RENDEZVOUS AND COORDINATION IN OFDM-BASED DYNAMIC SPECTRUM ACCESS NETWORKS

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DECLARATION

I hereby declare that the work described in this thesis is, except where otherwise stated, entirely my own work and has not been submitted as an exercise for a degree at this or any other university.

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Paul Sutton

September 25, 2008.

SUMMARY

This dissertation shows that intentionally embedded *cyclostationary signatures* provide a robust and flexible technique for overcoming the challenge of network rendezvous and coordination in emerging Dynamic Spectrum Access Networks (DySPANs).

Conventional wireless systems operate within fixed frequency ranges and rely upon exclusively-assigned licenses for interference avoidance. In contrast, DySPANs dynamically reconfigure their parameters of operation in order to exploit unused spectrum resources while using an awareness of their environment to avoid the creation of harmful interference. In this way, DySPANs achieve high levels of spectrum use efficiency and offer a solution to the 'spectrum scarcity' issue being faced by telecommunications regulators around the world.

The benefits of DySPAN systems arise due to their high levels of flexibility. However, with this increased flexibility comes the challenge of network rendezvous and coordination. The fixed operating parameters of conventional wireless systems facilitate the establishment and maintenance of communication links between network devices. In contrast, DySPAN systems use operating parameters which are no longer fixed, but are dynamically adapted in response to the operating environment. Under these conditions, network rendezvous and coordination can no longer be achieved using conventional techniques and new approaches must be developed.

This dissertation explores the use of cyclostationary signal processing as an enabling tool for rendezvous in DySPAN systems. It has been shown that this signal processing approach can leverage the inherent cyclic features of communications signals to accomplish a range of critical tasks including signal detection, classification and synchronization. However, this dissertation argues that a number of significant drawbacks can be associated with the use of these inherent signal features to achieve DySPAN rendezvous. Instead, the dissertation proposes the use of intentionally embedded cyclic features and shows that these artificial *cyclostationary signatures* can be employed to overcome the drawbacks involved in the detection of inherent cyclic features and provide an effective, practical solution to the challenge of DySPAN rendezvous and coordination.

The dissertation first outlines emerging DySPAN systems, examines the regulatory and technical advances which are making these systems possible and highlights the challenge of DySPAN rendezvous and coordination. The benefits of cyclostationary signal analysis are examined in the context of these emerging systems and the use of Orthogonal Frequency Division Multiplexing (OFDM) subcarrier mapping to generate artificial cyclic features is proposed. Simulations are used to explore the use of these cyclostationary signatures and results are used to prove them an effective tool for facilitating signal detection, network identification and frequency acquisition. The practical utility of embedded cyclic features is highlighted through the implementation of a prototype DySPAN transceiver. Using this prototype, experiments are carried out to verify simulation results and to show that cyclostationary signatures provide a robust, flexible mechanism for achieving DySPAN rendezvous and coordination.

In developing cyclostationary signatures as a powerful tool for overcoming the challenge of DySPAN rendezvous and coordination, this dissertation represents a significant step towards the realization of practical Dynamic Spectrum Access Networks (DySPANs) and creates a firm foundation upon which to advance the future development of highly reconfigurable, robust wireless communication systems.

ACKNOWLEDGEMENTS

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1. INTRODUCTION

1.1 Overview

This dissertation shows that intentionally embedded cyclic features or *cyclostationary signatures* are an effective tool for overcoming the challenge of rendezvous and coordination in emerging multi-carrier Dynamic Spectrum Access Networks (DySPANs).

At a time of rapidly increasing demand for innovative new wireless systems and services worldwide, DySPANs herald a paradigm shift in the way in which these systems exploit the radio-frequency spectrum. Conventional wireless systems operate within fixed frequency ranges and rely upon exclusively-assigned licenses for interference avoidance. In contrast, DySPANs dynamically reconfigure their parameters of operation in order to exploit unused spectrum resources while using an awareness of their environment to avoid the creation of harmful interference. In this way, DySPANs achieve new levels of spectrum use efficiency and offer a solution to the 'spectrum scarcity' issue being faced by telecommunications regulators around the world.

However, before the concept of dynamic spectrum access can become a reality, many challenges must first be overcome. In terms of spectrum regulation policy, reforms are needed to move away from the traditional *command-and-control* approach under which DySPAN systems cannot exist, and toward more flexible policies which better reflect the dynamic nature of emerging wireless technologies. While spectrum policy reform is essential in order to support innovative dynamic spectrum systems, these reforms are also motivated by the emergence of advanced technologies which make those systems feasible. As the potential benefits of DySPAN technologies become recognized, spectrum regulators become more willing to accommodate them.

Just as the potential benefits of DySPAN technologies are considerable, so too are the technical challenges presented by such systems. Key among these is the challenge of DySPAN rendezvous and coordination. The fixed operating parameters of conventional wireless systems facilitate the establishment and maintenance of communication links between network devices. In a DySPAN system however, these operating parameters are no longer fixed, but are dynamically adapted in response to the operating environment. Under these conditions, the straightforward rendezvous mechanisms of conventional networks cannot be employed and new techniques must be developed.

This dissertation explores the role which can be played by cyclostationary signal analysis in overcoming the challenge of DySPAN rendezvous and coordination. This signal processing approach exploits the innate periodicities which underlie many natural and man-made signals. In the case of telecommunications signals, it has been shown that cyclostationary signal analysis can be employed to accomplish a range of key tasks including signal detection, classification and synchronization. The approach appears to hold much potential as an enabling tool for rendezvous in DySPAN systems. However, there are a number of recognized drawbacks associated with the cyclostationary analysis of inherent cyclic signal features. Therefore, this dissertation proposes the use of intentionally embedded *cyclostationary signatures*. It is shown that these artificial cyclic features permit the challenge of DySPAN rendezvous and coordination to be addressed while overcoming the drawbacks typically associated with cyclostationary signal analysis.

1.2 Towards Dynamic Spectrum Access

The chaotic early days of radio broadcasting in the US in the 1920s left a legacy of tight 'command-and-control' regulation which has shaped spectrum policy to the present day. While the inefficiencies of such a rigid system were recognized as early as the 1950s, it is only in the past decade that regulators have begun to seriously consider a number of alternative approaches. Since the early arguments of Herzel and Coase [7, 8], the case for greater flexibility in spectrum management has been made by a range of commentators including economists, lawyers and engineers. These commentators argue that rigid spectrum policies provide protection for incumbent spectrum licensees and create a barrier for new entrants, thus hindering competition and stifling innovation. Within the incumbent licensees themselves, innovation is further stunted by the 'mother-may-I' phenomenon, whereby any changes in spectrum usage must be assessed and approved by the regulator. These inflexibilities prevent spectrum resources from being devoted to their most productive uses and have led to the situation of apparent spectrum scarcity seen today where new systems and services cannot gain access to spectrum yet resources which are assigned to incumbent licensees are often severely underutilized.

The past decade has seen rapid increases in the demand for new wireless systems and services. As demand has increased, so too has the value placed on exclusive-use spectrum licenses, without which these systems cannot be deployed. Coupled with this has been the increasing economic value of spectrum usage, estimated at over £40bn in the UK in 2006 alone. As the importance of radio-frequency spectrum and the systems which use it have increased, regulators have begun to recognise the inefficiencies of the rigid command-and-control model and have started to examine alternative approaches which could support more productive use of spectrum.

In addition to these economic drivers, alternative approaches to spectrum management have been motivated by technological advances. Disruptive technologies such as software-defined radio (SDR) and ultra-wide band (UWB) have forced policy-makers to re-examine the assumptions about wireless systems which underlie current regulations. While the radio broadcast technologies of the early 20th century depended upon strict regulation of spectrum access to prevent interference, advances in wireless technologies have made it possible for heterogeneous systems to coexist in common frequency bands while autonomously avoiding the creation of harmful interference.

