<td>Radio Resource Control</td>
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<td>RRM</td>
<td>Radio Resource Management</td>
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<td>Abbreviation</td>
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<tr>
<td>SAC</td>
<td>Spectrum Access Control</td>
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<tr>
<td>SB</td>
<td>Spectrum Broker</td>
</tr>
<tr>
<td>SCC</td>
<td>Standard Coordinating Committee</td>
</tr>
<tr>
<td>SCOUT</td>
<td>Smart User Centric Communication Environment</td>
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<tr>
<td>SDR</td>
<td>Software Defined Radio</td>
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<tr>
<td>SEG</td>
<td>Spectrum Efficiency Gain</td>
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<tr>
<td>SM</td>
<td>Spectrum Management</td>
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<tr>
<td>SME</td>
<td>Spectrum Management Entity</td>
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<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
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<tr>
<td>SO</td>
<td>Secondary Operator</td>
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<tr>
<td>SR</td>
<td>Satisfaction Ratio</td>
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<tr>
<td>SS</td>
<td>Spectrum Sharing</td>
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<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
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<tr>
<td>TPC</td>
<td>Transmit Power Control</td>
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<tr>
<td>TRUST</td>
<td>Transparently Reconfigurable Ubiquitous Terminal</td>
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<tr>
<td>UE</td>
<td>User Equipment</td>
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<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunication Service</td>
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<tr>
<td>UNII</td>
<td>Unlicensed National Information Infrastructure</td>
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<tr>
<td>UWB</td>
<td>Ultra Wide Band</td>
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<tr>
<td>WAPECS</td>
<td>Wireless Access Policy for Electronic Communication Services</td>
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<tr>
<td>WCDMA</td>
<td>Wideband Code Division Multiple Access</td>
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<td>WiFi</td>
<td>Wireless Fidelity</td>
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<tr>
<td>WINNER</td>
<td>Wireless World Initiative New Radio</td>
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<td>WLAN</td>
<td>Wireless Local Area Network</td>
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<tr>
<td>WRC</td>
<td>World Radio Conference</td>
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<tr>
<td>WWRF</td>
<td>Wireless World Research Forum</td>
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Chapter 1

1 Introduction

1.1 Introduction

The radio spectrum is the portion of the electromagnetic spectrum used for different forms of communication services. It is fundamental to the operation of all types of radio communication services. Like most other natural resource, it is both valuable and finite. It is in view of this that different countries have setup regulatory bodies such as the Office of Communications (OFCOM), [OFFI04a] in the United Kingdom (UK) and the Federal Communications Commission (FCC), [FEDE4a] in the United States of America (USA). These regulatory authorities are responsible for finding ways of optimally using this invaluable resource to promote innovative technologies and services for the benefit of mankind. They are charged with managing the radio spectrum developing market oriented allocations and assignment reform policies, as well as protecting the licensed users from harmful interference.

Spectrum measurements conducted by research bodies such as the Shared Spectrum Company [SHAR09], USA and regulatory authorities including OFCOM [OFFI06b], have shown that a significant portion of the spectrum is idle at any given time or geographical location. The sporadic use of this important resource leads to serious inefficiency, which needs to be reversed. In order to reverse the current trend, a comprehensive set of technical, economic and regulatory strategies are necessary. These strategies are discussed later in this thesis. The implication of this is that, a re-think on how the spectrum is currently being accessed is a real necessity, to prevent future shortage of this valuable resource.

The current shortage is mainly due to the static outdated allocation policies [UFAT09] by regulatory authorities. In this method, a fixed block of spectrum is licensed to an operator over a considerable period of time, typically ten years or longer. This is referred to as Fixed Spectrum Allocation (FSA). The advantage of this traditional approach is that it is
simple and effectively limits interference coordination through the use of guard bands [LEAV04b]. However, its major shortcoming is that it does not allow efficient and flexible use of the spectrum in a dynamic manner. In other words, it is access limited. It further limits the rapid deployment of innovative technologies, as witnessed in the unlicensed band (2.4GHz). These spectrum policies are clearly outdated and inadequate to manage the technology needs of the future.

1.2 An Alternative to Fixed Spectrum Allocation

The Spectrum Allocation Charts for the United States [UFAT09] shows a heavily fragmented use of the radio spectrum by a number of wireless technologies, products and services. The increased demand for wireless services and application is straining the current FSA spectrum management regime. Recent studies also indicate that there is a sharp contrast in terms of usage across the band [AKYI06]. For example, while the Industrial Scientific and Medical (ISM) band is over-utilized, the television and land mobile radio bands are most often underutilised, mainly during the off peak period. According to the FCC Spectrum Task Force [FEDE03c] [GEIR07], the spectrum utilization rates vary between fifteen and eighty five percent.

The shortcomings identified with the “command and control” is that explicit licensing for a lengthy period of time cripples innovations, encourages underutilization and is clearly inadequate to cope with increasing demand. Dynamic Spectrum Sharing (DSS) provides a “technology toolbox” of alternatives to better address the inefficiencies arising from FSA. The term “technology toolbox” is used because the realization of DSS depends on the development of new technologies.

The taxonomy of terminologies used in this work is presented in section 1.2.1.

1.2.1 Taxonomy of terminologies

The following terms have been defined as used in this thesis.

- Fixed Spectrum Allocation (FSA): A method of allocating the spectrum by the regulator, in which the spectrum license is held over a long period of time. In this method, guard bands are provided between the allocated blocks of spectrum to reduce interference. Therefore, spectrum cannot be shared or used dynamically during idle periods.
Dynamic Spectrum Sharing (DSS): Dynamic Spectrum Sharing (DSS) is defined as all purposes that aim to free up constraints on the use of the radio spectrum. This is done dynamically over space (geographical location) and time (temporal) thereby reducing or completely eliminating the occurrence of white spaces. The term constraint refers to “access constraints” which impede the flexible use of the spectrum. DSS can also be terminal controlled or network controlled. The two approaches have their prospects and consequences. This is discussed in Chapter two of this thesis.

Dynamic Spectrum Allocation (DSA): This is the method of allocating spectrum in a dynamic manner between multiple systems, at certain predefined intervals in order to increase the overall spectrum efficiency of the systems involved. The DSA process is usually network controlled.

Inter operator Spectrum Access Control (I-SAC): This refers to all methods which tend to compensate for short term variations in spectrum demand. This short term fluctuation is usually over a short time scale, typically of the order of a few seconds. It could run separately or in conjunction with DSA depending on the degree of traffic correlation seen on the two networks sharing the spectrum.

Primary and Secondary Operator: The Primary Operator (PO) is the operator that lends its spectrum resources to another operator that requires the resource on a temporary basis. The Secondary Operator (SO) is the operator that suffers temporary capacity crises and requires additional resources from the primary system. These terms are mainly applied to the non-pooled spectrum sharing scenario discussed later in the thesis.

The main DSS techniques can be broadly classified based on where the intelligence is embedded. This could either be centralised, distributed or a combination of methods. The pure centralised approach is sometimes called “Dynamic Spectrum Allocation (DSA)”. In the original visions of MITOLA, the inventor of Cognitive Radio (CR), the pure cognitive terminal makes the intelligent decision on when, where and how to use the spectrum [MITO00]. However, more recently, CR research has evolved into cooperation between several cognitive terminals. These cognitive terminals form a cognitive network and
exchange detection information, as a way of reliably detecting the primary system [YUCE09]. A key enabler for CR is Software Defined Radio (SDR). SDR is also commonly cited in the literature as Spectrum Agile Radio (SAR), Software Radio (SR) or intelligent radio [BERL05a]. A detailed description including its salient characteristics is given in Chapter two.

In order to provide a holistic approach to tackling the problem of spectrum sharing between multiple operators, there is the need to address four main challenges namely; technical, regulatory, standardization, and economic constraints (see Figure 1). The technical challenges focus on technological solutions in the form of hardware and software needed to implement DSS. For example, the detection of vacant spectrum (white or grey spectrum opportunities) requires significant hardware changes to the currently existing receiver designs. Improvement in the sensitivity of the radio, linearity and dynamic range is necessary to cope with multi-gigahertz wideband signals, in order to reliably detect primary users [CABR04]. In terms of software, a high level of reconfiguration realized through dynamic protocols and policies is also necessary [BERL05a]. This could be in the form of policy-based meta-language that will translate policy rules into radio behaviour controls based on situation. These changes will be necessary both on the network as well as the terminal side. Software Defined Radio (SDR) [JOND05] is therefore viewed as a key enabler for DSS. SDR allows quick changes in operating characteristics e.g. waveforms through software downloads, in order to put the detected spectrum opportunity to the best use.

As outlined earlier, the inefficiencies due to the current regulatory regime could be viewed as the price paid for reliable communication. This is because it is effective in dealing with interference between systems with no further coordination necessary between systems. Since DSS offers significant benefits by combining the best of worlds that is, providing interference conditions similar to FSA and at the same higher spectrum utilisation. Therefore it is clear that some interference coordination is necessary within a heterogeneous system landscape.

Some shift in the current policy is necessary if the potential of DSS is to be fully realized. Spectrum licenses for certain services were not transferable before in the UK. The move in the direction of spectrum trading and liberalisation [RAMS05] by OFCOM towards the end of 2004 is seen as a step in the right direction. Spectrum trading allows changes in license ownership for certain band of spectrum to create a much more dynamic market
than is presently witnessed. On the other hand liberalisation [OFFI04b] enables third party reconfiguration and change of use. This will lead to the emergence of new and alternative services. Standardisation activities [IEEE09b] aimed at harmonising the different standard to allow the effective cooperative and co-existence is of great importance. Finally, to capture the benefits of DSS, viable economic and business models are necessary by network providers/operators in terms of service offerings and new potential applications that can exploit this technology. The inter-relationship between the four important areas discussed above is illustrated in Figure 1.

![Figure 1. Main factors affecting the deployment of DSS systems](image)

The developments in all four areas namely, technical, regulatory, standardization and economic models will need to run in parallel to unlock the full potential of DSS systems. The arrow in Figure 1 shows the priority areas in growing order of importance. According to this thesis, the technical issues represented in Figure 1 are considered the most important since it provides a leverage for the standards and regulatory activities. It provides a basis for demonstrating to operators and regulatory authorities the different technology options available to raise spectrum efficiency without causing unwanted interference. It further determines how the technologies could be combined to make important business models, necessary to increase their revenue. The important aspects of the regulatory and standardization activities are discussed in chapter two.
1.3 Thesis Structure

This thesis is organised into seven chapters. Chapter 1 gives a background into Dynamic Spectrum Sharing (DSS) issues and the flexible use of spectrum. It introduces the taxonomy used in this work, and the underlying motivation for the work in this thesis.

Chapter 2 provides a comprehensive survey on the current ways of using the spectrum. It highlights the shortcomings of the current Fixed Spectrum Allocation (FSA) approach. The chapter also addresses the different models for flexible spectrum management and DSS techniques that are available as an alternative FSA. It provides a new classification of management techniques according to where the decision making is taking place (network or terminal centric). The advantages and disadvantages of each method are presented. Finally related project work and a summary of their main contributions are provided in the chapter.

Chapter 3 provides a detailed description of the problem of spectrum sharing from a centralised perspective within the cellular network context. The UMTS radio resource aspects relating to this thesis is presented. The traffic model used in this work and different aspects of the scenarios being investigated is also discussed. The proposed multi-access framework to address centralised spectrum sharing is described. The solutions are broken into short, medium, long term solutions.

Chapter 4 presents the proposed improved DSA algorithm and the inter-operator spectrum access control. The pool based and non-pool based algorithms are also presented as well as the results for the improved DSA scheme are also presented.

Chapter 5 presents the functional architecture to address spectrum sharing. The options to minimise cross network signalling are discussed. An analysis of the total number of call setup messages and the queuing gains on the home network is presented.

Chapter 6 discusses the spectrum efficiency metric used in the evaluation of the proposed algorithms. It presents the different components of the MATLAB software tool that has been developed and how this is used in measuring the efficiency gain. Furthermore, the numerical results of the proposed algorithms and a discussion of the results are presented in this section.

Chapter 7 provides a conclusion and summary of achievements and possible areas of future research.
1.4 Novel Work

A new protocol for implementing network centric dynamic spectrum sharing has been proposed and investigated. The improved dynamic spectrum allocation algorithm combines existing DSA with inter-operator spectrum optimisation to achieve improvements in the spectrum efficiency gain. Inter-operator spectrum access control (I-SAC) provides additional gain due to its faster response to the spectrum demands of the network. This algorithm is shown to perform well with additional spectrum efficiency gains of up to four percent in negatively correlated traffic situations.

The non-pool and pool based algorithm is proposed to address multi-operator spectrum sharing in correlated traffic situations. The simulation results show that a spectrum efficiency gain of thirty six percent can be achieved on the secondary system in the non-pooled algorithm for unequal number of carriers between the operators (i.e. primary with two carriers and secondary system with one carrier). The sharing approach does not impact negatively on the primary system. Furthermore, the effect of increasing the number of carriers on the spectrum efficiency gain has been investigated.

In the proposed pool based algorithm where resources are pooled together, a significant spectrum sharing can be achieved due to statistical multiplexing of connection request through a common spectrum access control. The impact of varying the bandwidth on the achievable gain has also been presented. This algorithm has also been investigated under uniform and non-uniform traffic conditions. The results presented have also demonstrated that for acceptable delays of between one to two seconds, capacity improvements of up to four percent can be achieved.

Furthermore, the architecture and signalling aspect of the proposed algorithm have also been investigated. The signalling takes into account RAN based as well as connection establishment signalling within the network.

Based on the proposed hierarchical framework to address multi-operator radio resource management, a software simulation tool has been developed and calibrated using MATLAB. This software tool is used in the evaluation the proposed spectrum sharing algorithms.
Chapter 2

2 Spectrum Management methods

This chapter addresses the different models available for spectrum sharing. It provides a framework for a detailed understanding of the spectrum sharing problem. It gives an insight into the current trend in flexible spectrum use. It also presents a classification of the radio spectrum as well as spectrum management techniques together with the pros and cons of each approach. Finally, a number of related research activities together with regulatory and standardization work are introduced.

2.1 Current trends in spectrum use

The explosive growth of capacity-hungry applications is proving a real challenge for the wireless industry. In the United States, almost all of the frequency bands below 60 GHz are already allocated to at least one Radio Access Technology (RAT). This can be seen in the US Frequency Allocation Table [UFAT09]. A similar trend is observed in the United Kingdom as reported by OFCOM [OFFI06a]. Hence to serve the demands of applications, more and more wireless systems and standards are being designed to work in license-exempt bands, such as the Industrial, Scientific and Medical band (2.4 GHz ISM band) and the Unlicensed National Information Infrastructure band (5 GHz UNII band). Consequently, the increasing number of active radios operating in these bands result in an unacceptable level of interference among systems. Given such problems caused by limited spectrum availability, increased spectrum usage efficiency is becoming far more of a necessity. As discussed later, cognitive radio or network based methods can be used to improve spectrum efficiency. In this thesis, we focus on centralised spectrum sharing solutions to achieve these goals. The centralised approach is chosen, since significant intelligence or knowledge is contained on the network side. Therefore, taking advantage of this knowledge and improving on it through adequate protocols and polices is seen as a viable and useful alternative to the CR paradigm. The solutions are investigated from a number of different perspectives within the context of cellular...
wireless networks. This thesis also concentrates on network centric techniques to realise increased spectrum utility.

Currently, mobile wireless operators do not share spectrum between each other. This is due to a number of technical, regulatory and economic reasons which need to be addressed. While network operators are interested in increasing their revenue by accommodating more subscribers, they are careful about exchanging/sharing operational information with their competitors. This means they are interested in any form of limited sharing which gives them independence in terms of subscribers and service offered. Similarly the regulatory authority has a statutory responsibility to prevent monopoly and therefore, will block any form of sharing that could potentially monopolise the market and prevent healthy competition. This gives rise to different types of sharing solutions which could be tightly or loosely coupled. How tightly or loosely coupled a sharing solution will be depends on the network elements and degree of flexibility involved.

The cost of clean spectrum as witnessed in the last 3G auction exercise [KELL08] is becoming increasingly expensive. Spectrum auction is the preferred method of making spectrum available to intending users due to its numerous advantages. It is less bureaucratic, more transparent and less subjective compared to the “beauty contest” approach. It favours new entrants rather than incumbent operator with well established track record. Furthermore, a well designed auction awards the license to the operator that can generate the greatest economic benefit.

### 2.2 Radio Spectrum Classification

The portion of the electromagnetic spectrum used for radio communication is called the “radio spectrum”. From a regulatory perspective, the classification depends on the type of service to be deployed, as well as whether a license is required or not. The types of service include broadcasting, satellite, radio astronomy, mobile communications etc. The spectrum license determines the rights associated with its use.

The national regulatory authorities such as OFCOM (UK), FCC (US), Commerce Commission (CC), New Zealand, are responsible for awarding licensed rights. From a regulatory perspective, a license may or may not be needed based on the type of service to be deployed. A full definition of the different radio service could be found in reference [INTE94], [WITH99]. Table 1 gives a breakdown of the different portions of the radio spectrum.
Chapter 2. Spectrum Management Methods

spectrum according to the International Telecommunication Union Radiocommunication Sector (ITU-R) and their common applications.

<table>
<thead>
<tr>
<th>Band Name</th>
<th>Abbrev.</th>
<th>ITU Band</th>
<th>Frequency/Wavelength</th>
<th>Useful Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>subHertz</td>
<td>subHz</td>
<td>0</td>
<td>&lt; 3 Hz</td>
<td>Man-made and natural electromagnetic waves from earth, ionosphere, planets</td>
</tr>
<tr>
<td>Extremely Low</td>
<td>ELF</td>
<td>1</td>
<td>3-30 Hz</td>
<td>Submarine communications</td>
</tr>
<tr>
<td>Frequency</td>
<td></td>
<td></td>
<td>10^3 - 10^4 km</td>
<td></td>
</tr>
<tr>
<td>Super Low Frequency</td>
<td>SLF</td>
<td>2</td>
<td>30-300 Hz</td>
<td>Submarine communications</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10^4 - 10^3 km</td>
<td></td>
</tr>
<tr>
<td>Ultra Low Frequency</td>
<td>ULF</td>
<td>3</td>
<td>300-3000 Hz</td>
<td>Communication within mines</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10^2 - 10^3 km</td>
<td></td>
</tr>
<tr>
<td>Very Low Frequency</td>
<td>VLF</td>
<td>4</td>
<td>3-30 kHz</td>
<td>Submarine communication, avalanche beacons, wireless heart rate monitors etc.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10^2 - 10 km</td>
<td></td>
</tr>
<tr>
<td>Low Frequency</td>
<td>LF</td>
<td>5</td>
<td>30-300 kHz</td>
<td>Navigation, time signals, AM long waves, broadcasting, RFID</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10 - 1 km</td>
<td></td>
</tr>
<tr>
<td>Medium Frequency</td>
<td>MF</td>
<td>6</td>
<td>300-3000 kHz</td>
<td>AM(medium)wave broadcast</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1-10^4 km</td>
<td></td>
</tr>
<tr>
<td>High Frequency</td>
<td>HF</td>
<td>7</td>
<td>3-30 MHz</td>
<td>Shortwave broadcasts, amateur radio and over the horizon aviation communications, RFID</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10^1 - 10^2 km</td>
<td></td>
</tr>
<tr>
<td>Very High Frequency</td>
<td>VHF</td>
<td>8</td>
<td>30-300 MHz</td>
<td>FM, television broadcast and line of sight ground-to-aircraft and aircraft-to-aircraft communication, Land Mobile and Maritime Mobile communications</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10^2 - 10^3 km</td>
<td></td>
</tr>
<tr>
<td>Ultra High</td>
<td>UHF</td>
<td>9</td>
<td>300-3000 MHz</td>
<td>Television broadcasts, microwave ovens,</td>
</tr>
</tbody>
</table>
Chapter 2. Spectrum Management Methods

<table>
<thead>
<tr>
<th>Frequency</th>
<th>SHF</th>
<th>10</th>
<th>3-30 GHz</th>
<th>10^3-10^4 km</th>
<th>mobile phones, wireless LAN, Bluetooth, GPS and two way radio such as land Mobile, FRS and GMRS radio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super High Frequency</td>
<td>SHF</td>
<td>10</td>
<td>3-30 GHz</td>
<td>10^3-10^4 km</td>
<td>Microwave devices, wireless LAN, most modern radars</td>
</tr>
<tr>
<td>Extremely High Frequency</td>
<td>EHF</td>
<td>11</td>
<td>30-300 GHz</td>
<td>10^5-10^6 km</td>
<td>Radio astronomy, high frequency microwave and radio relay</td>
</tr>
<tr>
<td>TeraHertz</td>
<td>THz</td>
<td>12</td>
<td>300-3000 GHz</td>
<td>10^6-10^7 km</td>
<td>Terahertz imaging with potential to replace X-rays in some medical applications, ultra fast molecular dynamics, terahertz computing.</td>
</tr>
</tbody>
</table>

Table 1 Radio frequency Classification and their applications

2.2.1 Unlicensed versus Licensed Spectrum

It is also known as the license-exempt band. The unlicensed spectrum is usually shared by multiple wireless devices. This band could be considered as a “public park” for wireless devices. There are usually no regulations in sharing of unlicensed spectrum aside from transmission power limitations, twinned with a spectrum mask to avoid interference to other spectrum bands. There may also be requirements specific to the different types of devices that the unlicensed spectrum might be used for (see, e.g., [OFFI09]). This band is most suitable for mobile wireless applications requiring sporadic access and can tolerate varying delays e. g electronic mail. The Industrial Scientific and Medical (ISM) band operating between 2.4 - 2.5GHz is a good example. It used for Wireless Local Area Networks (WLAN) and Wireless Fidelity (Wi-Fi) systems.

Licensed spectrum on the other hand, requires a license granted by a regulatory body such as OFCOM, UK or FCC, US. Sharing of licensed spectrum is far more challenging, and of far greater interest than the unlicensed case. For this reason, this thesis concentrates on licensed spectrum sharing amongst cellular operators. There are strict regulatory rules
Chapter 2. Spectrum Management Methods

concerning licensed spectrum access. These have traditionally stipulated access behaviours of the devices, as well as the owners, and the permitted usage purposes of the spectrum [COSO08]. This “ring-fencing” of spectrum for an entity and purpose, generally leads to the sharing of licensed spectrum only being possible on a primary/secondary basis [AKYI06]. The licensed band is exclusively used by the licensed owner also called the “primary system”. The system granted temporary permission by the primary system to use the spectrum is referred to as the “secondary system”. Moreover, in sharing licensed spectrum, interference to the primary system must always be avoided. In terms of the variety of combination of ownership models for spectrum, some of these issues have been presented in [ISTD04], [ISTO06]. Different ownership models for entities such as the spectrum, base stations, radio access and core network have been addressed in [ISTO06], [LEAV04b].

2.3 Overview of Spectrum Sharing Techniques

Many spectrum sharing techniques have been proposed in literature [AKYI06], [IEEE09a]. The proposed technique depends on the scenario considered. Spectrum sharing among wireless systems can occur either horizontally or vertically [DEVR06a], [KRUY03]. If all radios have the same right to access a particular band, as is the case in unlicensed bands, horizontal spectrum sharing is implied. On the other hand, if one system (typically, the owner of the license to the band) has a higher priority to access the band than other systems, then this refers to vertical spectrum sharing. Generally, vertical spectrum sharing is envisaged through secondary spectrum access, whereby the licensed band is shared but only with the consent of the license owner. The sharing is between the license owner and a lower priority networks, that is, the secondary network.

Technically speaking, spectrum can be shared in the realms of time, space, frequency, power, or a combination of the above. Spectrum sharing in the time domain involves systems using a band at different time intervals (timeslots), for example by exploiting a listen-before-talk etiquette. Another possibility here, which is complicated by the fact that it requires synchronization among transmitters, is to use idle time-slots in a Time Division Multiple Access (TDMA) context. Spectrum sharing in the frequency domain involves transmitting such that no frequency overlap occurs among the coexisting systems. In
many such cases however, it might be necessary for a system to consolidate several smaller idle frequency bands to create a transmission opportunity, through using multi-carrier modulation approaches such as Orthogonal Frequency Division Multiplexing (OFDM). In the spatial domain, spectrum sharing might benefit from the realization that spectrum occupancy varies from location to location. Hence a system might use a band in a specific location if other systems are not present at that location.

The transmission opportunities arising from spectrum sharing in the domains of time, space, frequency, or a combination of these, are generally called “spectrum holes” or “white spaces” [DEVR06a], [DEVR06b]. However, spectrum might also be shared in the power domain. For example, a system might be permitted to transmit with a higher power in any of the above domains (time, space, frequency, or any combination), providing that these transmissions do not affect the interference tolerance threshold at other systems’ receivers. Spectrum transmission opportunities in this context are known as “grey spaces” [HAYK05]. Moreover, the imposed interference to other single receivers might be minimized by using spread-spectrum techniques, for example through Ultra Wide Band (UWB) communications or through the sharing of codes in a Code Division Multiple Access (CDMA) scenario. Such methods, where open access to the other systems’ bands through spread spectrum with low transmission power is allowed, are known as underlay transmission [HAYK05].

2.3.1 Spectrum Sharing Model

It is important to understand the three main models available according to the existing literature. These models define the approach used by operators and devices, using the spectrum band. The three main models are;

1. Spectrum Commons Model
2. Property Rights Model
3. Cooperative versus non-cooperative Model

2.3.1.1 Spectrum Commons Model

In the spectrum commons model [PEHA05], [ZHAO07], spectrum is shared with no device given a clear priority over the other. Policies usually define if the devices
Chapter 2. Spectrum Management Methods

cooprate or merely coexist. The success witnessed today in the unlicensed Industrial Scientific and Medical (ISM) band e.g Wi-Fi has led many proponents to support this model. The main advantage of this model is that it leads to the creation of innovative technologies and services for supporting low-powered inexpensive mobile/portable devices in an ad-hoc manner. The main problem associated with the use of this band results from the “Tragedy of Commons” [SATA98]. It occurs when too many devices are deployed to share the spectrum. This problem arises due to an inherent lack of incentive by the different devices operating in the band to use the spectrum efficiently. The users exhibit greedy behavior (longer channel occupancy/higher transmit power). This behavior is individually optimal; however, it limits the aggregate network throughput (collectively sub-optimal). The problem can be mitigated through the careful design of a spectrum-etiquette. This could be in the form of penalty for wasteful use and a reward for good behaviour. The “Listen Before Talk” (LBT) approach investigated in [SATA98], [RAYC03] is another efficient way to address this problem.

2.3.1.2 Property Rights Model

Property rights work mainly through licensing. It may or may not allow license holders to sell use of their licenses. Furthermore, there is the issue of how long the licenses issued should be held i.e whether on a temporary or permanent basis. In the temporary rights for example, the licenses are renewable every decade. This allows the regulators to intervene, but again creates uncertainty which may hinder long term investments by the spectrum license holders. Some of the approaches under spectrum property rights are captured in [ZHAO07] and dynamic spectrum allocation [LEAV04a], [BUDD05]. It is also important to consider the degree of flexibility since complete flexibility prevents the regulatory authorities from imposing standards which could be harmful in the long run.

2.3.1.3 Cooperative versus Non-cooperative Model

In cooperative strategies [ZHAN09], the systems involved in spectrum sharing are sharing information on whether or not to use the spectrum at any particular instance. This is done through the nodes of the primary system communication with the secondary system to identify opportunities. The reverse is true for the non-cooperative scenarios. In
Chapter 2. Spectrum Management Methods

the non-cooperative scenarios [JIA07], the secondary system needs to characterise the spectrum of the primary system well enough to avoid causing interference. There are direct cost implications on monitoring, analysis as well as sharing the acquired information between nodes. An information database or registry is proposed by OFCOM in [ROKE07] as a solution to reduce the cost and risk of identifying available spectrum. There is however the issue of frequency of update of the registry, reliability of the database, geographical availability of this database as well as ownership of the database (government or private) which needs to be addressed.

2.3.2 Architecture Management Solutions

The architectural management method targets the mechanism for coordinating or managing the use of the spectrum. The management method consist of several entities all working closely together to ensure that the spectrum is used in the most optimal way collectively. Several researches under the headings such dynamic spectrum management, flexible spectrum use, advanced spectrum management, opportunistic spectrum management can be found in literature [BERL05b]. Cognitive Radio (CR), Software Defined Radio (SDR), Spectrum Agile Radio (SAR) and Software Reconfigurable Radio (SRR) are associated paradigms found in literature to cover the broad heading of terminal/device centric decision making [HAYK05]. Similarly, dynamic spectrum allocation, semi-static spectrum management are used to cover the general class of centralized decision making.

The efficient use of these technologies to achieve the goals of spectrum sharing (i.e. increased spectrum efficiency) depends on how the behaviour of both the network and advanced radio devices are controlled. Hence effective spectrum management solutions can be considered as both a network and radio issue [BERL05b].

This thesis classifies the architectural management solutions under three main headings shown in Figure 2.

2. Distributed Spectrum Management.
Centralized Spectrum Management

The control of the access to the spectrum is managed by the Spectrum Manager (SM) sometimes referred to as the Spectrum Broker or the "Meta-Operator" [BERL05b], [BUDD05]. This is usually typical of an organised or infrastructured network. The SM determines the spectrum opportunities and to which RAN spectrum should be allocated according to some established policy. It is important that the spectrum policy should be executed by a neutral body especially when fairness is a major requirement. Figure 4 shows an example of centralised spectrum management. An example of where this can be applied in principle could be in real time spectrum trading/auctioning [ATTA08].

The allocation and release process of spectrum to the RANs means some form of exclusivity is still present. It could therefore be argued that this form of management does not completely eliminate white/grey spaces compared to the distributed management. The time scale and allocation interval plays a significant role on the achievable Spectrum Efficiency Gain (SEG). Simulations in [LEAV04b] have investigated the effect of DSA interval on DVB-T and UMTS spectrum sharing. However, the impact of call by call optimization has not been investigated. It is shown that increasing the DSA assessment period to above 2-3 hours is detrimental to the SEG due to the outdated values of the traffic estimation algorithm. Similarly, lowering the values below the threshold increases the signalling and control overhead. Therefore an optimal value for the DSA interval is a trade-off between the signalling and the DSA gain.
Distributed Spectrum Management

This usually refers to the cognitive radio system. The CR concept that first originated from Mitola [MITO09] is a fusion of Software Defined Radio (SDR) and intelligent signal processing. A generic CR operates according to the cognitive cycle shown in Figure 3. It has three important elements. These include; an understanding of the communication requirements of the user, its radio frequency environment (radio scene analysis), the relevant network and regulatory policies which apply to it.

The cognitive states in the cycle shown in Figure 3 are continuous and regular knowledge updates is necessary. The knowledge may be obtained from some cognitive database that holds spectrum map information, or it may be acquired from dedicated cognitive node on a regular basis. There is currently no consensus as to the real definition of a CR, however, we present three useful definitions which sufficiently addresses some salient features of a cognitive radio in Table 2.

<table>
<thead>
<tr>
<th>Cognitive Radio Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The cognitive radio, built on a software-defined radio, is defined as an intelligent wireless communication system that is aware of its environment and uses the methodology of understanding-by-building to learn from the environment and adapt to statistical variations in the input stimuli, with two primary objectives in mind: highly reliable communication whenever and wherever needed; efficient utilization of the radio spectrum [HAYK05].</td>
</tr>
<tr>
<td>2. A radio in which communication systems are aware of their environment and internal state and can make decisions about their radio operating behaviour based on that information and predefined objectives. The environmental information may or may not include location information related to communication systems [SOFT06].</td>
</tr>
<tr>
<td>3. A cognitive radio is an intelligent communication device that is aware of its environment and application needs, and can reconfigure itself to optimize quality of service [LE05].</td>
</tr>
</tbody>
</table>

Table 2: Important Cognitive Radio Definitions
In each of these definitions, there is an agreement in terms of the basic functionalities of the CR including its awareness of the environment as well as its ability to adapt and reconfigure. The difference arises from the degree of cognition or machine intelligence necessary to make them function effectively. In addition, apart from the large scale complexity involved in building CR device, there is also the growing debate on whether such devices are really necessary. To improve the reliability of detecting spectrum opportunities by locally sensing nodes, "collaborative detection" also known as cognitive networking has been advanced in the works presented in Cogmesh [CHEN07].

The term Dynamic Spectrum Selection is sometimes used interchangeably with CR. The concept developed by the European Telecommunication Standard Institute (ETSI) initially originated from Digitally Enhanced Cordless Telecommunications (DECT) [ELBE94] system. The original DECT frequency...
band is 1880MHz-1900MHz and it is still used in many countries today. DECT was introduced in the early 1980s as digital portable phones for supporting home and corporate/office applications.