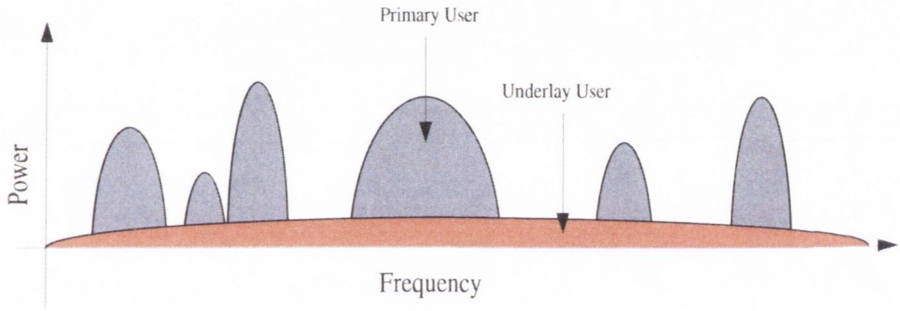


Fig. 1.1: Underlay spectrum access.

Co-channel operation can be achieved by transmitting a very low power signal across a very wide band of frequencies. In this way, the signal power level remains below the noise floor experienced by other wireless systems and so does not cause harmful interference. This is the approach used in some forms of UWB, an advanced form of which can be employed in DySPAN systems. This form of coexistence is termed *underlay* spectrum use and is illustrated in Fig. 1.1.

In contrast, SDR technology can be used to permit a wireless system to occupy spectrum resources which are underutilized at a given time and place. SDR systems allow operating parameters of a radio to be reconfigured using software and so provide a very high level of flexibility. This flexibility can be used to occupy idle spectrum resources. These spectrum *white spaces* are detected by devices within the network and temporarily used to form communication links. While using those idle frequency bands, the SDR system must perform monitoring to ensure that they remain idle. Upon detection of another, higher priority system, the spectrum resources are immediately

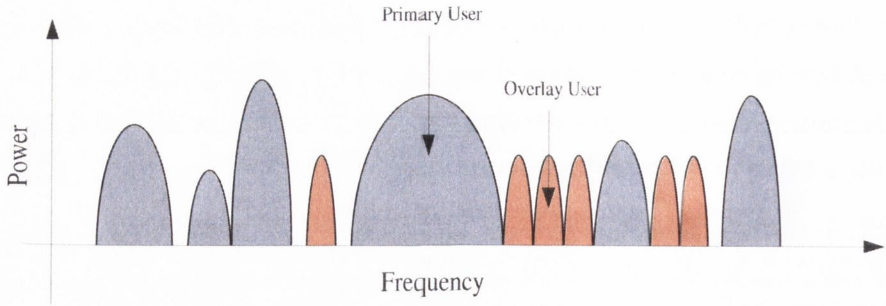


Fig. 1.2: Overlay spectrum access.

vacated in order to avoid the creation of harmful interference. This form of coexistence is termed *overlay* access and is illustrated in Fig. 1.2.

Just as these technologies motivate a change in spectrum policy, the introduction of more flexible policies support those technologies and stimulate new innovation. In this way, neither technological advances nor spectrum policy reform alone can ensure the efficient and productive use of radio-frequency spectrum. Rather, a combined approach in which policy and technology both inform and drive the other can guarantee that the maximum benefit is derived.

Enabled by advances in both technology and spectrum policy, Dynamic Spectrum Access Networks (DySPANs) are systems of wireless devices which coordinate to form networks using idle spectrum resources. As the availability of these idle resources or spectrum *white spaces* may vary over time, location and frequency, DySPAN systems must be capable of developing an awareness of the radio environment, identifying those resources which are unused and utilizing them while avoiding the creation of harmful interference for other spectrum users. In this way, DySPANs can achieve very high levels of spectrum use efficiency while protecting incumbent users. By reducing the entry barriers that currently exist for new systems and services, DySPANs can also foster innovation and encourage competition in spectrum use.

SDR introduces a new level of reconfigurability and flexibility to wireless networks by allowing the operating parameters of a radio to be controlled using software. Generic hardware components are used to support a wide range of communications signals and standards which can be easily reprogrammed in order to change the functionality of the device. This benefit is highly attractive to equipment suppliers who can develop more efficient value-chains. Using a small number of hardware components, a wide range of wireless devices can be manufactured, simply using software reprogramming. However, as well as supporting multiple existing standards upon a generic platform, SDR technology allows new, highly flexible standards to be developed in which waveforms and protocols can be reconfigured at run-time and tailored to the operating environment. It is this flexibility which makes the concept of overlay dynamic spectrum access possible.

A transmission scheme underlying many of these new, flexible SDR-based systems is Orthogonal Frequency Division Multiplexing (OFDM). OFDM is a multicarrier transmission scheme in which a high-rate data stream is converted to a number of lower-rate, parallel streams which are transmitted using multiple closely-spaced carriers. Using this approach, OFDM systems provide robustness to inter-symbol interference (ISI) while greatly simplifying transmit and receive architectures through the availability of efficient digital implementations. Due to these advantages, OFDM already forms the core of many of the existing wireless standards in use today including Institute of Electrical and Electronics Engineers (IEEE) 802.11 [9], IEEE 802.16 [10], Digital Audio Broadcasting (DAB) [11] and Terrestrial Digital Video Broadcasting (DVB-T) [12]. However, OFDM also provides a number of unique advantages in the context of emerging DySPAN systems.

An OFDM signal is generated in the frequency domain by individually modulating a number of parallel subcarriers. Upon a highly flexible SDR-based platform, these subcarriers can be individually manipulated and, in this way, the spectral shape of the transmitted signal can be dynamically altered. In the context of DySPAN systems, this permits an OFDM-based waveform to be tailored to the idle spectrum resources being utilized. Further advantages for dynamic spectrum access arise due to the use of a Fourier transform in OFDM receivers. These are discussed in Chapter 5.

While emerging technologies such as SDR and flexible OFDM-based waveforms are key in enabling DySPAN systems, there remain significant technical challenges to be overcome before these systems can be realised. This dissertation addresses one such challenge: DySPAN rendezvous and coordination.

The issue of rendezvous and coordination in DySPAN systems arises due to the exploitation of unused spectrum resources. The availability of these spectrum white spaces can vary over time and between geographic locations. As a result, DySPAN devices may not have á priori knowledge of the operating frequencies being used by the network. Furthermore, as the availability of white space spectrum can depend upon the spectrum occupancy of other spectrum users, those operating frequencies may change unpredictably. Within conventional wireless networks, rendezvous mechanisms typically rely upon the use of operating frequencies which are fixed and known in advance or which can be determined using fixed-frequency control channels. Under dynamic spectrum access, operating frequencies are no longer fixed and static control channels may not be supported. Therefore, conventional rendezvous and coordination techniques cannot be employed. Instead, novel mechanisms are required to support network discovery, link establishment and link maintenance.

1.3 Enabling DySPANs: Cyclostationary Signatures

This dissertation presents a novel solution to the challenge of rendezvous and coordination in OFDM-based DySPAN systems using intentionally embedded *cyclostationary signatures*.

Many of the communications signals used today exhibit underlying periodicities which arise due to the processes used in their generation. It has been shown that these latent periodicities or *cyclic features* can be discovered using cyclostationary signal analysis and exploited to achieve a number of critical tasks including signal detection, classification and synchronization. One possible solution to the issue of DySPAN rendezvous and coordination would involve the exploitation of these inherent cyclic signal features. However this approach suffers from a number of drawbacks including the requirement for long signal observation times and considerable computational complexity.

Therefore, instead of using inherent cyclic signal features, this dissertation proposes the use of intentionally embedded, artificial cyclic features or *cyclostationary signatures*. These cyclostationary signatures can be generated in OFDM-based waveforms using low-complexity techniques and, as they are continuously present in the data-carrying signal, can be viewed as a form of signal watermark. By detecting, analysing and exploiting embedded signatures, DySPAN devices can perform network discovery and establish communication links with limited prior knowledge about the operating parameters being used within the network. In the case where these communication links are unexpectedly broken, embedded signatures permit devices to re-establish those links and thus maintain communications. Furthermore, by using intentionally embedded signatures rather than inherent signal features, many of the drawbacks typically associated with cyclostationary signal analysis can be avoided.

1.4 Key Contributions

In addressing the issue of rendezvous and coordination in emerging DySPAN systems, the dissertation makes the following contributions:

Emerging DySPAN Systems and the challenge of Rendezvous and Coordination

The dissertation provides an overview of emerging dynamic spectrum access technologies and examines the regulatory and technical advances which are making these technologies possible. In the area of spectrum policy the issue of regulatory reform is addressed and the key arguments in its favour are outlined. Chapter 3 highlights the issue of rendezvous and coordination in these emerging DySPAN systems. The impact of increasing system flexibility on rendezvous requirements is illustrated using examples of wireless systems both currently deployed and in development. It is shown that as communication systems become more reconfigurable and adaptive, the importance of rendezvous and coordination for network formation and maintenance is increased. This motivates the development of novel rendezvous mechanisms tailored to the unique requirements of DySPAN systems.