Intermediate or Mixed Spectrum Management

As the name implies, this management method combines both centralised and distributed management. This is indicative of the fact that Beyond Third Generation (B3G) system will need to coexist as well as cooperate with currently existing system GSM/WLAN/UMTS/UMTS-LTE or Digital Video Broadcast-Terrestrial (DVB-T) according to the deployed scenario. In this regards, cognitive devices act secondary devices in the cellular band or TV band, or as equals in the unlicensed band. A typical example of a mixed deployment is shown in Figure 4. In the lower part of Figure 4, both the centralised and distributed spectrum management occur in the spectrum landscape. The heterogeneous nature of Next Generation Networks (NGN) comprising different system means a combination of spectrum management methods is also likely to occur.
Figure 4 Future heterogeneous spectrum sharing landscape

Figure 4 depicts our view of the spectrum management landscape in future wireless domain. The top left shows the pure centralized management. The spectrum manager obtains a global view of the spectrum needs of the Radio Access Networks (RAN) through the Spectrum Management Entity (SME). The SME resides inside the RAN and is responsible for all spectrum related activities such as spectrum estimation and negotiation. The SME operates in conjunction with the existing radio resource management functionalities in the RAN such as the Node Bs and the Radio Network Controller (RNC). The top right corner
Chapter 2. Spectrum Management Methods

illustrates a purely cognitive domain in which devices collaborate to share sensing information. The cognitive devices may exist with or without legacy devices depending on how they are deployed. The legacy devices are already operating in the spectrum space and the CR must avoid undue interference by using spectrum sensing techniques identified in [YUCE09]. The bottom half of Figure 4 depicts a combination/coexistence of both the purely cognitive and centralized management methods. It is therefore clear that there will be a coexistence of all the three architectural management solutions in the near future.

2.4 Regulatory and Standardization Activity

These are essential components for advancing the DSS technology and systems. As stated in Chapter 1, the optimal solution for the realisation of the full potential of DSS will need to find the right balance between appropriate regulatory and standardization, technical and economic solutions. In addition to the technical issue already described, this section presents a summary of ongoing regulatory and standardization efforts in this area within the last decade.

2.4.1 Regulatory Activities

Regulatory effort aims at developing a proper policy framework for DSS. This will help to accelerate and drive the new technologies in the area. The major consideration for policy maker is the issue of interference management. One of the metrics initially proposed by the FCC in 2003 is the interference temperature (IT) [FEDE03b], [KOL06]. This concept shifts emphasis from the transmitter side to the receive side. A loose implication of this is that rather than focus on the transmit power level and spectrum mask on the transmit side, the secondary transmitter should recognise when their transmissions causes unacceptable interference to the primary receiver. This has however been firmly retracted due to controversies surrounding implementation of this concept [FEDE07b].

In realization of the importance of novel spectrum management techniques and their potential to improve system performances, regulators around the world are introducing
new measures and rules to improve spectrum efficiency. The FCC in the US have released several key documents, for instance “Cognitive Radio Technologies Proceeding (CRTP)” [FEDE03a], “Unlicensed Operation in the TV Broadcast Bands” [FEDE04a] and another on the development of secondary spectrum markets [FEDE04b]. Moreover, several proposals have been submitted to the FCC, which in turn have been published for consultation. One example is the US Rail Network’s proposal to use the 88-108 MHz FM broadcast band for informing passengers in mass transit rail cars [FEDE06]. Another example is the Google Inc. proposal of a “Real-Time Airwaves Auction Model” for 700 MHz TV bands, geared at the deployment of interactive broadband services in those bands [FEDE07a].

On the 4th of November 2008, the FCC announced the opening up of the unused broadcast TV spectrum to unlicensed white space devices [FEDE08]. These devices will use geolocation and spectrum sensing technology [SHEL09] to prevent interference to TV broadcasters and wireless microphone devices already using the band. Also a manifestation of the intense interest by the research community in this area is evidenced by the outcomes from the Dynamic Spectrum Access Network (DySpAN) Conference [IEEE09a] and Crowncom [INTE09] conferences. These conferences are dedicated to the field of dynamic spectrum access.

In Europe, the European Parliament adopted a resolution in February 2007 which encourages the European Commission (EC) to consider allocating license-free bands as a result of migration of terrestrial television from analogue to digital [EURO07]. New initiatives such as the Wireless Access Policy for Electronic Communications Services (WAPECS) [WIRE08] have been introduced under the European Union (EU) framework. WAPECS is a European Union initiative aimed at allowing more flexible use of the spectrum for mobile, broadcasting, fixed wireless and other electronic communication services. The set of frequency bands identified by EU member states for WAPECS have been specified in [WAPE08]. In these bands, a range of electronic communication services may be offered on a technology and service neutral basis in compliance with certain technical requirements to avoid interference. The WAPECS principle can apply to both licensed and unlicensed frequency bands.

In the UK, the Office of Communications (OFCOM) has also shown genuine interest in liberalizing spectrum usage [OFFI06b]. The vision of OFCOM as a light-touch regulator is to move away from the command and control methods thereby allowing market forces
to prevail. Some of the key changes to the existing regulations will include, reducing the spectrum portions for “command and control”, and increasing both the licensed exempt and market-controlled spectrum portions. OFCOM plans to increase the use of license exemption beyond 6.9 percent. As at today, command and control is used in 21.6 percent, License Exemption in 6.9 percent and Market mechanism in 71.5 percent [OFFI04a] of the spectrum bands. These figures are based on projections in 2000 and the “command and control” figures are set to shrink even further as we approach the next decade (2020). The license exempt band represents a key area for new technologies. Already, innovative device such as WiFi and BlueTooth have been deployed in this band. Interference will continue to be managed in this spectrum portion by reducing the transmit power levels, and restricting service range to less than hundred meters [OFFI04a].

In Ireland, the Commission for Communications Regulation (ComReg) published a consultation in April 2007 on Dynamic Spectrum Access [IREL07]. The consultation is aimed at increasing public awareness on the technology developments in the area of dynamic spectrum access. Many other regulators worldwide are pursuing similar paths.

2.4.2 Standardization Activities

The objective of standardisation efforts is to develop supporting standards dealing with new technologies and techniques being developed for next generation radio and advanced spectrum management. The IEEE P.1900 [IEEE09b] commenced work in 2005 on the standards for supporting new technologies for cognitive radio and advanced spectrum management. The body was replaced in April 2007 by the Standards Coordinating Committee (SCC41). SCC41 has continued to develop standards related to dynamic spectrum access networks. The focus has been on improved use of spectrum. New techniques and methods of dynamic spectrum access require managing interference, coordination of wireless technologies and include network management and information sharing. The work of the IEEE 1900.x working groups (six working groups) continues under SCC41.
2.5 Related Research Work

This section addresses some of the technical work within the last decade and their main contributions to the spectrum sharing work area. It is worth noting that although there are other projects, the most notable ones related to the work in this thesis are presented here.

- **Defence Advanced Research Project Agency (DARPA)**

  The DARPA Next Generation (XG) [DARP09] program has initially investigated dynamic spectrum access with the aim of developing new technologies and system concepts (including new waveforms) to intelligently redistribute the spectrum through opportunistic access. Some of its accomplishments include the definition of policies and radio interfaces to support cognitive technologies.

- **Transparently Reconfigurable Ubiquitous Terminal (TRUST) project**

  The IST-TRUST [FARN00] project specifically addressed the development of reconfigurable terminal platforms from both the user friendly perspective as well as the underlying technologies. The primary goal was to realise the user potential of reconfigurable radio systems. This was achieved by understanding the user requirements from a system perspective, translating these into a technology requirement, and then advancing terminal and network technologies through validation.

- **Dynamic Radio for IP-Services in Vehicular Environments (DRiVE)**

  The project IST-DRiVE [ISTD04] investigated the convergence of cellular and broadcast networks to lay a foundation for cost effective provisioning of IP-based in-vehicular multimedia services. The spectrum efficiency work specifically focused on how to optimise the interworking solutions between different radio network such as GSM, GPRS, UMTS, DAB, DVB-T in a common dynamically allocated frequency range and to enhance cooperation between the network elements and applications in an adaptive manner. The key outcomes from the DRiVE project included the enumeration of different sharing scenarios for UMTS and DVB-T networks and improved interworking solutions for spectrum management. New methods of frequency allocation and coexistence for the
systems under consideration were also developed. Such methods included the contiguous and fragmented DSA techniques.

- **Spectrum Efficient Uni- and Multicast Services Over Dynamic Multi-Radio Networks in Vehicular Environments (OverDRiVE)**

The predecessor of the DRiVE project is the IST-OVERDRiVE (Spectrum Efficient Uni- and Multicast over Dynamic Radio Networks in Vehicular Environments) [ISTO06]. It investigated the delivery of spectrum efficient multi and uni-cast services to vehicles. The key outcomes from this work included the development of spectrum sharing mechanisms between systems using Dynamic Spectrum Allocation (DSA) according to the actual load. The project also investigated in greater details the allocation techniques reported in the DRIVE project. Significant spectrum sharing gains in the region 20 percent was reported for the methods investigated.

- **End to End Reconfigurability project (E2R)**

The first phase of the E2R Project [ISTE04] commenced in January 2004 and ended December 2005. The project was structured into six technical work-packages (WP), corresponding to six main research fields. Two additional work-packages were dedicated to project management and dissemination, standardization and training: WP5 titled “Evolution of Radio Resource and Spectrum Management” aimed at developing mechanisms for dynamic allocation of radio resources. This required research into combining reconfigurable technology and support structures (from pure terminal perspectives, e.g. Cognitive Radio, to network oriented perspectives, e.g. Joint Radio Resource Management (JRRM) and flexible network planning) with novel resource management techniques that are capable to control the complete spectrum in a local area. Deployment of such technology required a new approach to regulation and economics of spectrum. Hence the second major aim of this research was to develop, based on the results of the system research and tight collaboration between regulators, national authorities etc, new options and mechanisms to enable more progressive spectrum regulation and market-based approaches, and to facilitate a more efficient resource usage. The detailed results and achievements can be found in deliverables contained in [ISTE04].
Chapter 2. Spectrum Management Methods

The second phase of this project started 1st January 2006. The WP3 titled “Efficiency Enhancements for Radio Resource and Spectrum” aimed to enable and broaden the range of mechanisms available to increase the efficiency of radio resource usage. The theoretical tools, algorithms and mechanisms that were investigated included the whole range from reconfigurability enabled service independent allocation of spectrum to JRRM in single and multi-operator scenarios with heterogeneous access systems. This contribution was made in varying forms as one of the drivers for the development of sensing and detection mechanisms for cognitive resource allocation. WP6 sought to establish a common framework in the European R&D area of cognitive radios and networks, contributing to their definition and future role.

WP6 studied and analyzed the architecture and network mechanisms for reconfigurable and cognitive network components. It also assessed reconfigurable and self-adaptive resources (both radio and core network ones) and related algorithms on the basis of dynamic evolution of radio channel, traffic conditions and usage.

- Mobile Virtual Centre of Excellence Core 4 research project (MobileVCE)

The Mobile Virtual Centre of Excellence (MVCE) which is a consortium of leading telecommunication companies and academic institutions started a project to investigate spectrum efficiency in its core four program in January 2006 [MOBI09]. The primary objective was to develop efficient mechanisms for wireless communication which will significantly reduce the cost per bit through improved delivery efficiency. The work on spectrum efficiency targeted the evaluation and derivation of the achievable gain considering a spectrum pool. The analysis took into account the interference environment and channel occupancy in frequency, space and time.

- End to End Efficiency Project (E3)

The End to End Efficiency (E^3) Project [ISTE08] commenced in 2008 and is sponsored by the European Union. It consolidated on the achievements of the E2R phase one and two program. It aims at integrating cognitive wireless systems in the Beyond Third Generation (B3G) network. E^3 optimised the use of the radio resources and spectrum, following cognitive radio and cognitive network paradigms (autonomic management,
learning, experience, knowledge as well as context, profiles, policies). The management functions were distributed over different network elements at various levels of the system topology. A management agility plane was required for supporting the most efficient use of the cooperating technologies, at local, regional, and global levels.

- **Smart User Centric Communication Environment (SCOUT)**
  The IST-SCOUT [ISTS02] program began in 2002. It focused on validating concepts for supporting reconfigurable terminal for wireless access technologies. The goal was to extend the All-IP mobile networks for supporting terminal reconfiguration by looking at concepts in the network and technologies to support users. Work package two addressed user, operator and regulators visions for reconfiguration while work page three examined terminal reconfiguration management from a management plane perspective.

- **Wireless World Initiative New Radio (WINNER) Project**
  The phase one of the Wireless World Initiative New Radio (WINNER) [ISTW04] project began in 2004. The broad visions of the WINNER project aimed to develop requirements and usage scenarios for WINNER radio systems. Furthermore, radio interface technologies and network topologies required to support ubiquitous service have been proposed. Specifically within the spectrum sharing work area, efficient and flexible radio resource management algorithms are being developed. Some radio level integration and interworking solution within the vision of WINNER system level architecture have also been developed. A spectrum demand estimation calculator for estimating the spectrum requirements of IMT-2000 and IMT-Advanced systems are part of the important outputs from this project. Currently the predecessor of the phase two project, WINNER+ [ISTW04] project is focused on IMT-Advanced issues.

➤ **Project Summary and key contributions**

In the following section, the contributions of some important projects to the spectrum sharing work area are presented in Table 3. The main contributions are classified according to the focus/objectives of the project.
**Table 3 Related work area and their contributions**

Based on a summary of existing works in the literature, a classification based on the location of the intelligent decision making entity is presented in Table 4. The decision maker could be located in the terminal, network or both. The table further highlights the operational characteristics, as well as the advantages and disadvantages of each approach. A detailed discussion on this is contained in our published work [SALA09].
<table>
<thead>
<tr>
<th>Management/Embedded Intelligence</th>
<th>Centralized involving a structured network.</th>
<th>Distributed and operates in ad-hoc manner.</th>
<th>Mixed (can be both central and distributed).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complexity</td>
<td>Spectrum management platform required in operator's network.</td>
<td>New and purely cognitive terminals are needed</td>
<td>Medium level of cognitive complexity required in mobiles and network.</td>
</tr>
<tr>
<td>Signal processing</td>
<td>Traffic prediction and load estimation needed.</td>
<td>Large signal processing involved.</td>
<td>Medium level and lower compared to DSS.</td>
</tr>
<tr>
<td>Operational modes</td>
<td>Supports real time (time bounded leases) and non real time modes.</td>
<td>Same as DSA although studied more in the real time domain</td>
<td>More likely to precede pure DSS in terms of evolution.</td>
</tr>
<tr>
<td>Scalability</td>
<td>As the system size increases, the centralized decision maker may become over-loaded. A hierarchical architecture would improve scalability.</td>
<td>The amount of signalling overhead may get prohibitive as network dimensions (nodes) increases</td>
<td>More scalable compared to both DSA and DSS.</td>
</tr>
<tr>
<td>Resource Allocation duration</td>
<td>Takes a considerably longer amount of time to complete i.e (few minutes/hours).</td>
<td>Shorter completion time typically milliseconds.</td>
<td>The completion time is of the order of a few seconds.</td>
</tr>
</tbody>
</table>

Table 4 Architectural Management Solutions
In summary, this chapter has presented a state of the art survey on the spectrum sharing topic. The important models, radio spectrum classification and spectrum sharing techniques have been discussed. Furthermore, a classification of the architectural solutions based on where the decision making entity resides has been presented. A summary of technical work related to the issues being addressed in this thesis has been discussed. Finally the pros and cons guiding the selection of each solution approach are addressed. The next chapter focuses on challenges within the domain of cellular mobile network.
Chapter 3

3 Cellular Systems Spectrum Management

This chapter addresses the various aspects of spectrum use in a cellular wireless network. It provides a framework for a coordinated and cooperative approach to the problem of centralised spectrum access. The traffic assumptions used, as well as the proposed hierarchical solution for multi-operator radio resource management is also discussed in this chapter.

3.1 Multi-radio DSA algorithms

The evolutionary steps in the development of DSA algorithms are captured in the Figure 5. Prior to 2000 research on dynamic spectrum allocation has been studied under the related topic of Dynamic Channel Allocation (DCA) [KATZ96]. DCA algorithms attempt to allocate channels to base stations and access points with the goal of minimising co-channel interference among nearby cells. Several heuristic and non-heuristic techniques such as [ARGY99], [BOGG01] have been applied to address DCA. Following on from 2000, research in the last decade has focused on RAN based spectrum sharing solutions. These steps have been investigated in [ISTD04] using UMTS and DVB-T RANs. The degree of complexity, from the architecture point of view and the required processing time from the coordination point of view, is increasing from the static approach in Figure 5(a), through to Cell-by-Cell DSA method in Figure 5(d).

Both the contiguous and fragmented DSA schemes, i.e. Figure 5(b) and Figure 5(c) respectively, share spectrum at the RAN level with suitable guard bands for mitigating interference. Figure 5(d) is a Cell-by-Cell DSA scheme, which is similar to Dynamic Channel Allocation (DCA) [KATZ96] in the sense that the radio spectrum is shared between the participating RANs at the cell level. Given any of these DSA approaches, the DSA gain is measured in terms of the load increase supported over particular RANs when DSA is employed, as compared with the FSA approach. The achievable DSA gain depends on the level of correlation of traffic demands among the spectrum sharing RANs,
among other factors. A lower correlation in peak traffic demands indicates a correspondingly higher gain.

![Evolutionary steps for centralized sharing schemes](image)

**Figure 5** Evolutionary steps for centralized sharing schemes [LEAV04b]

To benefit from DSA, coordination and control is provided through centralized network entities which imply additional signalling overhead. Strategies to address DSA involve joint network coordination and management of resources among multiple operators and meta-operators. Some aspects of such shared networks are defined in a 3GPP document [THIR06a], focusing on architecture and functionality requirements, where sharing is specified as being at the RAN or Core-Network (CN) level.

It is interesting to note that, there are currently no solutions that are targeted at how two similar network operators could effectively share the spectrum available to them. This is particularly of great interest considering the fact any solution could be seen as a step towards further reducing the cost of communication services to consumers. Furthermore, with the current GSM licenses set to expire across Europe in this decade, cooperative and coordinated spectrum sharing solutions amongst wireless providers could provide better alternatives for using the GSM 900 MHz re-farmed frequency and the UMTS Extension Band (2500-2690 MHz).
3.2 Dynamics of cellular system spectrum use

The licensed band for cellular mobile communications in UK is mainly 900MHz and 1800MHz for GSM and 1900MHz and 2100MHz for UMTS systems [THIR09a]. Extensive measurements carried out according to [WILL08], [HOLL07] and [GUO07] show that further optimisation of spectrum use is possible despite the fact that it is more used compared to other spectrum band. Of notable interest is the fact that the large scale measurements done in [WILL08], [GUO07] which is based on actual data collected from base stations also reveal that spectrum opportunities do exist. This is in contrast with the techniques used in [RENK07], [KAMA05] based on active sensing of energy.

The motivation for the choice of this band is due to the fact that as operators continue to witness a surge in demand for bandwidth intensive applications, the limiting cost of clean spectrum as witnessed in the recent 3G spectrum auction [OFFI00] in the UK, means operators must resort to creative ways of using the spectrum by cooperating with each other. Secondly, this cooperation serves as an alternative to Cognitive spectrum usage, which could take longer to realise [COGN07]. This is partly due to the challenging requirements for building these devices, as well as the growing debate on the actual level of cognition necessary in such future cognitive networks. Additionally, as the UMTS band is used around the world, the engineering devices and application of this band is well understood. For the purpose of this thesis, the UMTS network is used as a case study, however, the underlying principles could still be applied if necessary in other bands as well.

The UMTS system is typically designed for a broad range of service classes. The main service classes according to [HOLM07] are shown in the Table 5.

Conversational Class: The conversational class is defined for real-time applications with short predictable response time. Symmetrical transmission is assumed without the buffering of data and with a guaranteed data rate.

Streaming Class: This is also defined for real-time applications. It assumes asymmetric transmissions with possible buffering of data but with a guaranteed data rate.

Interactive Class: This is defined for non-real time applications with variable response time. It is also used for asymmetric transmission with possible buffering but without guaranteed data rate.
## Background Class

This is defined for non real time applications i.e. applications with long response times. It is also used for asymmetric transmission with possible buffering of data without a guaranteed data rate.

<table>
<thead>
<tr>
<th>Service Class</th>
<th>Service type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conversational</td>
<td>Voice, video, telephony, video gaming.</td>
</tr>
<tr>
<td>Streaming</td>
<td>Multimedia, video on demand, webcast.</td>
</tr>
<tr>
<td>Interactive</td>
<td>Web browsing, database access.</td>
</tr>
<tr>
<td>Background</td>
<td>Email, Short Message Service (SMS), downloading.</td>
</tr>
</tbody>
</table>

Table 5 UMTS Service classes [HOLM07]

Currently, spectrum sharing is not implemented between operators mainly due to regulatory and technical reasons. This thesis investigates from a technical perspective how this could be carried out in the future in a cooperative, coordinated and efficient way. Furthermore, it is commonly thought that during the busy hour, spectrum sharing is not possible between multiple operators of a RAT such as UMTS if they have equal number of carriers, as the busy hour is the same for all operators. However this does not imply that the peak of each operator’s load during the busy hour is the same. There are several reasons why the peak of the operator’s load could be different. This could be due to differences in market penetration, service quality and pricing of the operators. Variety of service offerings to encourage off-peak network usage could cause a shift in the peak between the traffic profiles. Furthermore the demand for spectrum in all the cells belonging to multiple operators in any particular place is not the same; these differences could be exploited for spectrum sharing purposes. There are consequences associated with cooperative spectrum sharing. These penalties are usually in the form of control and signalling overhead associated with spectrum sharing. This thesis investigates potential ways to minimise overheads. The degree of cooperation primarily determines how much information is shared between the operators involved.

### 3.2.1 UMTS Capacity Analysis

The UMTS design is such that the uplink and downlink are considered to be asymmetric in terms of their traffic behaviour. In this thesis, the resource management schemes focus
mainly on the UMTS uplink. According to [HOLM07], the uplink capacity of the UMTS network can be estimated is given in (1) as

\[ N = \frac{W}{R} \times \eta_{UL} \times \left( \frac{1}{v} \right) \times \left( \frac{1}{1+i} \right) \times G \]  

(1)

Where \( W/R \) is the processing gain, \( \eta_{UL} \) is the uplink load, \( v \) is the reverse link voice activity factor, \( G \) is the sectorization gain, \( E_b/N_0 \) is the ratio of energy per bit to the noise spectral density. The value \( i \) is the other cell to own cell interference ratio which is a function of the cell environment or cell isolation. Based on the admission control criteria of the network, the users accepted into the network are assigned an uplink code by the radio network controller (RNC).

The call admission criteria can be capacity based, SNR based or throughput based depending on the algorithm used. If we assume that a fixed number of users can be supported on a 5 MHz bandwidth of UMTS spectrum and the demand for the spectrum is Poisson distributed. If we equally assume that each channel is represented by an uplink code assignment. Then the Erlang- B assumption [RAPP02] can be used to estimate the network traffic. The Grade of Service (GOS) which is the probability that a new call arriving be served is given in (2) as

\[ P_b = B(k, m) = \frac{\sum_{n=0}^{m} k^n}{m!} \times \frac{\left( \frac{1}{1+i} \right)}{G} \]  

(2)

where \( P_b \) is the probability of blocking

\( m \) is the number of resources or channels in the system

\( k \) is the total amount of traffic offered in Erlangs

For a 5 MHz carrier that can accommodate fifty voice channels, if the blocking probability \( (P_b) \) is selected to be two percent, then the total amount of traffic offered can be approximated to 40.2 Erlangs from the Erlang-B tables [RAPP02]. Due to the wideband nature of Code Division Multiple Access (CDMA) the notion of a free channel is quite different from that of a Global System for Mobile Communication (GSM) system. Consider a GSM system operating in the same amount of spectrum as a UMTS, since the GSM carrier is 200 KHz wide, then twenty five carriers can be obtained. There are eight
Chapter 3. Cellular Spectrum Management

channels per carrier, which means a total of two hundred channels are available. If a GSM reuse factor of 4 is assumed, then there will 50 channels available at each base station. The probability of carrier freeness plotted in [LEAV04b] shows that it is more likely that a GSM carrier will be available compared to the UMTS. For the purpose of this study, the codes are assumed to be the equivalent of channels to be allocated. Hence the terms are used interchangeably throughout this work.

3.2.2 Inter-operator uplink interference analysis

On the uplink, the main interference components include the same cell interference, the other cell interference and the interference due to the other operator re-using the spectrum i.e inter-operator interference. The total interference is given in (3) by

$$I_{\text{TOTAL}} = I_{\text{same-cell}} + I_{\text{other-cell}} + I_{\text{inter-operator}}$$

(3)

The same cell interference is made up of a superposition of signals from other mobile units at the base station. This is given in equation (4) as

$$I_{\text{same-cell}} = (M - 1) \times S \times \alpha_r$$

(4)

where $M$ is the number of mobile in the cell

$S$ is the power of each mobile at the receiver

$\alpha_r$ is the reverse link voice activity factor

The other cell interference can be reasonably modelled according to [LEE98] as (5)

$$I_{\text{other-cell}} = (MS\alpha_r)\xi$$

(5)

where $\xi$ is the reuse fraction.

Following a similar deduction as the inter-operator interference equation is presented as (6)
Chapter 3. Cellular Spectrum Management

\[ I_{\text{inter operator}} = (kS\alpha_r)\beta \]  

(6)

Where \( \beta \) is the inter-operator interference factor and \( k \) is the users in the second operator reusing the borrowed spectrum belonging to another operator. For simplicity and ease of modelling inter-operator interference is modelled as a capacity reduction due to Adjacent Channel Interference (ACI). According to [HOLM07], the worst case scenario assumes a two percent capacity loss.

Combining (4), (5) and (6) gives (7)

\[ I_{\text{Total}} = (M - 1)S\alpha_r + (MS\alpha_r)\zeta + (kS\alpha_r)\beta \]  

(7)

3.3 Proposed Inter-operator resource management framework

A new layered multi-operator framework is proposed to address spectrum sharing between two UMTS cellular operators. One of the contributions of this work is to provide a comprehensive strategy to address this issue. The proposed layered approach addresses spectrum sharing and radio resource management at different levels taking into account the time scale of operation. It is important to define some concepts central to the overall resource management objectives as used in this thesis.

- Pool versus Non-pooled based sharing

The scenarios investigated are classified as pooled and non-pooled based sharing according to how the resource and the infrastructure are shared. This is elaborated upon in subsequent chapters. However, a distinction between the pooled and non-pooled approach is made here. The pool based spectrum sharing is defined as an approach in which the resource (spectrum) is available to be shared on a pool basis without prioritized access between the two operators. Hence there is no notion of a primary and secondary operator. In the non-pool based spectrum sharing, there is however a primary and secondary operator. The primary operator has sufficient spectrum resource and “lends” the available capacity for a period of time to another system that needs the resource. The secondary system is the
system that suffers temporary capacity crisis and borrows additional resource from
the primary system.

➢ **Dynamic Spectrum Allocation**
Dynamic Spectrum Allocation (DSA) is defined as a network-centric allocation in
which the spectrum resource (code in this case) is allocated to the participating
networks on the basis of the estimated traffic demand over a given future interval,
subject to resource availability. This takes longer to complete, typically some few
hours or several minutes. It is the opposite of Fixed Spectrum Allocation (FSA)
where no spectrum sharing takes place.

➢ **Intra-operator Spectrum Management**
These include all processes by which a single operator attempts to optimize the
use of spectrum resource allocated to the RAN. Examples of this include,
Transmit Power Control (TPC), Intra-operator load sharing/load balancing, Call
Admission Control (CAC) etc. Dynamic resource management on a cell by cell
level is also considered as part of this strategy. Based on timescale, this is used to
account for fast variation in spectrum usage, of the order of milliseconds to few
seconds. It is therefore faster and more rapid compared to inter-operator spectrum
management.

➢ **Inter-operator Spectrum Management**
These include all processes by which two or several operators attempt to optimize the
use of the spectrum resource available to them. Some form of pre-established
co-operation is required between the involved operators. The optimization of the
spectrum usage is on a longer time scale compared to Intra-operator based
solutions.

An example of this is Joint Radio Resource Management (JRRM). JRRM refers
to the mechanism by which a common algorithm takes into account the overall
spectrum availability in all the different Radio Access Networks (RAN) in order
to make better allocation decisions. To realise this algorithm in practice, some
suitable network architecture and procedures must be established [ATTA08],
Network interworking strategies to address the different degrees of complexities between the heterogeneous networks are therefore a real necessity. Based on the above definitions it is clear that the resource management objectives could be short, long or medium term. An operating network is therefore required to make adequate provisions to meet these goals. A short term objective for example could be an instantaneous fluctuation or temporary change in traffic demand. To address this goal, legacy techniques such as intra-network handover (horizontal handover) [CHO09], dynamic power control, call admission control [LIU05] or resource scheduling [PUTT08] could be used. A longer term objective could be in the form of spectrum borrowing to cope with a longer exchange of resource between Radio Access Networks (RAN). Therefore the resource management objective is categorized according to duration in which the resource needs of the network must be fulfilled.

To meet these challenges, the thesis proposes a hierarchical framework that addresses the spectrum needs of the two operators according to different timescale. A description of the components of the proposed hierarchical solution is shown in Figure 6. According to Figure 6, the low level spectrum management (LLSM) occurs at the lowest layer of resource exchange. Its timescale of operation is of the order of seconds.

At the next layer of resource management is the medium level spectrum management (MLSM). It reacts to a much slower variation in spectrum use compared to the (LLSM). For instance two RANs belonging to the same operator could exchange spectrum without the need to negotiate through a higher level entity. An example of this could be the exchange of resource between WLAN and UMTS networks belonging to the same operator. This is however not considered in this work, since it is assumed that each operator has a single RAN through which it provides service to the users. The resource allocation timescale within the LLSM is typically of the order of few minutes.

As shown in Figure 6, additional information such as user location, distribution and mobility information could serve as input to the decision making process.
At the top and closely interacting with the global spectrum broker is the High Level SM (HLSM). It responds to slower variations compared to MLSM. It is proposed to use this for a coarse allocation of the spectrum, while the LLSM is used to track faster variations. The HLSM is responsible for inter-operator spectrum sharing and may act in conjunction with one or more functional network entities to make decisions. The details on the architecture are discussed later in Chapter five. The algorithm description of the process involved is shown in Figure 7.
Chapter 3. Cellular Spectrum Management

Figure 7 Flowchart description of proposed spectrum sharing solution

Figure 7 shows a generic algorithm description of the layered process involved in resource sharing between multiple operators. The novelty arises from the fact that the
operators adopt a hierarchical cooperative approach in order to share the resource. The DSA algorithm runs in conjunction with the inter-operator SAC. The Inter-operator SAC is a faster adaptation to spectrum needs of the operators. The definition of I-SAC is presented in Chapter one and its mode of operation are discussed in detail in Chapter four. A holistic approach is therefore proposed in the design of the spectrum sharing algorithm. Throughout this work, the term resource refers to the shared codes between the RANs belonging to the two UMTS operators. It is important to note that at each level, resource optimization is required using a combination of legacy and new techniques (power control, connection admission control, horizontal and vertical handoffs, and inter-operator resource scheduling) in order to achieve the desired overall spectrum efficiency gain. According to Figure 7, a resource allocation request in the network triggers the low level spectrum management functionality (LLSM). The specific techniques at this level will encompass legacy resource management strategies. Both intra-operator handoffs and load sharing schemes are important techniques at this level. The time scale for operation at this level is considered to be of the order of milliseconds.

If the resource optimization criteria can be met at this level, no further interaction with higher layers is necessary and the resource is granted to the user. The inability of the system to satisfy the UE at the lower levels triggers the Medium Level Spectrum Management (MLSM) subsystem. This subsystem tries to accommodate the request following the failure of the LLSM. The time scale for the MLSM operation is longer compared to the LLSM but shorter compared to the High Level Spectrum Management (HLSM). This will be of the order of few minutes. The failure of MLSM to address the spectrum needs of the user triggers the HLSM functionality.

3.4 Traffic Assumptions

The traffic model used in this work is inspired from the work in [WILL08], [ALME99]. The variation in the use of the spectrum between the two UMTS network operators could follow different patterns. This variation depends on the type of service and according to the observation interval of the use of the resource. This could be on packet level, session level, daily or weekly or even seasonal level. According to [EURO98] [LEAV04b], the packet level variations are due to the bursty nature of packet transmissions. An example
of this can be seen in the web-browsing and file transfer applications. This is the smallest and perhaps most challenging spectrum opportunities that could be exploited. The session level variations are due to Poisson nature of call arrival and departure processes occurring in a system. The daily, weekly and seasonal levels also exist as a result variations in user behaviour over such observation period. Usually the smaller the observation period, the more challenging it is to exploit such opportunities.

The underlying traffic assumption used in this work is as shown in Figure 8. The bottom figure shows two network operators (A and B) with exactly the same traffic profile over a twenty four hour daily period. This could be considered as the worst case scenario. The top left corner of Figure 8 shows that if the worst case pattern is observed at micro-level, then temporal fluctuations do exist over a shorter time scale.