Cyclostationary Signatures: Enabling DySPAN Systems

Cyclostationary signal analysis is presented as a signal processing technique with significant advantages in the context of DySPAN rendezvous. The main disadvantages typically associated with the use of this approach are outlined and intentionally embedded cyclic features or *cyclostationary signatures* are presented as a powerful and flexible tool for achieving rendezvous and coordination in multi-carrier DySPAN systems while overcoming these drawbacks. Signal processing architectures for the generation, detection and analysis of cyclostationary signatures are developed and computer simulations are used to show that these architectures provide excellent performance in the key areas of signal detection, network identification and frequency acquisition.

Transceiver Prototype Development

A highly reconfigurable software radio based platform for DySPAN experimentation is presented in Chapter 7. The dissertation describes the implementation of a prototype OFDM transceiver upon this platform which uses embedded cyclostationary signatures to achieve rendezvous and coordination. The key design decisions taken in implementing the transceiver are examined and a number of design variations are discussed.

Experimental Transceiver Analysis

Using a prototype OFDM transceiver, the dissertation describes a range of experiments used to examine the performance of cyclostationary features when embedded in real-world signals and leveraged to achieve signal detection, network identification and frequency acquisition. The results of these experiments are presented and used to illustrate the value of embedded cyclic features when employed to overcome the challenge of DySPAN rendezvous and coordination.

1.5 Chapter Outline

The dissertation is organized as follows. Chapter 2 examines spectrum regulation and the policy reforms currently being considered by regulators to facilitate emerging wireless technologies and promote spectrum use efficiency. Chapter 3 looks at emerging Dynamic Spectrum Access Networks (DySPANs) and discusses the unique challenge of rendezvous and coordination which arises within these systems. Chapter 4 presents cyclostationary signal analysis as a powerful signal processing tool for enabling DySPAN rendezvous and coordination. The key advantages of the approach are outlined and a number of critical limitations are identified. The novel use of embedded cyclostationary signatures for rendezvous and coordination in OFDM-based DySPANs is proposed in Chapter 5. The advantages of this approach are discussed and algorithms for signature generation and detection are outlined. Chapter 6 presents the results of computer simulations assessing the performance of these cyclostationary signatures when employed in DySPAN systems. The implementation of a prototype transceiver using embedded cyclostationary signatures is examined in Chapter 7 and experimental results obtained using this implementation are presented in Chapter 8. Finally, Chapter 9 summarizes conclusions from this work and suggests areas for future investigation.

1.6 Publications Record

The following publications relate directly to this dissertation:

- *Cyclostationary Signatures in Practical Cognitive Radio Applications*, Sutton, P.D., Nolan, K.E. and Doyle, L.E. , IEEE Journal on Selected Areas in Communications special issue - Cognitive Radio:Theory and Applications, Vol. 26, No. 1, pp.13-24, January 2008.

- *Cyclostationary Signature Detection in Multipath Rayleigh Fading Environments*, Sutton, P.D., Lotze, J., Nolan, K.E., Doyle, L.E., In Proceedings of 2nd International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM), August 1-3rd, 2007.

- *Cyclostationary Signatures for Rendezvous in OFDM-based Dynamic Spectrum Access Networks*, Sutton, P.D., Nolan, K.E., Doyle, L.E., In Proceedings of the 2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN), April 17-20, 2007.

- *A Platform for Dynamic Spectrum Experimentation*, Doyle, L.E., Sutton, P.D. et al., In Proceedings of the First International Workshop on Technology and Policy for Accessing Spectrum (TAPAS), Boston, August 1-5 2006.

2. SPECTRUM MANAGEMENT

2.1 Introduction

Worldwide demand for wireless systems and services has grown rapidly over the past 20 years and is expected to continue to do so for the foreseeable future. Driven to a large extent by the popularity of mobile telephony, the economic importance of these systems and services has grown accordingly. As Figure 2.1 illustrates, the mobile telephony market in 2005 in the US alone consisted of over 200 million subscribers and created revenues of over $115bn [1].

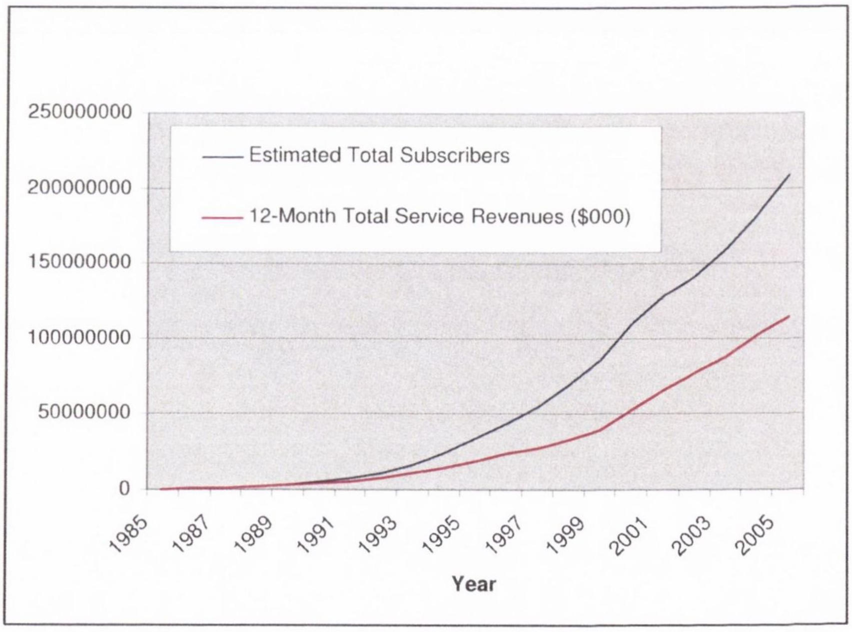


Fig. 2.1: Growth of the US Mobile Telephony Market 1985-2005. Source:[1]

The 'sine qua non' [13] of any wireless system is the radio spectrum - the set of frequencies used to transmit information from one location to another. Thus, as demand for systems and services has grown, so too has demand for access to suitable radio spectrum. While spectrum can be viewed as an infinite resource, there are limits to the number of services which may be simultaneously supported by a given band of frequencies. Therefore, as competition increases for access to a given set of frequencies, the value associated with that spectrum increases rapidly. This was seen most clearly in the case of the first auctions used for the assignment of spectrum licences in the UK in 2000. For 5 Third Generation mobile telephone licenses, covering 155 MHz of spectrum, a total price of £22.5bn was paid [14]. Although a direct economic benefit may be realised through the auctioning of valuable spectrum licenses in this way, even more significant benefits may be generated by the services provided through use of those licenses. One estimation places the total value of spectrum use at over £40bn in the UK in 2006 alone [3]. This constitutes a rise of over 50% on similar estimates for 2002 [2], as illustrated in Figure 2.2. Similarly, in Ireland, spectrum use accounted for 1.4% of total gross domestic product (GDP) in 2003, an increase of 25% on the previous year alone.

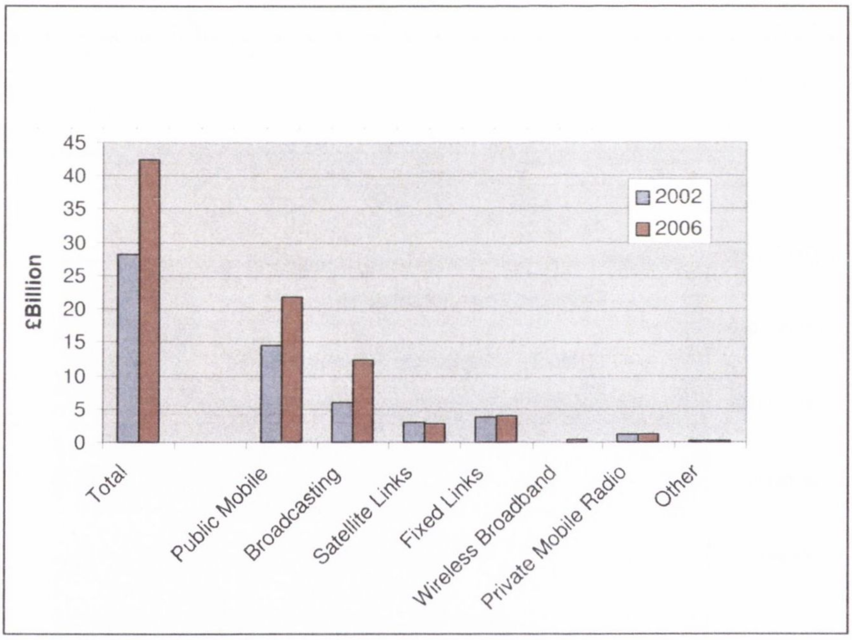


Fig. 2.2: Economic Impact of the Use of Radio Spectrum in the UK. Source:[2, 3]

As the value associated with radio spectrum has increased, more focus has been placed upon deriving the maximum value that society can gain from the use of that spectrum. This, in fact, is the key purpose of spectrum management.