Similarly, the traffic variation captured on the top right corner of the same figure, shows that a relative difference in the peak to peak traffic of two networks is equally possible. This relative difference could vary realistically between (±5 percent to ±10 percent).

There are different reasons why the traffic pattern between two networks could show a lesser degree of correlation than expected. This could be due to market based incentives by network providers to encourage off peak use, differences in market penetration or even a prolonged period of unusual activity, etc.
In any case, different forms of traffic correlation combinations between the two networks could equally exist from positive to negative correlation values. This works uses the negative correlation as a starting point. It considers suitable algorithms to achieve sharing between two operators under different conditions.

Figure 9 shows a negative correlation between the two operator's traffic profiles. The degree of correlation in this case is -0.2. The degree of correlation determines the type of spectrum sharing approach to be used. In this case, the two networks are able to
complement each other better, in order to obtain a significant increase in the spectrum efficiency gain.

![Figure 9 Example of a negative traffic correlation for two operators](image)

In Figure 10, the peaks for the two networks rise and fall simultaneously over the course of the day. The normalised traffic profile for the two operators could vary between five percent and ten percent. In this case sharing can also take place to utilise the remaining capacity available on Network B.

![Figure 10 Example of a traffic pattern between two operators with a relative difference in loading](image)
In Figure 11, the shifted peaks can also be taken utilised by either Network A or B to increase spectrum efficiency. This could be as a result of some price incentives offered by the operators. This incentive forces the peak to occur at slightly different times.

![Figure 11 Showing network operators with shifted traffic peaks](image)

The following basic traffic curves are possible due to the reasons explained earlier. This could range from a negative correlation to a high degree of correlation. The traffic correlation shown in Figure 12(a) to Figure 12(e) varies between 0.8 and 1, that is, eighty percent to hundred percent traffic correlation. This can be considered a reasonable assumption for similar operators.
Chapter 3. Cellular Spectrum Management

Figure 12a Traffic Correlation < 0.8

Figure 12b Traffic Correlation > 0.85

Figure 12c Traffic Correlation > 0.9

Figure 12d Traffic Correlation > 0.95

Figure 12e Traffic Correlation = 1

Figure 12 Traffic correlation values between 0.8 - 1
3.4.1 Basic call model assumptions

The call arrival process is based on Poisson distribution, with a mean exponential call holding time of one hundred and twenty seconds. To improve channel availability and eliminate extreme values of call holding time generated during the simulation process, a modified truncated call holding time is used in the simulator. The call holding time varies between ten seconds and two hundred and forty seconds. Unrealistic values are removed by regenerating the call hold time to fall within the interval above. Figure 13 shows the Call Holding Time (CHT) without truncation.

The truncation process helps to eliminate extreme values. It also helps to provide simulations results more representative of real and practical systems due to the reasons mentioned above.
3.4.2 Network and Terminal Considerations

The behaviour of the terminal and network is essential for the operation of spectrum sharing to take. It is an important assumption that the terminal is tuneable over the required range of frequency. This implies that the radio systems need to be equipped with transceivers that can operate on a variety of carrier frequencies and (potentially) use different access technologies. Hence there is no limitation in terms of frequency agility and receiver front end design for the terminal.

Furthermore, it is also assumed the network equipment is also reconfigurable and able to adapt to the different spectrum available within a relatively short period of time. Network and terminal reconfigurability is realised both in hardware and software. The other main network constraint is in terms of processing DSA related information and the memory to store such information. It is an assumption that the solutions that eliminate these barriers exist. Some of these elements have been discussed in [TUTT02].

3.5 Non-pool based Algorithm

In the non-pool based algorithm, there is always a primary and secondary operator. The primary and secondary operators are as defined earlier. There is a deliberate attempt to protect the performance of the primary system from deterioration due to sharing. There are several variants of this algorithm depending upon whether queuing is applied or not. For example to minimize signalling problems, the user may be queued first on the home network after which it could be transferred or blocked if no capacity still exists.

Similarly, if an intelligent agent is employed, the user could be seamlessly routed in a transparent manner to the new network with any queuing on the home network. The disadvantage of this is that there will be increased signalling load on the network. Again once on the foreign network, different levels of priority could be possible, for example if the new network has users waiting to be admitted to the network a decision has to be made. Whether to accept or drop the foreign call will depend on the incentives or agreement involved. If a user is declined, the users could be queued on its home network until capacity becomes available or transferred onto the new network based on the decision made by an intelligent network agent.

Statistical multiplexing technique is used to improve the overall spectrum efficiency of both networks. It should be noted that, if the primary system requires the use of its
network at any time, the secondary user is terminated to protect the primary network. This algorithm is studied more in the context of network interworking strategies and the delays are longer compared to the case of integrated network or joint radio resource management where resources are pooled together.

In summary, this chapter has presented different aspects of dynamic spectrum use in a cellular network. The traffic assumptions in terms of the different traffic profile present between two operators have also been discussed. Finally, the hierarchical framework to address spectrum sharing according to the different timescales based on the resource management objectives has been presented. The next chapter presents the proposed improved DSA algorithm.
Chapter 4

4 Improved Dynamic Spectrum Allocation

This chapter presents the improved dynamic spectrum allocation technique based on some concepts established in the previous chapters. The improved DSA technique combines the pure DSA scheme proposed in [LEAV04b], together with the inter-operator SAC to achieve higher performance in negatively correlated traffic situations. DSA operates at RAN level, while I-SAC operates on a call by call level. Additionally, the various aspects of the improved DSA algorithm and the operational constraints on the algorithm are presented.

4.1 Improved DSA Operations

The operation of the Improved Dynamic Spectrum Allocation (IDSA) process is RAN based and managed by a central authority such as Spectrum Manager (SM), as well as on a call by call level by a common multi-operator algorithm. The main difference between the improved scheme and the pure DSA scheme is that the RAN based allocation is complimented by inter-operator spectrum optimisation. This is described later in this chapter. In pure DSA, carriers are dynamically allocated between networks according to an optimum time scale. The time scale depends on the two networks involved, the actual observed traffic on the networks, and the amount signalling overhead that can be tolerated. Generally, there should be significant complimentary characteristics in the traffic profile for the pure DSA algorithm to operate. Simplified versions of the algorithms have been considered in [LEAV04b] in the form of fragmented, contiguous DSA. However, this could also take the form of spectrum trading whereby an auctioning mechanism may be considered as presented in [SALL06], [SENG09]. Regardless of the approach considered some basic underlying element feature in all the approaches. The details of these are described below. Four main components are identified. These include;
Chapter 4. Improved Dynamic Spectrum Allocation

1. The DSA Trigger
2. Network Traffic Estimation
4. Inter-operator spectrum optimisation.

These components initiate, execute, and monitor the DSA process from time to time. A number of sub-routines and algorithms are present in each stage and a detailed description of the components is presented next. Figure 14 shows the main stages involved in pure DSA [LEAV04b], the network load is estimated after the trigger. This is then translated into a resource requirement to determine the actual amount of codes required by each RAN. Finally, allocation is made according to the allocation algorithm.

![Diagram of DSA process]

Figure 14 Showing the basic operation of the DSA algorithm
4.1.1 Network Intelligence (Load history)

As stated earlier, one of the main differences between the CR technique and the network-centric allocation is the fact that network-based intelligence is used. Therefore, while a CR is required to sense and identify spectrum opportunities [SAHA06], in the case of network-centric DSA, knowledge in the form of a load history is processed and used as the basis for allocation decision. The load history can be acquired according to the level of accuracy necessary for prediction. For example, the traffic pattern seen on the RAN at different instances of time can be collected for every weekday (including weekends) over a considerable period of time.

Particular days of the week could show some form of similarities which could be used to make predictions. For example, 11:00 am on Friday could show some similarities which can be used for prediction. How this data is processed and presented into a form usable by the spectrum sharing algorithm is important. Time series and different interpolation techniques can be used to make the data points more robust. In addition, the load history could be further adapted to seasonal variation or slow term changes such as subscriber growth [LEAV04b].

In any case, the major limitation of the load history is the fact that it cannot adapt to fast changes such as emergency situations e.g. accidents, sporting events, campaign rallies etc. There is therefore a practical limitation for its use. Nonetheless, it serves as a very important tool for the network to make decision on RAN allocation.

4.1.2 DSA trigger

This indicates when the DSA algorithm is required to run. The implementation of the DSA trigger should be such that the observation period for the RAN traffic is large enough to cause a change in the traffic requirement. DSA is not required all the time, rather than run at predetermined set times, it is important to target the DSA trigger to operators only when a re-allocation is necessary. Based on the work in [LEAV04b], thirty minutes to one hour is considered optimal.
4.1.3 Network traffic estimation

DSA generally involves a timeline allocation of network resource (spectrum) based on the exhibited traffic pattern. Time series data techniques are therefore used for statistical modelling [PAPO02], [FERN02]. The prediction tools described below, will allow the load estimator shown in Figure 16 to accurately predict the network load and hence the spectrum requirement of the network on an interval basis. Let the series $Y = \{Y_t | t \in T\}$ denote the traffic prediction series, where $T$ is the sampling time index. The set of past observed values $X = \{X_1, X_2, \ldots\}$ is used for predicting the future elements of $Y$. If the set of observed values represent the mean values of the traffic, the general practice is to use Autoregressive (AR) or Moving Average (MA) models [PAPO02]. The AR estimation, based on $p$ past observed samples, is calculated by,

$$Y_t = \sum_{i=1}^{p} \phi_i X_{t-i} + W_t,$$  \hspace{1cm} (8)

where $\phi_i$ is the parameter of the model and $W_t$ is the error term, commonly white noise with zero mean and variance $\sigma^2$. The AR parameters $\phi_i$ can be calculated using Yule-Walker equations [PAPO02].

The MA estimation of order $q$ is defined as:

$$Y_t = W_t + \sum_{i=1}^{q} \theta_i W_{t-i},$$  \hspace{1cm} (9)

where $\theta_i$ is the model parameter and $W_t$ are i.i.d. error samples as before. A more general approach is an Autoregressive Moving Average (ARMA) model which combines the AR and MA models [FERN90], [PAPO02].

All the above-mentioned models assume ergodicity and stationarity for the estimated variables, i.e. the mean traffic values. Other generalizations such as Autoregressive Integrated Moving Average (ARIMA) [MILL90] can be used for estimating non-stationary processes.
Chapter 4. Improved Dynamic Spectrum Allocation

To estimate peak traffic values, in addition to the above methods, the use of linear and non-linear regression techniques is common practice [ISTD07]. A linear regression estimation of \( Y_t \) might be based on only the past values of the observed traffic, \( \{X_{t-p},X_{t-p+1}, \ldots, X_t\} \), for an arbitrary \( p \). This is called extrapolation. If the current value of the observation is also used, the method is called interpolation. The general equation for linear regression can be written as

\[
Y_t = \alpha + \beta X_t + \epsilon_t, \quad (10)
\]

where \( \alpha \) is the intercept, \( \beta \) is the slope, and \( \epsilon_t \) is the error term. To estimate the intercept and slope, different approaches such as the Least Square (LS), Maximum Likelihood (ML), or Bayesian methods can be utilized [MILL90].

There is a trade-off between accuracy and complexity of the different traffic prediction techniques. Since different DSA scenarios need to meet different requirements, it is not practical to select one estimation approach as being optimal for all scenarios. Some comparative studies on the performance and complexity of different traffic estimation methods, covering a limited number of selected approaches, are available in the literature, see e.g., [FENG05] and [FERN02].

Clearly within the DSA context, it can be seen that prediction tools are fundamental to network centric algorithms since they derive their knowledge of the network behaviour through these network prediction tools. The overall process of operation of this module is shown in Figure 15. Initially, an error threshold is set to determine the reliability of the historical data being used in the prediction.

The work in [LEAV04b] has considered the different ways of making the historical data into a form that can be used, as an input to this process. The current traffic load is obtained and then compared. If it falls within the required threshold then the history data is used as the basis for prediction in the next interval, otherwise some more accurate schemes as described above is used. It should be pointed out that the main technical constraint in terms of measuring the current RAN traffic is purely related to memory and hardware processing. However, it is an assumption that these two are realisable. The output is then translated into a spectrum requirement that is usable by the DSA algorithm using interpolation techniques [LEAV04b].
Chapter 4. Improved Dynamic Spectrum Allocation

Set an error threshold for prediction

Obtain current load of the RAN

Compare the current load with the load history

Load historical data from the database registry

Is the output within error threshold

Yes

Use load history as basis for prediction

No

Discard historical data and select a prediction algorithm

Output predicted traffic for the next interval

Translation into spectrum RAN requirement

Pass as input to the Allocation algorithm

Data registry

Figure 15 Flowchart description of the network traffic estimation process
Chapter 4. Improved Dynamic Spectrum Allocation

The output decision ($H$) from Figure 15 forms the input to the spectrum allocation section.

4.1.4 Spectrum Allocation

The allocation of spectrum resources could follow a number of schemes. Some of the important centralised schemes have been investigated in [ACHA09], [SALL08]. In this thesis we propose a mechanism that addresses radio resource allocation according to short, medium and long term requirements. The short term allocation occurs on a small time scale typically few seconds, the medium term allocation is typically of the order of some few minutes while the long term allocation take place over a much longer time interval typically hours. For the pure DSA used in this work, the weighted parameter scheme proposed in [LEAV04b] is used as a starting point due to its numerous advantages over the other schemes.

4.1.5 Inter-operator spectrum optimisation

In addition to the pure DSA, the operators are able migrate users between their networks in order to adapt to fast changes in the use of the spectrum. The call by call optimisation increases the capacity gain through improved statistical multiplexing. The mechanism for achieving this is referred to as the inter-operator spectrum access control. This algorithm runs at every other time when the DSA algorithm is not running, hence providing a finer layer of optimisation to support the high level DSA.

4.1.6 RAN based allocation schemes

RAN based allocation algorithms are very important in the study of DSA schemes. There are different priority based schemes that allocate by giving priority to one network over the other. Also allocation schemes can combine one or more criteria to obtain the benefit of both i.e improved performance and fairness at different load regimes (load, medium and high load). The important ones considered in this thesis are presented in the section.
• Equal Allocation Scheme
This allocates the same number of channel to the RAN without taking into account any further information from the RAN or it uses a random selection method if insufficient channel is available to be allocated to the two RANs [LEAV04b]. Figure 16 shows a flow description of its operation.

![Flowchart of the equal allocation algorithm](image)

• Random Allocation Scheme
In the RAN allocation scheme, RANs demanding spectrum are allocated on a random basis. The random scheme does not take into account any further information from the RAN, thus it is inherently fair in its allocation approach, but sub-optimal in terms of efficiency performance.
Chapter 4. Improved Dynamic Spectrum Allocation

- **Highest Request Scheme**
  The scheme bases its allocation decision on the highest number of requested carriers [LEAV04b]. For example if two RAN A and B are both requesting three and five carriers respectively, then RAN B gets priority if there is a spare carrier to be awarded. If both require exactly the same number of carriers then any RAN is randomly selected. Figure 17 shows a description of the process involved in the highest request schemes.

- **Lowest Allocation Scheme**
  The RAN with the least allocation get more spectrum in an attempt to re-distribute spectrum to avoid consistently starve a RAN with low allocations. If both show the same number of allocated carrier then the random selection method is used.
• Weighted Parameter Scheme
The weighting scheme combine two allocation criteria to using a weighting formula to determine which RAN get the spectrum. A weighting factor is applied to each criterion e.g allocated carrier and requested carrier, based on which an overall weight for each RAN is calculated. The lowest allocated carrier and the highest requested carrier is considered. The weighting scheme combines some salient advantages of all the other allocation schemes and it is therefore chosen in

Figure 17 Flowchart description of the highest allocation scheme
this study. For example if equal weighting is assigned to the “allocate and request”
criteria then each will be 0.5. Then the overall weight of each RAN if the allocated
carriers on A and B is \( C_{rx} \) and \( C_{ry} \), and the requested carriers on A and B is \( D_{rx} \) and \( D_{ry} \) respectively will be as follows:

\[
B_{rx} = B_a \left( \frac{C_{rx}}{C_{rx} + C_{ry}} \right) + B_b \left( \frac{D_{rx}}{D_{rx} + D_{ry}} \right)
\]

If \( B_a + B_b = 1 \) then,

\[
B_{rx} = \left\{ (1 - B_b) \left( \frac{C_{rx}}{C_{rx} + C_{ry}} \right) \right\} + B_b \left( \frac{D_{rx}}{D_{rx} + D_{ry}} \right)
\]

\[
B_{rx} = \left\{ \frac{C_{rx} - C_{rx} B_b}{C_{rx} + C_{ry}} \right\} + B_b \left( \frac{D_{rx}}{D_{rx} + D_{ry}} \right)
\]

where \( B_{rx} \) is the overall weight of RAN

\( B_a \) is the allocated carrier weighting factor

\( B_b \) is the requested carrier weighting factor

\( C_{rx} \) is the allocated carriers to RAN x

\( C_{ry} \) is the allocated carriers to RAN y

\( D_{rx} \) is the requested carriers by RAN x

\( D_{ry} \) is the requested carriers by RAN y

Figure 18 shows the operation of the static weighted parameter algorithm. The
spectrum requirement gives an input which is evaluated to see if both RANs
require spectrum. If this is the case a static weight is applied as discussed and the
RAN with the overall largest weight gets the resource, otherwise only the RAN
requiring the spectrum is allocated. This is the main scheme that is considered in
this thesis since according to [LEAV04b]; it outperforms all the other techniques
due to its better allocation decisions.
• **Dynamic Weighted Parameter Scheme**

This scheme represents a variant of the weighted scheme discussed above. In the dynamic weighted scheme, the weight applied to the allocated carriers and the requested carriers in each RAN is not static over the entire interval. Rather it is dynamic to account for some form of inherent fairness between the factors. As shown in Figure 18, the static parameter is replaced by a dynamic one, and this forms the basis of the overall weight calculations. This will also prevent a falsely declaring RAN to gain undue advantage if the allocated weights are made to be dynamic. This scheme is not used in this work due to its complexity.
4.2 Inter-operator Spectrum Access Control

The DSA scheme discussed above uses Inter-operator Spectrum Access Control (I-SAC) to achieve improved performance. I-SAC operates at all other times when DSA algorithm is not running to achieve a finer layer of granularity. The DSA can be seen to allocate spectrum coarsely, while I-SAC provides a finer level of spectrum optimisation on call by call basis. The blocked diagram of I-SAC is shown in Figure 19. When I-SAC is trigger, call requests are transferred across operator network according to the block diagram. It operates in conjunction with DSA as a method of re-balancing the load across the operator network. I-SAC also eliminates the need for extremely accurate or complex estimate tools.

![Block diagram of the Inter-operator SAC algorithm (new calls)](image)

According to Figure 19, the new incoming calls are checked against the call admission criteria of the secondary network; in this case their own network. The successful calls are accepted while the mobiles that cannot be temporarily accommodated are re-routed by the network to the primary system. The overall goal of I-SAC is to achieve improved statistical multiplexing by adapting to faster changes on the network. According to Figure 20, existing calls are also re-routed to the new network if there is a capacity crisis on the
secondary network. The flowchart shows the procedure for capacity search on the networks. The existing calls first search for capacity on their own networks.

![Flowchart](image_url)

**Figure 20** Block diagram of the Inter-operator SAC algorithm (existing calls)

The overall algorithm flowchart for the improved DSA is shown in Figure 21. According to the Figure 21, at all other times after the DSA algorithm has already made allocations, the I-SAC inter-operator algorithm runs to adapt to instantaneous fluctuations in traffic demand. Users that are unable to get served on their home network are redirected under the influence of the network management control to another network. The algorithm terminates shortly before commencement of DSA algorithm. Initially the algorithm runs as described earlier and once the DSA allocation is made, I-SAC continues to run until
the next DSA interval. If no DSA is required the algorithm keeps the existing allocation and waits until the next interval when a re-allocation is necessary.

![Block diagram of the Improved DSA algorithm](image)

**Figure 21 Block diagram of the Improved DSA algorithm**

### 4.3 Algorithm Operational constraints

The primary and most important constraint on the working of the SAC (or DSA in a centralised architecture) is that the allocations decided must not cause any undesired interference between the RANs that are sharing the spectrum, otherwise the whole purpose of spectrum sharing is lost. This is so important that it can rightly be described as
the primary criterion of any scheme that brings about any change in the radio spectrum allocation and is also important from the regulatory point of view.

It is a constraint on the working of the SAC algorithm that the minimum unit of spectrum that can be added or removed from the allocations is the bandwidth of the carrier required for that RAN. This essentially means that the spectrum cannot be allocated with an arbitrarily granularity.

Time period between reallocation of the radio spectrum is also an important constraint as for an efficient working of any spectrum-sharing scheme; the SAC algorithm has to be rapid enough to follow the changing spectrum demands of the RANs. However, reallocating the spectrum on a rapid basis also brings certain disadvantages such as signalling load on the network and the need to rapidly change the operating frequencies of the networks. Instantaneous allocation of frequency also has Quality of Service, Stability and hardware implications both (terminal devices and network).

Thus there is a trade-off in operating the SAC algorithm too frequently resulting in an increase in the signalling load, and operating infrequently resulting in inability to follow the changing patterns of the traffic load. Moreover, the time period between spectrum allocations also affects the load prediction quality, as typically it is difficult to predict the load too ahead in time with reliability.

Load prediction is another requirement expected from the SAC algorithm and as pointed out earlier it is related to the time interval between spectrum allocations. There may not be a need for load prediction if the time interval between spectrum allocations is quite small, as the load may not change substantially over a relatively small interval, but for relatively large inter-spectrum allocation intervals, load prediction is a necessity.

Based on the constraints identified, a summary of the main requirements for successful DSA operation is presented as follows:

1. For the purpose of spectrum reallocation, calls should not be dropped ideally but under certain circumstances selective call dropping may be appropriate to accommodate the satisfaction ratio of the RANs to achieve an overall improvement in performance. From a network architecture point of view, there is a need for a centralized spectrum manager, which must have knowledge about the spectrum usage and requirements of each network across the shared spectrum
band at that location. This resource information can be exchanged between the spectrum manager and the networks using dedicated signalling channels.

2. The centralized controller should coordinate, spatially and temporally, the resource allocations among participating networks. This must generally be done at certain defined periodic intervals.

3. Each network, through some form of traffic estimation and load prediction, should predict its resource requirements for the coming DSA interval.

4. The centralized controller must allocate spectrum using intelligent algorithms, in a way that minimizes interference between participating networks. It is also a requirement that this process should be done in a fair and efficient manner to ensure that overall system performance improves.

5. There is a short time interval during which spectrum reallocation takes place across multi-operator networks. The DSA process should guarantee no service interruption during such intervals.

6. There should be sufficient provision and backup in case of any failure in a participating network or the spectrum manager. The algorithms embedded in the spectrum manager should be robust against failure, stable, and glitch-free.

4.4 Performance evaluation of the improved DSA algorithm

This section compares the performance of the improved DSA with I-SAC with FSA. The weighted parameter algorithm is due to the earlier stated advantages it possesses over the other algorithm. The performance of the improved (DSA+I-SAC) is also compared with the pure DSA technique proposed in [LEAV04b] for similar weighting factors. In order to effectively compare the improvements from this technique, similar traffic curves are also used. The negatively correlated traffic curves used here is presented in Figure 9 of Chapter 3. A similar weighting parameter is also applied to the allocation and number of channel request criteria, i.e \( B_{\sigma} = 0.5 \) and \( B_{\beta} = 0.5 \) on both RAN. The performance curves are as shown below. Figure 22 show the performance for RAN A and Figure 23 shows the performance for RAN B. It is observed that all the DSA schemes offer significant capacity improvement compared to the FSA scheme. It can also be seen that the (DSA+I-SAC) scheme outperforms the pure weighted DSA scheme proposed in [LEAV04b] on both RANs. The improvement is due to the call by call optimisation occurring from the I-
SAC scheme. The gain on Network A is also larger than Network B due primarily to the traffic pattern used. This is due to the fact that Network A has more traffic peaks compared to Network B, hence it requests more allocations from the spectrum manager compared to the other network.

Figure 22 Performance curve of improved DSA (static WP) + I_SAC scheme (Network A)

Figure 23 Performance curve of improved DSA (static WP) + I_SAC scheme (Network B)
Chapter 4. Improved Dynamic Spectrum Allocation

According to Figure 22 and Figure 23 respectively, about three percent gain is obtained on both networks respectively. The additional gain is due to the statistical multiplexing gain achieved through the I-SAC algorithm.

4.4.1 Non pool Algorithm

In the non-pool algorithm described earlier, two scenarios are possible depending on whether the operator hold the same number of carrier or different number of carrier. As stated, the primary network is the network which is able to temporarily accommodate the users from another network that suffers a temporary capacity crisis. If a call cannot be admitted, the spectrum management node has to make a decision on whether to queue on the home network or re-direct to a new network.

The decision is based on the access probability which depends on the state of the network. There are several ways of obtaining this knowledge about the two networks. For example the load history could be used as a means of determining this information. When queuing is applied, a random exponential algorithm is implemented to avoid further congestion, such that user attempt a re-connection by selecting a certain time slot. This ensures that multiple users attempting a reconnection do not connect to the network at the same time. If this occurs then both users are not able to get the needed capacity. Only one retry is considered due to the sensitivity of speech traffic to delays. An analysis of the call setup messages is presented later. The delays considered fall within the maximum tolerable delay requirement for the service. The detailed result from this algorithm is presented in Chapter six.

As shown in the Figure 24, the spectrum management node checks the access probability of both networks and decides where the call should be passed onto. If the access probability of both network is the same then the call is retained on the home network to minimize signalling. The SM node acquires its intelligence from a traffic aware server within the network. The next section discusses two important variant of this algorithm.
CASE 1: EQUAL NUMBER OF CARRIERS

The two operators hold the same number of carrier, however we also assume that there could be a relative difference in the peak load between the two networks during the peak hour as shown in Chapter three. This could be exploited for the sharing purposes. The flowchart description of the algorithm is shown in Figure 25.
UNEQUAL NUMBER OF CARRIERS

In this case, the two operators have different number of carriers. For example, the primary system has two carriers and the secondary system has one carrier while the traffic pattern of the two networks is similar. This case also requires a modification of the call admission process, such that users dropped or blocked from the secondary operator can be supported on the primary system. However, there is a priority for the primary users in access to the primary system. When a blocked call on the secondary system is supported on the primary system, this call may be dropped if a new primary user requires access to the system. Since the primary network has control, it is able to set its operating point such that no degradation occurs as a result of sharing with secondary operator. Figure 26 shows a flowchart description of the algorithm.
According to Figure 26, a threshold is set on the primary system to protect its users. Each of the secondary users admitted on the primary system is tested against the admission criteria on the primary system. The admission criteria used is the instantaneous capacity of the primary system. This process avoids harmful degradation to the primary system. It also allows a significant increase in the spectrum sharing gain on the secondary network.
4.4.2 Pool based sharing

This represents another form of sharing in which the entire pool of spectrum is available on a non-exclusive basis to the sharing operators. Another form of this is when the operators have proprietary carriers and a relatively small pool is available as well for spectrum sharing. Initially each operator is allocated a certain amount of code from the pool and the users are allowed to use this on a first come first serve basis. As stated earlier, there is no notion of a primary and secondary operator since this process is dynamic in time, hence either of the network could be primary or secondary operator. As a result the networks involved are designated as network A and B respectively. Figure 27 shows a flowchart description of the pool based algorithm.

![Flowchart description of the pool based algorithm](image)

**Figure 27 Flowchart description of the pool based algorithm**
In summary, this chapter has presented the different aspects of the improved DSA algorithm. It has also presented the operational mode of I-SAC. The inter-operator SAC compliments the high level DSA to achieve higher efficiency. Discussions on the improved DSA result have also been presented. The non-pool and pool based algorithm have also been presented. The scenarios are based on the amount of carriers held by operators sharing the resource. The next chapter addresses the proposed architecture and signalling mechanism to facilitate DSA. This signalling mechanism is considered both at RAN and call setup levels.
Chapter 5

5 Architecture and Signalling

This section investigates the possible architecture required for spectrum sharing between two wireless operators. For spectrum sharing between multiple operators to take place, new spectrum management functionalities are necessary within the network. This chapter of the thesis presents the proposed architecture within the context of UMTS networks, as well as the signalling considerations. The implication on the network is also investigated. It also presents an analysis of the total call setup message involved in the proposed algorithms.

5.1 UMTS Spectrum Access Architecture

In the centralised spectrum sharing solution, different architecture may be envisaged depending on the relationship between the spectrum manager, radio access network, the core network, service provider and the mobile users. In addition to the legacy infrastructure, new functionalities such as database registry are necessary. This is to keep track of historical data on the network. Furthermore a spectrum management node is necessary to determine, how the allocations will progress between the two networks involved. The different ownership model that is possible to facilitate spectrum sharing has been discussed in [SAMM02], [LEAV04b].

The main solutions are classified as;

1. Integrated network solution
2. Network interworking solution.

In the integrated network approach, operators try to share or reuse some aspects of the network. An extreme form of an integrated solution could be the joint deployment and operation of a single network by more than one operator. More relevant to the current scenario witnessed today is the interworking approach. In this scenario, operators defined
common interfaces and platforms. Based on this common platforms radio resources decisions are being taken jointly. For the purpose of this work, elements of the UMTS networks are used in defining the functional entities required.

For the UMTS inter-operator sharing scenario, the sharing operators need to have some kind of co-ordination in the allocation of channelization / scrambling codes otherwise they will interfere with each other. Furthermore, issues like handover, power control, synchronization and channel estimation also need to be revisited in case of spectrum sharing operators, as new problems (e.g. if the base stations of two operators are not co-located, how will they do soft combining in case of handover) will arise. All these issues can be resolved if the operators are sharing the radio access network as well.

The sharing of the access network is something at which 3GPP has thought about but not from the perspective of spectrum sharing but from the perspective of reducing the deployment and operational / maintenance cost of UMTS networks [HOLMO7]. Their view of multiple operators sharing the radio access network is presented in [HOLMO7], [THI06a]. It illustrates that multiple core nodes are connected to the same RAN and the core nodes are operated by different operators i.e Multi-operator core network (MOCN).

In this work, we propose using the multi-operator core network (MOCN) with an intelligent spectrum management node within the network. Figure 28 shows the proposed view of the shared RAN together with the spectrum management node. The purpose of the spectrum management node is to determine when scarcity of resource exists on the home network and then determine if the UE can be supported on the new network or not. Since the RAN is shared, there is a common Medium Access Control (MAC) for both operators.

New functional entities will also be required for statistical prediction tool as well as a database registry for the load history. The statistical predictive tools are necessary to safeguard the accuracy of the information contained in the load history. The statistical prediction could be based on prediction tool similar to those defined in [MILL90], [FENG05]. The new entities will also be responsible for managing the resource exchange process (negotiation and release), Accounting, Authentication and Billing etc between the wireless operators.
By further extending the UMTS Network sharing concept proposed in [THIR06a], the spectrum management node has been included in Figure 28. This node handles all spectrum management related activities. Figure 29 shows the proposed architecture for the UMTS spectrum sharing. The DSA Node is responsible for all spectrum management activities including all the associated database and predictive algorithm needed for the process. The billing platform will manage pre-agreed billing between the operators depending on whether the resource sharing is on a long, medium or short time scale.
5.2 Signalling Mechanism

It is assumed that each of the networks participating in the sharing has a RAN spectrum controller interface (RSCI). This entity is responsible for all DSA related activity for a particular RAN. A particular operator may however also split its operations into DSA areas for ease of DSA management, with each area maintaining a DSA management unit. All the RSCI units for the different RANs connect with the central spectrum controller entity (CSCE). In this way spectrum negotiation, release and exchange of information necessary for command, control and operation of the overall DSA process can be effectively managed. There is an assumption that the network hardware supports the DSA
process, and that the user terminals based on commands through the air-interface with their respective base stations, are able to switch their operating frequencies. The signalling mode is based on the common signalling standard (CSS7) with a dedicated channel to managing DSA signalling between the different RANs.

There is a minimum interval within which spectrum transaction takes place. This is referred to as the DSA interval. During the period prior to DSA, the various RANs operate on the previously allocated spectrum, computation of spectrum needed or which need to be returned to the pool is also conducted. On establishment of the DSA trigger, the RANs exchange basic signalling information via the SCI with the CSCE. The CSCE looks up the spectrum register similar to the look up table for routers and determines what the allocation on the next interval will be, based on the allocation algorithms it operates. In the case of contention, a random allocation method is used to select which RAN to allocate spectrum.