Spectrum management is the process of organising how spectrum is used and by whom. By allowing as many efficient spectrum users as possible while ensuring that the interference between these users remains manageable, spectrum management can ensure that the maximum social and economic benefits are derived from spectrum use.

The purpose of this chapter is to examine the importance of spectrum management policy and to outline the relationship that exists between current and proposed management regimes and emerging Dynamic Spectrum Access Network (DySPAN) technologies. The key drawbacks of current spectrum management regimes are analysed and the policy reforms proposed to overcome these drawbacks are examined and compared. I show that these spectrum policy reforms offer significant opportunities for dynamic spectrum access technology and illustrate the key benefits that can be derived from development and deployment of these technologies.

This chapter is structured as follows. Section 2.2 examines the dominant spectrum management regimes used today. A brief historical perspective on spectrum regulation is provided in Section 2.2.1. This history illustrates how current spectrum policies have evolved and shows how some of the drawbacks associated with these policies have come about. A number of these drawbacks are examined in Section 2.2.2. Section 2.3 outlines new spectrum management regimes currently being considered by regulators and compares these regimes by analysing the spectrum policy reform debate which has spanned the past 50 years. Finally, Section 2.4 discusses the opportunities presented by new spectrum management regimes for DySPAN technology and concludes.

2.2 Spectrum Management Today

The dominant form of spectrum management in use today is commonly termed *command-and-control*. Under this approach, a regulator tightly restricts access to spectrum, assigning time-limited exclusive licenses to use specific ranges of frequencies, or frequency bands, over given geographical areas. These licenses strictly define the services to be delivered using the band and the technologies permitted as well as who provides and perhaps uses the services.

Although national regulatory bodies hold responsibility for spectrum management within specific countries, they may do so within broad guidelines laid down by the International Telecommunication Union (ITU) and other international bodies. The ITU is a specialised agency of the United Nations (UN) which broadly allocates spectrum between 9 kHz and 275 GHz for particular uses. In this way, a degree of harmonization between individual countries is achieved. Within these broad guidelines, national regulatory authorities are responsible for making more specific spectrum allocations and creating licenses to be assigned to particular parties. In Ireland this authority is the Commission for Communications Regulation (ComReg) while in the US and UK the Federal Communications Commission (FCC) and the Office of Communications (Ofcom) are responsible for spectrum management respectively.

The command-and-control regime of spectrum management permits national regulators to tightly control and monitor interference which can arise between services in neighbouring frequency bands and services in the same bands but in different geographical locations. By modelling interactions between wireless systems, the regulator can define license conditions such as transmission power levels and guard band sizes to minimize the risk of harmful interference. However, although this approach effectively mitigates the issue of interference, it involves a number of serious disadvantages. This section examines a number of these drawbacks and illustrates the motivation for spectrum policy reform. First, a brief history of spectrum regulation is provided in order to outline the background behind the command-and-control approach to spectrum management and the issues associated with it.

2.2.1 A Brief History of Telecommunications Regulation

In the U.S., regulation of radio spectrum access began in earnest following the 1912 Titanic disaster in which more than a thousand people lost their lives. Confusion over distress calls and possible interference from amateur radio operators were thought to have hampered rescue efforts. The Radio Act of 1912 provided for licensing of all transmitting apparatus for interstate or foreign commerce by the Secretary of Commerce and for licensing of all station operators [15]. However, with the emergence of radio broadcasting in the early 1920s, competition for the airwaves resulted in extensive interference on broadcasting channels. The Radio Act of 1912 proved inadequate as license restrictions could not be enforced and the Federal Radio Commission (FRC) was established with the Radio Act of 1927. The FRC (and later the FCC) was entrusted with responsibility for managing the radio spectrum and granted the power to classify radio stations, prescribe the nature of the service, assign bands of frequencies or wavelengths, determine station power and location and regulate apparatus to be used [16]. In Ireland, these responsibilities were retained by the Minister for Posts and Telegraphs in the Wireless Telegraphy Act of 1926 [17].

In the early days of spectrum regulation, a form of trusteeship model was typically employed where licensees were seen to be using a natural public resource to provide a public service. Under this model, regulators were tasked with managing the spectrum 'in the public interest'. With a poorly defined assignment policy, licences were assigned in a relatively ad-hoc manner. License applications were made for a particular purpose, frequency and place. Public notices permitted other applicants to come forward and in the event where more than one applicant applied, a comparative hearing was held to determine which applicant was 'more suitable' to discharge the public interest obligations of license-holding. These 'beauty contests' were often deemed to be politically influenced.

In the US in the 1980's the shortfallings of the comparative hearing process became apparent with the emergence of a large number of applicants for cellular telephone service licenses. Traditional processes would have greatly delayed the assignment of licenses and so a system of lotteries were adopted. Through these lotteries, licenses were rapidly assigned at no cost to applicants meeting a number of minimum qualifications. Many of these lucky applicants promptly 'flipped' their licences for large profits.

Recognizing the value now associated with spectrum licences, US congress in 1993 authorized the FCC to assign licenses through competitive bidding. Since then, 82 auctions have been held, yielding significant revenues for the Federal Government. In September 2006 alone, $13.7 billion was paid for 90 MHz of spectrum in the 1.7 and 2.1 GHz bands [18]. The use of spectrum auctions in the UK began in 2000 with the 3G license auctions in which £22.5bn was paid for licenses covering a total of 155 MHz of spectrum.

On 24th of January 2008, bidding will begin for the largest amount of mobile, broadband UHF spectrum ever auctioned in the US. The licenses in this 700 MHz TV band have a combined reserve of $10 billion but are expected to raise much more.

2.2.2 Critiques of Current Spectrum Policy

The *command-and-control* approach to spectrum regulation has proved highly effective at mitigating the creation of harmful interference. However, in tightly regulating who uses the spectrum and for what purpose, regulators have created the illusion of spectrum scarcity through serious inefficiencies and have severely stunted technological innovation and competition. This section examines a number of these problems and illustrates how they have arisen.

Inefficient Spectrum Use

As early as the 1950s, the inefficiencies of the 'wise man theory' of spectrum assignment whereby the regulator assigned spectrum on the basis of 'public interest' were recognised [8]. Rather than relying upon the wisdom of the regulator to allocate spectrum resources, Coase argued that an efficient market was the most effective tool for the allocation and assignment of scarce resources to their highest and best uses.

In illustrating the inefficiency of central planning for the allocation of scarce resources, Faulhaber and Farber [19] cite the example of GOSPLAN, the central planning agency in the former Soviet Union. GOSPLAN was responsible for carefully planning each sector of the Soviet economy. Each industry and factory was allocated a quota of scarce inputs and ordered to produce a specific output. Quotas and shipments were largely influenced by intense lobbying and political influences, resulting in 'woeful inefficiencies and wasted resources'. By managing spectrum in a centralized manner, regulators have experienced similar problems. Spectrum assignment procedures based on comparative hearings have been subject to lobbying and pressure from incumbent licensees, resulting in barriers for new entrants and favourable terms for incumbents.

Further spectrum usage inefficiencies arise due to restrictions placed on the transfer of license between users. These restrictions prevent the occurrence of many win-win trades which could facilitate new entrants and innovative technologies while providing compensation for former licensees. Instead, incumbents are reluctant to relinquish their hold on spectrum licenses and spectrum cannot be made available for new allocations and assignments. While licenses are in theory assigned for a limited duration, in practise they are almost always renewed and are often considered a key asset of the licensee. Indeed, in a 2003 US bankruptcy case involving NextWave [20] a spectrum license was considered an asset of the firm and attempts by the FCC to revoke the license failed. Ryan [21] examines the possibility of a similar situation occurring in Europe in the context of telecommunications companies which are struggling in the wake of the lucrative 3G spectrum auctions.

Inefficient spectrum use has arisen partially as a result of regulatory assignment procedures. However, these inefficiencies have been compounded by the use of strict spectrum allocation policies. While spectrum licenses are *assigned* to specific users, spectrum bands are also *allocated* for use by particular technologies and services. In allocating spectrum, a regulator dictates the technologies and services which may be offered using that spectrum. Furthermore, the regulator must forecast demand and allocate sufficient spectrum to meet that demand. Inefficiencies arise when these forecasts are inaccurate. For example, in the US in 1994, the FCC allocated spectrum on the basis of a projection of 54 million mobile service users by 2000. The year 2000 saw an estimated 110 million mobile service users and a lack of allocated spectrum to meet demand [22]. Similarly in Europe, the allocation of valuable spectrum for the unsuccessful ERMES paging and TFTS in-flight phone systems have resulted in that spectrum lying unused for over a decade [23].

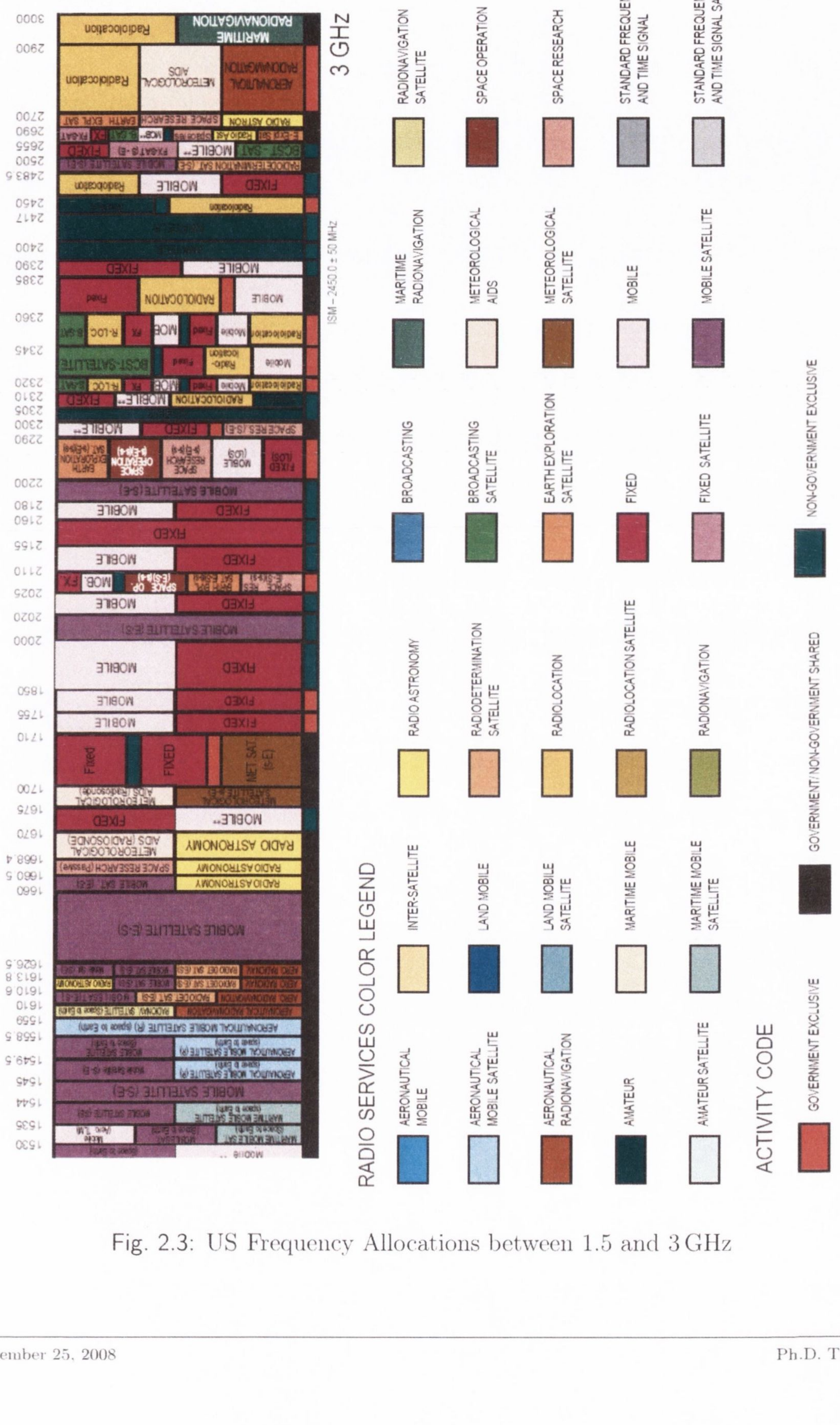


Fig. 2.3: US Frequency Allocations between 1.5 and 3 GHz

Stunted Innovation

As well as causing serious inefficiencies in spectrum usage, command-and-control regimes severely restrict technological innovation in a number of ways. Firstly, spectrum band allocation means that each new technology must be deemed worthy of an allocation by the regulator. Any technologies not allocated spectrum may never be tested in the marketplace. Secondly, spectrum assignment policies create barriers for new entrants, reducing competition and the need for innovation by incumbent license holders. Thirdly, innovation is stunted by the 'mother-may-I' phenomenon, a term coined by FCC Chairman Powell in 2002 describing the need for businesses to request permission from the FCC before modifying spectrum plans to respond to consumer demand [24]. However, in addition to these restrictions, many new technologies have been hamstrung simply as they do not fit into a system originally designed for regulation of broadcast radio in the early part of the last century. Such technologies include ultra-wide band (UWB), software-defined radio (SDR) and mesh networks [19].

The limitations of the command-and-control approach to spectrum management have been well documented since Coase's first argument in 1959. Recently however, regulators have begun to move away from such a tight management strategy and have started to explore new, flexible approaches to spectrum regulation. This change has been largely prompted by the severe shortage of spectrum available for new allocations and assignments in the face of increasing demand. This apparent scarcity coincides with numerous reports providing empirical evidence of spectrum usage inefficiency. The next section analyses some of this empirical evidence and illustrates ways in which more efficient spectrum use could be achieved. Section 2.3 then goes on to describe the issue of spectrum policy reform. Some of the proposed alternatives to command-and-control are examined and the key arguments in their favour are presented.

2.2.3 Spectrum Scarcity

In recent years, a number of reports have been published showing empirical evidence of spectrum resources which are seriously underutilized [25, 26, 27, 28, 29, 30]. At the same time, new technologies and services are suffering from a shortage of spectrum available for new allocations and assignments. This inconsistency has arisen due to highly inefficient spectrum management policies and is a key motivation for spectrum policy reform around the world.

Between April 16th and 18th, 2007, a series of spectrum occupancy measurements were made in Dublin by Shared Spectrum Company and Centre for Telecommunica-