The important inputs for the algorithm to run are supplied via the various RSCI, in the periods following the DSA trigger. At all other times between the DSA intervals, the inter-operator call by call optimisation occurs between the RANs. It operates in a way that the mobile users can be migrated from one network to another. The procedure for I-SAC is as described in section 4.2, Chapter four of this thesis. The I-SAC processes are for both new and existing calls within the network. The procedure ensures further statistical multiplexing of call arrivals to the network, thereby allowing further optimization on a call by call basis. Prior to the next spectrum requirement calculation, the call by call optimisation terminates to allow the next spectrum requirements to be determined.
5.3 Call setup delay analysis

The process of establishing a call involves a number of procedures before the resource is assigned to the user equipment (UE). The different phases of call setup include the Radio Resource Connection (RRC) establishment, security handshake, radio bearer setup, alerting, connect acknowledge, etc. There is a close interaction between the various elements of the operator's network (Node B, Radio Network Controller (RNC), core network) in order to initiate call setup. In the RRC establishment phase, a connection request is negotiated between the UE and the RNC [THIR09b]. Figure 31 shows the phases involved in the RRC connection establishment.
All the connection requests are assumed to originate from the UE. The UE is initially in the idle state. The UE can operate in different modes specified in [THIR09b], that is, in the idle or connected modes. In the connected mode, the acronym Cell_DCH is used to indicate the physical dedicated channel acquired by the UE. The main reason for the different mode of operation by UE is for terminal power efficiency, and network resource maximization. In this section, the call setup involved in FSA and DSA is analyzed. Three cases have been identified.

### 5.3.1 FSA or Non-shared mode

This refers to the mode when no spectrum sharing occurs. Users are only admitted in their home networks and no further measures are taken to admit the call, if the call admission fails on their home network. Hence, no inter network signalling is required. In the FSA mode, the call setup phase includes the Radio Resource Connection (RRC) establishment, security handshake, radio bearer setup, alerting, connect acknowledge, etc. In the FSA mode, the processes and the associated delay involved is shown in Figure 32 based on [THIR06b].
5.3.2 DSA with shared RNC mode

In the shared Radio Network Controller (RNC) mode, the operators share the same RNC. An agent in the RNC proactively monitors the base station loading of the two operators. In this case, the delay budget will be similar to that described in Figure 32. Since the information is contained in the network RNC, capacity can be served directly to the users without additional delays.

5.3.3 DSA with non-shared RNC mode

In the non-shared RNC mode, additional delay is incurred in granting resources on the foreign network. This is because the home network has to ascertain resource available on the new network, and then trigger and inter RNC connection handover. It is an assumption that the Common Pilot Channel (CPICH) of both operators can be decoded by
the terminal i.e mobile supporting network sharing. The call flow procedure for the DSA with non-shared RNC is shown in Figure 33. We further analyze the impact of queuing and call setup latency on the spectrum sharing gain in this work. If the UE is unable to get service from its network, the spectrum management entity which could be part of RNC or separate checks the next available network and then commands the mobile to listen to the pilot channel of the foreign network. Once service connection has been granted and completed, the mobile is able to camp normally on its home network, until spectrum scarcity re-occurs. According to Figure 33, the inter-RNC resource request involving the spectrum management entities on both RAN causes addition delays, and the overall call setup time in the non-shared takes longer to complete. For this reason, it is recommended to operate the recommended algorithm under the shared RNC mode to reduce call setup and handover latency.

Figure 33 DSA connection delays in non shared RNC mode
5.4 FSA with queuing on home network

In order to minimise the effect of cross network signalling, connection delays on home network is a solution compared to spectrum sharing with another operator. In this section, the benefits of queuing on the home network are investigated. The impact is shown for increasing number of carriers in the pool. It can be observed in all the three case from Figure 34 to Figure 36 that there is some improvement in the capacity on the two networks. It is also seen that as the queuing time increases, the probability of a user being able to find a channel also increases. The effect is diminished at high load when the access probability decreases primarily due to congestion.

![Figure 34 Queuing on home network with 1 carrier/operator](image)

Network Operator A

Network Operator B
Chapter 5. DSA Architecture and Signalling

Figure 35 Queuing on home network with 2 carriers/operator

Figure 36 Queuing on home network with 3 carriers/operator
The total call setup messages for DSA and FSA are compared in Figures 37 to Figure 39. The average call setup message for the two networks are identical, hence only one network is shown here. The setup messages are calculated based on the Figure 33 shown to previous section. It can be observed that at different values of user satisfaction the DSA with non-shared RNC provides the highest number of connection initial messages. This is due to the fact since the RNC is not shared; more messages are being exchanged to verify the capacity status of the new network before a transfer is triggered. In addition, the results also reveal that as the number of carriers are increased, more calls are being supported hence the signalling messages increases significantly with increased carriers.

![Bar chart comparing total call setup messages for DSA and FSA with shared and non-shared RNC](image)

**Figure 37 Total call setup messages with 1 carrier/operator**

Furthermore, it is also shown that with increased queuing time, the signalling load increases. It is therefore recommended to operate in the shared RNC mode to minimise problems associated with call setup message overhead. A similar trend in call setup load is observed when the number of carriers is increased in Figures 38 and Figure 39 respectively. Figure 39 has the highest amount of call setup messages due to a high number of users.
The results from Figure 38 and Figure 39 respectively show that for the non-shared RNC, the call setup penalty is highest and almost double the shared RNC scenario. Hence, it is recommended to share the radio network controller to minimise the signalling overhead.
Chapter 6

6 Performance Metric

This chapter of the thesis presents an analysis on how the spectrum efficiency metric is measured. It also presents a description of the multi-operator software tool used to evaluate the proposed algorithm. The chapter also presents the detailed result of the proposed algorithms together with a discussion of the main results.

6.1 Spectrum Efficiency Metric

There has been a number of spectrum efficiency metrics proposed in literature [LEAV04], [EURO98]. In order to effectively compare the results of the proposed algorithms, the guidelines specified in [EURO98] are used. The main performance metric used in this work is defined as the satisfaction ratio (SR). The terms satisfaction ratio and quality of service used throughout this thesis are the same. A user is considered to be satisfied if it is neither blocked nor dropped from obtaining a service connection. The SR is defined in (14) as:

\[
SR = \left(1 - (P_b + (w \times P_d))\right)
\]  

(14)

A weighting factor \(w\) of 10 is used to account for the fact that dropping of the users is more intolerable compared to the blocked users. The term in brackets in the above equation is defined as the Grade of Service. \(P_b\) is the call blocking probability defined according to equation (15) and \(P_d\) is the call dropping probability shown in equation (16).

\[
P_b = \frac{\text{Total Blocked Calls}}{\text{Total Number of Call Arrivals}}
\]  

(15)

\[
P_d = \frac{\text{Total Dropped Calls}}{\text{Total Number of Call Arrivals}}
\]  

(16)
Similarly for the performance evaluation of the call setup (initiation) phase, the main criteria that is used is the total number of call setup messages and the call setup delays. According to [EURO98], the spectrum efficiency is defined as the load supported at 98 percent user satisfaction level. The vertical axis of Figure 40 represents the quality of service (QoS) or satisfaction ratio (SR), while the horizontal axis represents the average load/cell/hour. At a satisfaction ratio of ninety eight percent, the average value of cell load denoted by $\delta$ is used as a measure for comparing the schemes proposed.

![Figure 40 Satisfaction ratio versus network load](image)

For the simulations represented in this work the load is directly proportional to the users or subscribers per cell for a given time. An example of how the Spectrum Efficiency Gain (SEG) is measured is shown in Figure 41. Throughout this work, the spectrum efficiency gain is also known as the DSA gain. The SEG is measured by comparing the number of subscribers/cell/hour for FSA and DSA at a user satisfaction level of ninety eight percent. The load supported by FSA at ninety eight percent SR ($\text{Load}_{\text{FSA, } 98\%}$) is also referred to $\alpha$, while DSA load at ninety eight percent SR ($\text{Load}_{\text{DSA, } 98\%}$) is represented by $\beta$. The difference between the two loads $\beta$ and $\alpha$ is considered to be gain as shown in Figure 41. The value of ninety eight percent SR is chosen according to [EURO98] because it guarantees the desired level of quality of service on the network.
The Spectrum Efficiency Gain ($Y$) can be calculated according to (17)

$$Y = \frac{\beta - \alpha}{\alpha} \times 100\%$$  \hspace{1cm} (17)

where: $\beta$ is the users/cell/hour of the DSA at ninety eight percent user satisfaction 
$\alpha$ is the users/cell/hour of the FSA at ninety eight percent user satisfaction
$Y$ is the spectrum efficiency gain in percent.

6.2 Multi-operator Simulation Software

In order to evaluate the performance of the spectrum sharing algorithms proposed, a software has been developed and calibrated in MATLAB following guidelines outlined in [RUMB99]. The system level simulator consists of several modules such as the traffic generator module, network control module, multi-operator cell grid module, performance metrics module etc. A detail on the guideline and methodology of the simulator is contained in [SALA10] while some calibration results are also presented in [MOBI08]. The block diagram showing the interactions between the different modules is presented in Figure 42 followed by a description of its functional components.
6.2.1 Traffic Generation Module (TGM)

The traffic module generates the relevant traffic information for the simulation. The users are assumed to be uniformly distributed over the coverage area. The subscriber arrival follows a Poisson process while the call duration follows an exponential distribution [TRAN04]. A truncated call holding time is used to eliminate extreme values. The traffic generation follows guidelines specified in [ZAND01]. In addition, each mobile station has a list of associated attributes. Examples of these attributes include mobile identification number, mobile arrival and departure times, handover times, handover cell, start operator and end operator etc. There is also provision to investigate uniform and non-uniform traffic situations within the network.

6.2.2 Cell Grid Module (CGM)

The cell grid module generates the cell layout. This is done according to the required cell parameters for the number of operators being investigated. The number of operators is currently set to two, but this can easily be adjusted if more than two operators are to be investigated. The CGM can be used to study collocated or displaced cell situations by adjusting the displacement angle according to the simulation requirements.

Border cells surrounding the cell under investigation can be easily identified for handover and interference calculation purposes. It also allows the selection of some cells as hotspot cells in order to investigate non-uniformly distributed traffic scenarios. These congested areas are particularly important in real network situation. Similarly, circular cells with overlapping boundaries or hexagonal cells can be plotted in the simulator as required. A cell radius of one kilometre is considered for most cases in this work and can be changed if necessary. The wraparound mobility model is used to maintain a constant user density.

6.2.3 Network Operator Module (NOM)

This module defines the number of operators for a given simulation scenario. It contains the network operator attributes such as the cell coverage, the number of base stations and users for the operator. Furthermore, the simulator allows the resources belonging to a given operator to be optimised independently or jointly through the algorithms proposed
in this thesis. The scenario investigated in this work assumes two operators covering the same geographical area.

6.2.4 Performance Metric Module (PMM)

The performance metric module is crucial to the overall functioning of the simulator. It computes and outputs the simulation results in terms of the connection blocking and dropping probabilities for FSA and DSA respectively. It also output the results of successful and unsuccessful call attempts as well as handover operations of the network. The PMM is linked to a Graphical User Interface (GUI) for ease of visualisation of the simulation results. The GUI function is optional and can be de-activated if necessary.

6.2.5 Graphic User Interface (GUI)

The Graphic User Interface (GUI) module is the user interface of the simulator. It gives flexibility to the user to change simulation preferences, settings, and optional parameters. It also allows easy visualisation and monitoring of the overall simulation progress. There are a wide range of parameters (spectrum bands, traffic parameters, system, plots and DSA parameters) that can be changed, to map the simulation to the appropriate scenario being investigated. The data entered in the GUI is passed to the simulator through this interface and the simulation runs accordingly. The GUI also captures simulation progress and displays the performance results for the entire simulation process. The spectrum module provides the various spectrum bands available for spectrum sharing. It is an optional feature and could be de-activated if necessary.

6.2.6 Spectrum Information Module (SIM)

This module is responsible for the selection of available spectrum resources prior to running the simulation. The selected spectrum could be available to the operators individually or jointly according to the algorithm selected. The selected spectrum is then used in the estimation of the capacity available in each cell on a dynamic basis.
6.2.7 DSA Protocol Module

This module is implemented to manage the spectrum allocation process. The different allocation algorithm according to the resource management objective is carried out by this module.

As shown in Figure 42, new users entering the network are assigned to a given operator cell and base station. The cell radius is assumed to be one kilometre. The traffic prediction module estimates the load at the forthcoming interval. The DSA module runs both the combined pure DSA and the I-SAC already discussed in Chapter 4. Interference from other cells belonging to the same operator and the other cells belonging to the other operator is estimated through the Network Control Module (NCM). Initial capacity
estimates and handovers are managed also by the NCM. The initial spectrum available is
determined by the spectrum module while perform metric module closely tied to the
NCM in Figure 42, outputs the results.

6.3 Simulator Calibration

The multi-operator simulator used in the investigation has been extensively calibrated.
The results produced compare reasonably with results widely published in literature
[LAIH02], [LEE98] for the test phase of this work. Modular testing was conducted by
considering single cell scenario initially and then benchmarking the results with known
ones. The main simulation parameter used is shown in Table 6. The FSA curve could be
plotted according to the timescale of operation.

<table>
<thead>
<tr>
<th>Service Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Service type</td>
<td>Speech traffic</td>
</tr>
<tr>
<td>Data rate</td>
<td>12.2 Kbps</td>
</tr>
<tr>
<td>Call Duration</td>
<td>Mean = 120 seconds (Exponential)</td>
</tr>
<tr>
<td>$E_b/N_0$</td>
<td>7 dB</td>
</tr>
<tr>
<td>Adjacent Channel Interference</td>
<td>2 %</td>
</tr>
<tr>
<td>Soft handover Gain</td>
<td>3 dB</td>
</tr>
<tr>
<td>Cell radius</td>
<td>1 Km</td>
</tr>
<tr>
<td>Voice Activity Factor</td>
<td>0.67</td>
</tr>
<tr>
<td>UMTS carrier bandwidth</td>
<td>5 MHz</td>
</tr>
<tr>
<td>Chip rate</td>
<td>3.84 MCps</td>
</tr>
<tr>
<td>Simulation borders</td>
<td>Wraparound mobility of MS at simulation borders</td>
</tr>
<tr>
<td>Propagation Model</td>
<td>Path loss model with 4th order power</td>
</tr>
</tbody>
</table>
Chapter 6. Spectrum Efficiency Performance

<table>
<thead>
<tr>
<th>User distribution</th>
<th>Uniform or Non-Uniform (with hotspot)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency re-use factor</td>
<td>1</td>
</tr>
<tr>
<td>Handover</td>
<td>Based on geometric cell boundaries</td>
</tr>
<tr>
<td>Total Number of cells</td>
<td>12 (with interference modelling)</td>
</tr>
<tr>
<td>Carrier distribution</td>
<td>Primary (variable), secondary (variable)</td>
</tr>
<tr>
<td>Cell layout</td>
<td>Hexagonal with omni-directional antenna</td>
</tr>
<tr>
<td></td>
<td>Deployment</td>
</tr>
</tbody>
</table>

Table 6 Simulation Parameters

The typical FSA calibration result for one to four carriers on one network is shown in Figure 43. The vertical axis represents the Quality of Service (QoS). The horizontal axis is the average mobile/cell/hour. The results show that an increase in the cell loading results in a drop in the QoS. The curves shift to the right as the number of carriers increase, indicating the increased subscriber density in the network as the number of deployed carriers by the UMTS operators increased. FSA curves are used as benchmarks for measuring the performance of the DSA protocol.

Figure 43 Typical FSA calibration results for different carriers on the network
6.4 Non pool based results (Unequal carriers)

Figure 44(a) and Figure 44(b) shows the result for the case when the primary and secondary operators have two carriers and one carrier respectively. The DSA curve of the secondary operator shows an improvement in capacity until a point, after which it starts to decrease. This initial increase is due to the additional capacity provided by the primary operator. It is observed that there is a point on the DSA curve after which no further increase in the gain is obtained. This is because the algorithm allows the primary users to have priority. Therefore, beyond the saturation point no further users from the secondary system are allowed access to the primary system’s resources.

In Figure 44(a), the DSA gain for the secondary operator is shown to be 36 percent. This value can be obtained by substituting the horizontal values in Figure 44(a) into (17). It is also important to note that there is no deterioration in the performance of the primary system using this sharing approach.
The impact of the algorithm with increasing number of carrier on both systems is presented in subsequent figures. Figure 45(a) and Figure 45(b) show the result when the number of carriers on both systems is increased. In this case, the primary operator has 3 carriers and the secondary operator has 2 carriers. It can be observed that the performance of the secondary system shown in Figure 45(a) follows a similar trend as discussed earlier. The DSA gain in this case is observed to be 26 percent. It is obtained using equation (17). There is also no degradation in the performance of primary systems as shown in Figure 45(b).