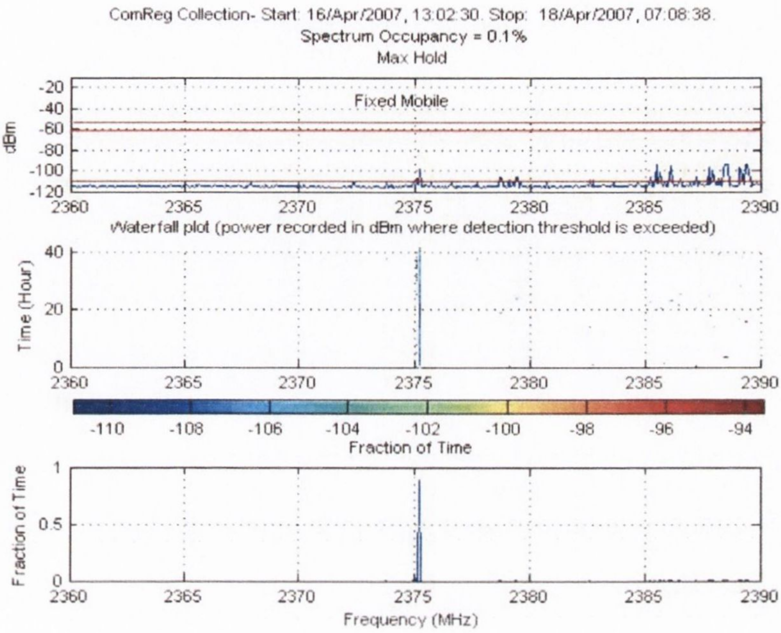


Fig. 2.4: Spectrum Occupancy in Dublin, 2.36-2.39 GHz

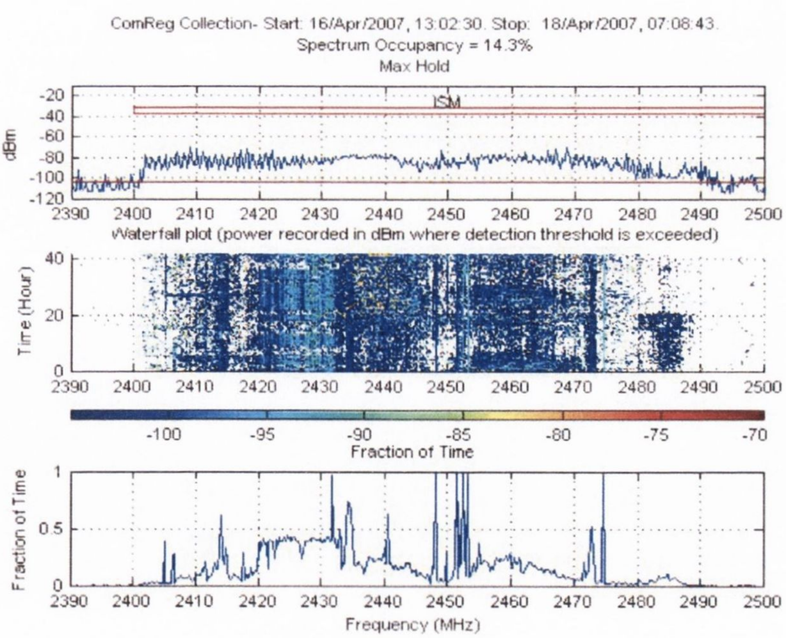


Fig. 2.5: Spectrum Occupancy in Dublin, 2.39-2.5 GHz

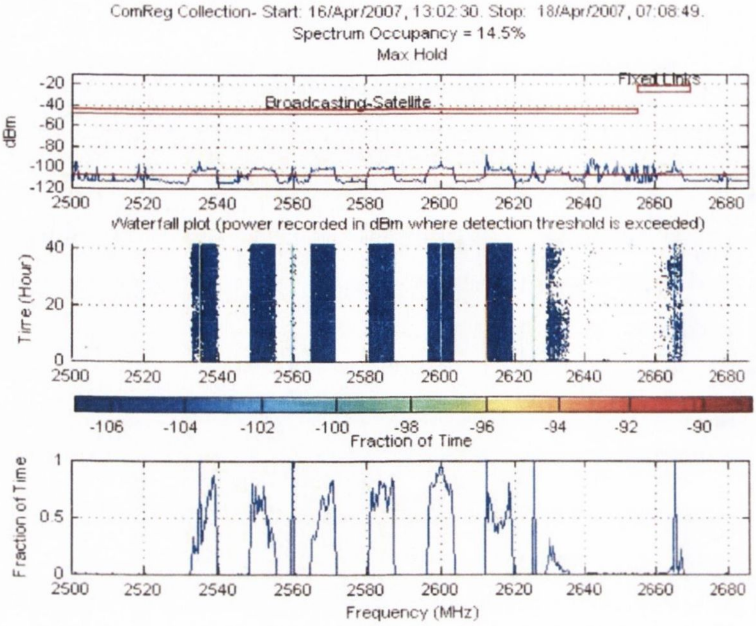


Fig. 2.6: Spectrum Occupancy in Dublin, 2.5-2.68 GHz

tions Value-Chain Research (CTVR) [31]. Measurements were taken from the roof of the Commission for Communications Regulation (ComReg) Building, located in Dublin city centre. A low-frequency discone antenna was used to measure signals between 100 MHz and 1 GHz. A second, high-frequency discone antenna was used to measure between 1 GHz and 3 GHz. Some of the results of these measurements are illustrated in Figs. 2.4, 2.5 and 2.6.

Fig. 2.4 shows occupancy in a range between 2.3 and 2.36 GHz, allocated in Ireland for fixed mobile access. The first chart shows the maximum power level detected at each frequency, the second shows a waterfall plot of the measured power and the third shows the fraction of time for which power levels exceeded a threshold. In this case the power threshold used was -110 dBm, this value just exceeding the level of the noise floor. Results illustrate the very low levels of occupancy within this band. Overall occupancy was measured to be 0.1%, suggesting that much greater use could be made of the band in this location.

Fig. 2.5 shows measurement results taken between 2.39 and 2.5 GHz, encompassing the Industrial, Scientific and Medical (ISM) band at 2.4 GHz. While much activity can be identified in the measured band, overall spectrum occupancy was just 14.3%. Within this band, it may be difficult to improve spectrum occupancy using conventional wireless systems without causing harmful interference. However, advanced DySPAN systems which are capable of sensing spectrum occupancy and using spectrum *white* *spaces* may be able to operate successfully in this location.

Measurement results taken between 2.5 and 2.68 GHz are shown in Fig. 2.6. Within this range, the main spectrum allocation is for broadcasting satellite. A number of satellite channels can be identified at spacings of approximately 15 MHz. Spectrum occupancy for the band was measured at 14.5%. It can be seen that this low occupancy figure arises in large part due to the wide guard bands which separate each satellite channel pair. In order to increase occupancy in this location, it may be possible to safely reduce the width of these guard band. Alternatively, these spaces could be utilized by secondary DySPAN systems on a non-interfering basis.

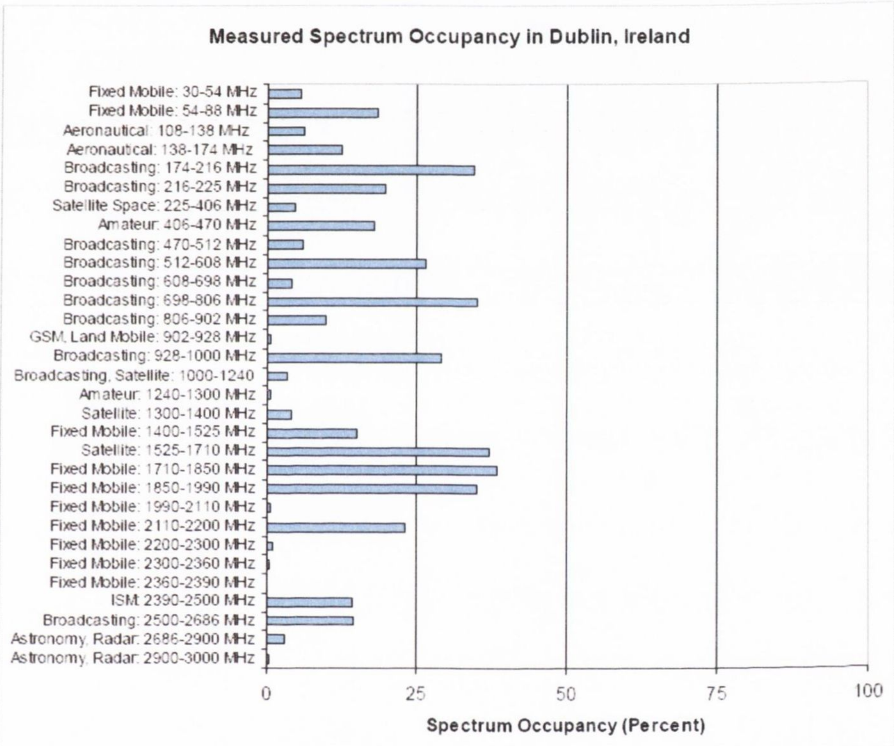


Fig. 2.7: Spectrum Occupancy in Dublin

Overall spectrum occupancy results for Dublin are illustrated in Fig. 2.7. Significant activity can be seen in a number of the broadcast, satellite and fixed mobile bands. Even within these bands however, total occupancy does not exceed 40%. Within a number of bands on the other hand, such as the fixed mobile band between 2.36 and 2.39 GHz, little or no activity was detected.

While Dublin could be considered a small city with relatively low urban density, measurements taken in locations such as New York and Chicago show similar patterns of occupancy. Fig. 2.8 illustrates the results of measurements taken in these locations.

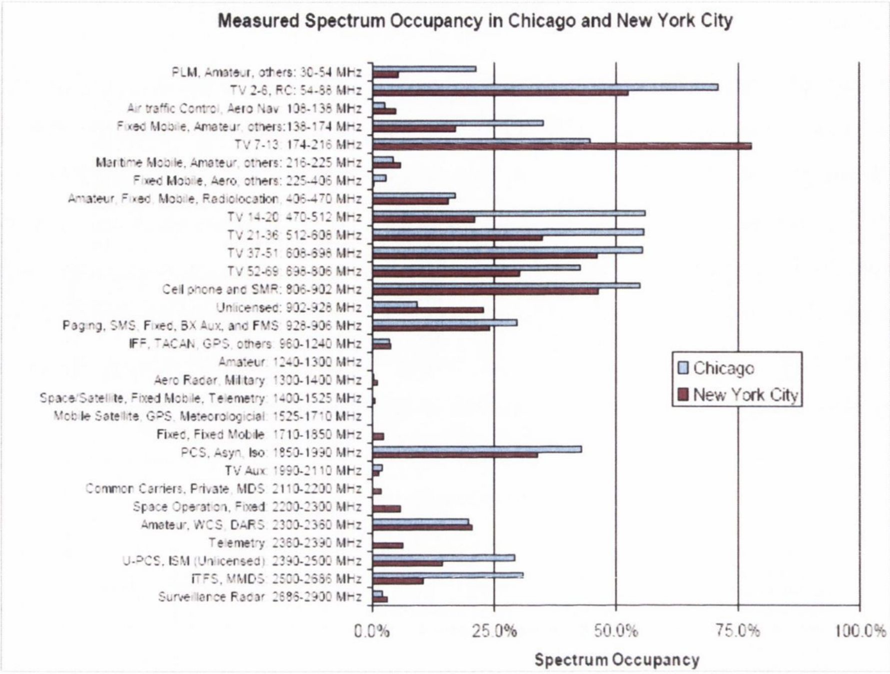


Fig. 2.8: Spectrum Occupancy in New York and Chicago

Furthermore, these measurements represent spectrum occupancy at locations with typically high demand for wireless systems and services. Measurements taken in more rural locations show much lower levels of occupancy. For example, in measurements taken at Riverbend Park, Great Falls, Virginia in 2004, average spectrum use (spectrum bands in which any activity was detected) between 30 and 2900 MHz was shown to be just 3.4% [25].

By introducing greater flexibility into the manner in which spectrum is regulated, it is hoped that these underutilized spectrum resources can be made available for use by new, emerging wireless technologies and services. In the next section, some of the key approaches suggested for achieving this flexibility are examined.

2.3 Spectrum Policy Reform

For the best part of half a century, the inefficiencies of a command-and-control approach to spectrum management have been recognized. In recent years, these inefficiencies have become more apparent as the demand for spectrum to support new, innovative technologies and services has increased. A look at the US frequency allocations illustrated in Fig. 2.3 would suggest that most frequency bands are fully utilized. However, empirical measurement data from around the world has shown that perceived spectrum scarcity is an illusion created by poor management and that an abundance of spectrum lies unused at any given time or place. In order to correct this imbalance, regulators have begun to explore new, flexible approaches to spectrum management.

In addition to the spectrum scarcity issue, a significant factor driving the exploration of new approaches to spectrum management has been the remarkable success of the 2.4 GHz ISM band and particularly the Institute of Electrical and Electronics Engineers (IEEE) 802.11 standard popularly known as Wi-Fi which uses it. Widely regarded as a 'garbage band' due to its use by equipment such as microwave ovens, the 2.4 GHz band was opened to use for communications without the need for a government license by the FCC in 1985. Since then, worldwide Wi-Fi popularity has grown significantly with annual industry revenue estimated at greater than $1bn in 2002 alone [32] and forecast to exceed $40bn by 2008 [33].

A significant step towards spectrum policy reform was made in 2002 with the establishment of the Spectrum Policy Task Force (SPTF) by the FCC. The SPTF was established with the aim of 'identifying and evaluating changes in spectrum policy that will increase the public benefits derived from the use of radio spectrum' [22]. Among its key findings and recommendations, the SPTF recognized that spectrum access was a more significant problem that of physical scarcity of spectrum in many bands. It noted that this was due in large part to legacy 'command-and-control' regulation and recommended the evolution of spectrum policy towards more flexible and market-oriented approaches. In addition, it was recognized that technological advances now made it possible to use spectrum more intensively and to be more interference tolerant than in the past. Similar findings and recommendations have been made in recent years by a number of regulatory bodies in other countries around the world including Ofcom in the UK [34] and the Australian Communications Authority (ACA) [35].

While many regulators are currently moving towards a more flexible approach to spectrum management, opinions on what form that flexibility should take are divided. Since 1959, there have been a considerable number of contributors to the spectrum reform debate, some with greatly differing opinions. The next section outlines this debate, presents some of the key contributors and examines their arguments.

2.3.1 The Debate

Key contributions to the spectrum management debate typically present a tripartite categorization of spectrum management regimes [22, 34]:

1. Command-and-Control

Year	Exclusive Use / Property Rights		Commons / Open Spectrum
1951	**Herzel** - "Public Interest" and the Market in Color Television Regulation		
1959	**Coase** - The Federal Communications Commission		
1969	**de Vany et al.** - A Property System for Market Allocation of the Electromagnetic Spectrum: A Legal-Economic-Engineering Study		
1975	**Minasian** - Property Rights in Radiation: An Alternative Approach to Radio Frequency Allocation		
1998	**de Vany** - Implementing a Market-Based Spectrum Policy		**Benkler** - Overcoming Agoraphobia **Noam** - Spectrum Auctions: Yesterday's Heresy, Today's Orthodoxy, Tomorrow's Anachronism...
1999	**Spiller and Cardilli** - Towards a Property Rights Approach to Communications Spectrum		
2000	**White** - "Propertyzing" the Electromagnetic Spectrum: Why It's Important, and How to Begin		
2001	**Hazlett** - The Wireless Craze, the Unlimited Bandwidth Myth, the Spectrum Auction Faux Pas and the Punchline to Ronald Coase's "Big Joke"		**Lessig** - The Future of Ideas
2002	**Kwerel and Williams** - A Proposal for a Rapid Transition to Market Allocation of Spectrum		**Werbach** - Open Spectrum:The New Wireless Paradigm **Benkler** - Some Economics of Wireless Communications **Reed** - When Less Is More **Buck** - Replacing Spectrum Auctions with a Spectrum Commons
2003		**Faulhaber and Farber** - Spectrum Management: Property Rights, Markets and the Commons	**Werbach** - Radio Revolution: The Coming Age of Unlicensed Wireless
2004		**Cave and Webb** - Spectrum licensing and spectrum commons - where to draw the line. **Goodman** - Spectrum Rights in the Telecosm to Come	
2005	**Matheson** - Flexible Spectrum Use Rights **Hazlett** - Spectrum Tragedies		**Lehr** - Managing Shared Access to a Spectrum Commons **Weiser** - Policing the Spectrum Commons
2006	**Hatfield and Weiser** - Toward Property Rights in Spectrum **Hazlett** - The Spectrum-Allocation Debate: An Analysis		

Fig. 2.9: Key contributions to the spectrum reform debate since 1951.

2. Property Rights / Exclusive Use

3. Spectrum Commons / Open Access

The first of these categories applies to the predominant form of spectrum management used in most countries today. This approach is commonly termed *command-and-control* and involves tight control of all spectrum access by a national regulator. Some of the main criticisms of this approach have already been examined in Section 2.2.2.

The second and third categories broadly cover the alternative approaches to spectrum management which have been proposed over the past half century. These are examined in turn below.

Property Rights / Exclusive Use

Like the command-and-control approach to spectrum management, the property rights model involves the assignment of exclusive-use licenses to specific parties. Where the two approaches differ is in the terms of those licenses and the freedom afforded to licensees. Under the command-and-control approach, licensees are tightly restricted in terms of services to be provided as well as equipment and technology to be used. It is this inflexibility which gives rise to the severe spectrum use inefficiencies typically associated with command-and-control.