![Figure 45 Performance curve for secondary operator (2 carriers) and primary operator (3 carriers)](image)

The same trend is equally observed with the number of carriers increased from three to four on the primary network and from two to three on the secondary. The results are shown in Figure 46(a) and Figure 46(b). Similarly, the gain is now observed to be about 9 percent for the secondary operator. The results also show no harmful degradation in the performance of the primary system due to this sharing approach.
It is worth noting, that the DSA gain decreases as the number of carriers on the network is increased, this is due to the fact that the traffic on the two networks is now increased. This is realistic considering the fact that more carriers are deployed in high traffic situations.

6.4.1 Non-pool based (Equal Carriers)

The result from the equal carrier case is shown below. It is interesting to note that the gain here is due to the fact that not all the cells belonging to the different operators are equally loaded and the difference in loading results in the gain. It is also observed that an increase in the variation causes increased DSA gain. Figure 47, Figure 48 and Figure 49 show the results for one, two and three carriers for the secondary operator. It is important to note that the result does not degrade the performance of primary system.
Chapter 6: Spectrum Efficiency Performance

Figure 47 Secondary performance curve (Non-pool) 1 carrier/operator

Figure 48 Secondary performance curve (Non-pool) 2 carriers/operator
6.4.2 Pool based (Uniform Traffic) results

This section presents the result for the pool based algorithm with different number of carriers in the spectrum pool. The case when queuing is applied is also considered. Similarly, the effect of uniform and non-uniform traffic on the spectrum sharing gain is discussed.

Figure 50(a) and Figure 50(b) shows the results of the pool based algorithm when both operators are sharing two carriers from the pool. The traffic correlation between the two operators is +1 indicating a worst case scenario. The DSA gain on network A and 2 is 9.2 percent and 9.1 percent respectively when no queuing is applied. According to both figures, it is shown that the DSA with 200ms queuing outperforms the other DSA schemes. With 100ms and 200ms queuing applied on network A, the DSA gain is observed to be 9.8 percent and 11.2 percent indicating on a marginal improvement in capacity. Similarly, the DSA gain on network B is 10.2 percent and 11.3 percent respectively for the same values of queuing times.
The values compare reasonably with the estimated theoretical trunking gain values. These theoretical values can be calculated according to [LEE95], assuming spatial information is ignored.

In Figure 51(a) and Figure 51(b), the queuing times is increased to see the overall effect on the DSA gain on both networks, it can be seen that the gains is increased when the queuing times is increased from milliseconds to values in second(s). According to Figures 51(a) and 51(b), it is also shown that the capacity improvement is greater at lower and medium load values compared to higher loads when congestion starts to occur. The DSA gain on network A is 12.3 percent and 13.9 percent respectively while for the same queuing times the spectrum sharing gain on network B is 12.1 percent and 13.7 percent. Table 7 summarises the results for the two carriers shared in a pool.
Table 7 provides a summary for the pool based results with two carriers.

<table>
<thead>
<tr>
<th>Delay (seconds)</th>
<th>Network A DSA Gain (%)</th>
<th>Network B DSA Gain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>9.20</td>
<td>9.10</td>
</tr>
<tr>
<td>0.1</td>
<td>9.80</td>
<td>10.20</td>
</tr>
<tr>
<td>0.2</td>
<td>11.20</td>
<td>11.30</td>
</tr>
<tr>
<td>1.0</td>
<td>12.30</td>
<td>12.10</td>
</tr>
<tr>
<td>2.0</td>
<td>13.90</td>
<td>13.70</td>
</tr>
</tbody>
</table>

Table 7 Results for two carriers

The results in Figure 52(a) and Figure 52(b) show the performance curve when the number of carriers in the pool is increased from two to four carriers and milliseconds delay is applied. It can be seen that spectrum sharing benefits both systems since DSA
spectrum efficiency performance scheme is better than the FSA scheme. The DSA gain on network A and B is approximately 6.6 percent and 6.2 percent respectively when there is no queuing applied. The DSA gain can be calculated by substituting the values on the horizontal axis into (17). The gain values represented capacity improvement achievable on the networks due to sharing. Furthermore it can be seen that there is a slight improvement in the performance measured on both systems when queuing is applied. In the case of network A, the 100ms and 200ms queuing improves the capacity slightly by 7.4 percent and 8.7 percent. Similarly for network B, the gain when the same queuing scheme is applied is 7.6 percent and 9.4 percent respectively. It is also seen that the higher the queuing times, the higher the measured value of the DSA gain. Hence the DSA scheme with 200ms performs best compared to the other schemes. It is also interesting to note that the effect of queuing is more beneficial at low and medium load.

Figure 52 Pool based performance curves for Network A and B (four carriers) milliseconds delay

According to Figure 53(a) and Figure 53(b), the queuing time when sharing four carriers in a pool is now increased from milliseconds to second(s) value. The gain on network A is observed to have increased to 9 percent and 10.3 percent respectively for queuing times of
one second and two seconds. The gain on network B is 10.2 percent and 11.7 percent for the same values of queuing delays.

![Graph A](image1)

![Graph B](image2)

**Figure 53 Pool based performance curves Network A and B (four carriers) second(s) delay**

Table 8 summarises the results for the four carriers shared in a pool.

<table>
<thead>
<tr>
<th>Delay (seconds)</th>
<th>Network A DSA Gain (%)</th>
<th>Network B DSA Gain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>6.60</td>
<td>6.20</td>
</tr>
<tr>
<td>0.1</td>
<td>7.40</td>
<td>7.60</td>
</tr>
<tr>
<td>0.2</td>
<td>8.70</td>
<td>9.40</td>
</tr>
<tr>
<td>1.0</td>
<td>9.00</td>
<td>10.20</td>
</tr>
<tr>
<td>2.0</td>
<td>10.30</td>
<td>11.70</td>
</tr>
</tbody>
</table>

**Table 8 Results for four carriers**
When the number of carriers in the pool is increased from four to six carriers, the performance of the curves is shown, it is interesting to note that although the number of carriers is increased, the spectrum sharing gain reduces compared to the previous case, and this is due to the fact that traffic per operator is increased as well. This is realistic considering the fact that the operators will normally deploy a higher number of carriers to support higher traffic situations. The measured gain on network A and B is shown to be 4.4 percent and 4.0 percent respectively with no queuing applied. It is also seen that the higher the queuing times, the higher is the measured value of the DSA gain on both networks. Hence the DSA scheme with 200ms performs best compared to all the other schemes. According to the Figure 54(a) and Figure 54(b), the gain on network A for 100ms and 200ms is 4.9 percent and 5.7 percent respectively, while on network B the gain is 4.6 percent and 5.9 percent for the same values of queuing times.

A. Network Operator A

B. Network Operator B

Figure 54 Pool based performance curves for Network A and B (six carriers) milliseconds delay

In order to determine the impact of the queuing time on the DSA gain, the queuing time for the service request is increased from values in milliseconds to seconds when both operators share six carriers. According to Figure 55(a) and Figure 55(b), it is observed
that there is a significant improvement in the capacity of both systems compared to the previous case shown. The capacity improvement on network A is shown to be 5.9 percent and 6.2 percent with 1 second and 2 seconds queuing times. The DSA gain on network B for the same value of queuing times is 6.4 percent and 6.8 percent. Overall, the results for the proposed pool based algorithm compares reasonably with the theoretical results in [LEE95].

![Figure 55 Pool based performance curves for Network A and B (six carriers) second (s) delay](image)

<table>
<thead>
<tr>
<th>Delay (seconds)</th>
<th>Network A DSA Gain (%)</th>
<th>Network B DSA Gain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>4.40</td>
<td>4.00</td>
</tr>
<tr>
<td>0.1</td>
<td>4.90</td>
<td>4.60</td>
</tr>
<tr>
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<td>5.70</td>
<td>5.90</td>
</tr>
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<td>5.90</td>
<td>6.40</td>
</tr>
<tr>
<td>2.0</td>
<td>6.20</td>
<td>6.80</td>
</tr>
</tbody>
</table>

Table 9 Results for six carriers
6.4.3 Pool based (Non-uniform traffic) results

In the non uniform traffic case, three non-dynamic hotspot cells were included in the coverage area of both networks to reflect a situation where there is unusually high connection request. This is typical in areas such as airport, train stations or stadium. Only the static hotspots are considered, as the hotspot is assumed to be non-dynamic over the observed interval. The high call volume in the hotspot cells is modelled as a percentage increase in call volume compared to the neighbouring cells.

Figure 56(a) and Figure 56(b) shows the results when three cells each with a five percent increase in connection request is placed within the simulation area. The results show that the DSA schemes generally perform better than the FSA scheme. As shown before, the higher the queuing delays, the better the performance at low and medium load conditions. The DSA scheme with two seconds delay performs best compared to the other FSA scheme. It is also interesting to note that initially queuing delays provide some benefit to the network, until congestion starts to set in, beyond this point, all the DSA schemes exhibit similar performance.

![Graph A](image1.png)  ![Graph B](image2.png)

A. Network operator A  B. Network operator B

Figure 56 Pool based performance with six carriers (5% hotspot)
In order to determine the effect of increasing the call volume in the hotspot cells on the DSA performance, the connection requests in the three hotspots cells was increased from five percent to ten percent. According to Figure 57(a) and Figure 57(b), it is interesting to note that compared to the previous case when the connection requests in the hotspots was five percent, the DSA performance for ten percent converges quicker to the FSA curve. Similarly, the gain at ninety eight percent satisfaction ratio is also significantly lower compared to the previous case discussed.

**Figure 57 Pool based performance with six carriers (10% hotspot)**

**Impact of correlation on DSA gain**

It is important to note that the worst scenario occurs when there is a correlation of +1 in the traffic profile of the two operators. For a realistic value of correlation between +0.8 to +1, it is seen that the DSA performance is improved when the correlation is decreased. The simulation was conducted for the case of six carriers in the spectrum pool. This is shown in Figure 58. The correlation of +0.8 gives the best performance at 98 percent Quality of Service (QoS).
Figure 58 DSA gain performance at different correlation values

Table 10 summarises the result for the impact of correlation on the DSA gains. The results show that as the correlation increases the DSA gain decreases.

<table>
<thead>
<tr>
<th>Traffic correlation</th>
<th>Network DSA Gain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.80</td>
<td>7.20</td>
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<tr>
<td>0.85</td>
<td>6.50</td>
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<tr>
<td>0.90</td>
<td>5.80</td>
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<tr>
<td>0.95</td>
<td>5.10</td>
</tr>
<tr>
<td>1.00</td>
<td>4.20</td>
</tr>
</tbody>
</table>

Table 10 Summary of result for different correlation value
Chapter 7. Conclusions and Future Work

Based on the research work that has been carried out in this thesis, this chapter provides a summary of the main outcomes, and further outlines the path for future development work in this research area.

7.1 Conclusions

This thesis has investigated the problem of spectrum sharing between two wireless operators. The limitations of the current spectrum management method have been discussed. The different prospects and consequences of the cooperative and coordinated spectrum sharing between two mobile wireless operators have been presented. The problem of spectrum sharing between two cellular operators has been investigated using the Universal Mobile Telecommunication Service (UMTS) network as a case study. Currently, two UMTS operators do not share the spectrum, due to a coincidence in traffic peak during the peak hour periods. However, despite the similarity in peak hour periods between the two operators, the loading during the peak hour could be different. This difference in the peak hour loading could be exploited for the purpose of sharing as demonstrated in the specific traffic curves previously discussed. The thesis further exploits the use of the intelligence embedded in the network, together with new additional spectrum management information to achieve improvement in spectrum usage.

Furthermore, a holistic approach to address the problem of spectrum sharing using a combination of Dynamic Spectrum Allocation (DSA) and inter operator spectrum access control (I-SAC) has been proposed. The advantage of the proposed scheme over the previously studied scheme is that, in addition to the Radio Access Network (RAN) based
allocation, it is also able to adapt to the fast changes in spectrum demands on the network.

This fast adaptation is due to the incorporation of the inter-operator SAC mechanism. The proposed scheme outperforms the pure DSA scheme proposed in [LEAV04b], under negatively correlated traffic situations by up to four percent.

Furthermore, in highly correlated traffic situations the non-pool and pooled based algorithm have been proposed. The results show that in the proposed non-pool based algorithm, with the secondary operator having one carrier and the primary operator holding two carriers, spectrum sharing gains of up to thirty six percent can be achieved on the secondary system. The results also show that the performance of the non-pool algorithm approaches Fixed Spectrum Allocation (FSA) at high load when congestion occurs, and therefore no further sharing can take place. This spectrum sharing approach does not degrade the primary system. Furthermore, as the traffic is increased to match the increase in bandwidth, the spectrum sharing gain also reduces accordingly, due to the increased traffic.

Similarly, when the resources are pooled together, that is, there are no primary or secondary operators, the spectrum sharing gain achievable approaches the theoretical trunking gain with no spatial information included in the traffic model. In the case of two carriers (5MHz/carrier) being shared in a pool between the two operators, spectrum sharing gains of up to ten percent can be achieved on both networks. The spectrum sharing gain is as a result of the statistical multiplexing of connection requests due to the pool based algorithm. The results show that when both operators shared six carriers (30MHz) in a pool, the spectrum sharing gain is about four percent for the worst case scenario. The worst case scenario occurs when the traffic correlation on both the two networks is maximum i.e (+1). Results have also revealed that as the traffic correlation reduces the capacity gain for the two operators’ increases. This is due to the fact that a
higher degree of opportunity exists between the two networks to support each other, for the purpose of spectrum sharing. For a realistic value of traffic correlation expected between the two UMTS networks, i.e. +1 to 0.8, the spectrum sharing gain varies between four percent and seven percent respectively.

Furthermore, the impact of queuing the connection requests has been investigated. The results show that for tolerable values of connection delays between one and two seconds, additional spectrum sharing gains up to four percent can be achieved on both networks. Similarly for the deployment of the spectrum sharing algorithm, a significantly high gain is obtained when the operators have unequal demands in the cells sharing the spectrum. As shown in the case when hotspots are included in the analysis, the achieved gain reduces significantly by up to two percent on both networks, since both operators have simultaneously high traffic.

The cost implication in terms of the signalling load on the network has also been investigated. Additional overhead occurs due to spectrum sharing at RAN level. The interfaces and type of information required has been specified in this work. It is also worth noting that the total call setup messages are also increased due to this sharing approach. The penalty associated with signalling overhead can be minimised by re-using the resource management entity in this case the Radio Network Controller (RNC).

A proposed architecture to achieve inter-operator spectrum sharing has also been presented. The proposed architecture incorporates a spectrum management node called the DSA node. The node will handle the triggers at intervals. It will also be responsible for the computation of traffic load estimates as well as the initiation of inter-operator SAC process. This architecture allows minimal disruption to the currently existing infrastructure.
In summary, cooperative spectrum sharing between operators can achieve significant spectrum efficiency gains up to thirty six percent (non-pool scenario) and ten percent (pool scenario) with two carriers in a pool. The proposed algorithms could be recommended to operators to further improve their capacity, while re-using some aspects of the network in order to minimize the signalling overhead and maximise the spectrum efficiency gains.

7.2 Future Work

In this thesis we have considered several aspects of spectrum sharing as it relates to a coordinated approach between two similar operators, using the UMTS network as a case study. We have primarily considered two networks. As a basis for future work, it will be necessary to consider, how spectrum sharing may be implemented between more than two networks in the packet based domain. Regarding this, it will be necessary to develop and characterise an aggregate source traffic model to be used. Different packet based services such as; video streaming, Voice over Internet Protocol (VoIP), Hypertext transfer protocol (HTTP) web browsing, File Transfer Protocol (FTP) exhibit different traffic behaviours from a system level perspective. Hence, determining how these behaviours affect the overall spectral efficiency will be important for the investigation.

Furthermore, the notion of a transmission opportunity and the type of services that can reuse such opportunity will differ from one type of traffic to the other. Therefore, it is important to fully characterise a spectrum opportunity based on the type of service(s) involved, in order to establish, if further packet multiplexing can achieve significant efficiency gains at packet level. Some aspects of power control and interference management will also be important in the packet domain. It will be necessary to investigate how transmission success or failure at the MAC layer affects the overall
system capacity in terms of the throughput. Interference is likely to be higher when more than two operators are involved, therefore it will be interesting to consider interference coordination and management when more than two operators share the spectrum.

It will also be necessary to investigate additional allocation algorithms that will be more suitable for packet traffic data. Furthermore it would be useful to consider the practical implementation of the proposed algorithm and issues such as fairness and stability on the network. A theoretical and analytical insight into packet based modelling techniques will also be worth researching. Signalling aspect and delays for packet connections will also need to be revisited to see how they impact on the overall spectral efficiency gain.

Regarding the simulation modelling issues and the extension of the currently available software, the current multi-operator simulator software could be further enhanced to incorporate additional traffic and service types. This will facilitate the study of DSA in packet based systems.
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