In contrast, the property rights model offers licensees much greater flexibility to decide the manner in which licensed spectrum is used. Under this model, licenses are defined in terms which are technology and service neutral. Such terms can define spectrum usage rights in the context of frequency, time and space as well as transmit and receive power levels or distributions. Further flexibility is afforded regarding change of use and change of ownership. Under this model for example, a licensee would be free to use a spectrum band currently supporting a Global System for Mobile (GSM) network to operate a Worldwide Interoperability for Microwave Access (WiMAX) system instead. Change of ownership flexibility would permit that same licensee to transfer license rights to a third party. Alternatively, a licensee could choose to offer secondary usage rights to a third party in order to permit secondary access to licensed spectrum on a non-interfering basis. This could be achieved using underlay or overlay dynamic spectrum access.

By allowing change of ownership and change of spectrum use, the property rights model permits market forces to dictate spectrum use. An efficient secondary market for spectrum licenses would thus ensure a high level of spectrum use efficiency under this model. However, a key difficulty associated with the model lies in the definition of technology-neutral spectrum rights. In particular, licensee entitlements and obligations regarding harmful interference are not trivially defined. While interference depends upon the properties of a transmitting device, it is also a function of the receiver which is affected. What is defined as unacceptable interference for a particular receiver may not be a problem for an alternative, high quality receiver with more effective radio frequency (RF) filters. These issues are further addressed in Section 2.3.2.

Spectrum Commons / Open Access

Contrasting with the property rights model is the commons, unlicensed or open access model. Rather than granting exclusive usage rights to a single licensee, the commons approach permits shared access to the spectrum resource by a number of users which have equal priority.

This is similar to the approach currently used in the ISM bands defined by the ITU. Perhaps the most well-known ISM band is the 2.4 to 2.5 GHz band used to support IEEE 802.11 b/g wireless local area networks (WLANs). In this band, wireless systems are afforded little protection from harmful interference and must coexist with any other ISM systems. In spite of this however, the availability of the 2.45 GHz band for unlicensed use has resulted in significant innovation in wireless systems. IEEE 802.11 systems are currently deployed in millions of hotspots all over the world with rapidly increasing numbers of users.

Although the unlicensed approach adopted for the ISM spectrum bands has been highly successful, a recognized danger of this approach is the so-called *tragedy of the commons*. The tragedy of the commons arises when free access to a finite resource is coupled with unrestricted demand. Under these conditions, overuse of the free finite resource may occur, resulting in that resource becoming unusable. In the case of the ISM bands this would involve a large number of systems causing high levels of interference in a single band within a given area, making that band unusable for all systems concerned.

In order to avoid the danger of the tragedy of the commons, the open access model of spectrum management would involve the use of an agreed protocol or etiquette. This protocol or etiquette would permit wireless systems to gain access to spectrum while limiting the creation of harmful interference, allocating spectrum in times of congestion and resolving conflicts. Only those users who choose to conform with this protocol would be granted access. In this way, decision-making authority can be devolved to the users of the spectrum resource in the commons model.

A difficulty associated with the commons model of spectrum management is the definition of an acceptable protocol for use by heterogeneous wireless systems. While a simple protocol could permit a wider range of systems to use the spectrum band in question, a more complex protocol may be required in order to ensure coexistence without the creation of harmful interference and conflicts. A more detailed discussion of the challenges involved can be found at [36]. However, in overcoming these challenges, a successful spectrum commons would greatly reduce barriers to entry currently experienced by new wireless systems and services. In this way, the spectrum commons approach could encourage competition and foster innovation while promoting spectrum use efficiency.

In spite of the differences between the proposed property rights and commons models of spectrum management, both approaches would provide opportunities for the deployment of DySPAN systems through the support of spectrum sharing. Spectrum sharing under the property rights model can be achieved through secondary spectrum access. This could occur where two wireless systems operate using a single spectrum assignment. While one system may operate with priority access, the second system could use same spectrum on a non-interfering basis through dynamic spectrum access techniques such as underlay or overlay access. In contrast, spectrum sharing under the commons model involves a number of users with equal priority. These users must rely upon dynamic spectrum access techniques to support coexistence and the mitigation of harmful interference.

In the past 10 years, as the value of spectrum has become increasingly recognized, the spectrum reform debate has attracted considerable attention. Fig. 2.9 outlines a number of the most significant contributions to the debate. In the following sections, I outline the development of the exclusive-use and commons models by examining some of these contributions.

2.3.2 The Property Rights Argument

The argument for property rights in spectrum began with Herzel in 1951 [7]. In an article discussing colour television regulation, he noted that frequency channels were a scarce factor of production. As radio regulation involves the allocation of these channels, he argued that this allocation should be an economic decision and not a policing decision. Accordingly, he proposed that channels should be leased to the highest bidder.

Herzel's initial argument greatly influenced the economist Coase. In his seminal article 'The Federal Communications Commission' [8] published in 1959, Coase examined the inefficiency of a spectrum allocation scheme controlled by a national regulator for the 'public interest, necessity or convenience'. In his argument he stated 'An allocation scheme costs something to administer, will itself lead to a misallocation of resources and may encourage some monopolistic tendencies'. He observed that scarce resources in the American economic system were typically allocated using a pricing mechanism and for this approach to succeed, a system of well-defined *property rights* is required.

The idea of a property right in spectrum was presented in terms of the right to use a specific frequency or band of frequencies. In his discussion, Coase recognized the need for a more liberal regulatory approach by the FCC. He argued that while market forces could be used to effectively determine the way in which frequencies were used, the enforcement of detailed regulations for the operation of stations by the FCC would severely limit the extent to which this could occur. Instead, he observed that property rights should include a definition of the extent to which those rights could be transferred and combined through the market. In addition, Coase addressed the issue of interference between operators on the same or adjacent frequencies. He suggested that by clearly delimiting the rights of operators to create interference, market transactions could be relied upon to ensure the gain from interference would more than offset the harm it produced.

The spectrum property rights approach was advanced in 1969 by DeVany et al [37] through an explicit definition of a system of property rights. A system based on the dimensions of time, area and spectrum (TAS) was proposed. In the proposal *time* refers to the time during which a transmission occurs. *Area* describes geographical limits, outside of which the field strength due to the transmission does not exceed a specified limit. Similarly, the third dimension, *spectrum*, refers to a band of frequencies bounded by upper and lower limits outside of which the field strength due to the transmission does not exceed a certain limit. In addition to defining rights, DeVany examined how the proposed property system dealt with issues including radio wave propagation variation, multipath propagation and intermodulation interference.

Continuing the argument for property rights in 1975, Minasian [38] argued that a rigid system of spectrum use specifications was unlikely to give rise to an efficient use of that spectrum. In order to maximize the value of production, a regulator must have all information concerning the value of resources in alternative uses. Minasian stated that, as changing technology continually enlarges the range of alternative resource uses, any rigid system cannot take all information regarding those uses into account. In addition to the DeVany concept of emission rights over time, space and area, he proposed a system including admission, use and transfer rights. Admission rights address the need to exclude others from licensed spectrum resources. Use rights permit a license holder to choose technologies and services from all alternatives legally open to him, under the restrictions of emission and admission rights. Transfer rights permit a license holder to transfer those emission and admission rights to others in whole or in part.

As well as suggesting a system of suitable property rights for spectrum, DeVany in 1998 advocated the unbundling of spectrum from broadcast and transmission facilities [39]. Unbundling refers to the process of relaxing the restrictions of spectrum licenses such that the license-owner is free to choose the services and technologies deployed under the terms of that license. In this way, standardization and price discovery would be enabled. This in turn would permit the development of liquid secondary markets with lower transaction and entry costs, encouraging competition. In this way, liquidity in the aftermarket for spectrum would be greatly improved, increasing the extent to which market forces determine spectrum allocation and thus improving the efficiency with which spectrum is used.

A set of specific building blocks for a property rights approach to spectrum regulation were outlined by Spiller and Cardilli in 1999 [40]. The first of these proposed building blocks was the right to property in spectrum, as proposed by Coase in 1959. The second entailed the right to use that spectrum rather than the right to provide a particular service and the third provided for the handling of interference through tort law. In addition, Spiller and Cardilli cited examples of spectrum property rights successfully applied in New Zealand and Guatemala.

In 2000, White [41] used the analogy of real estate to argue for spectrum property rights. In drawing parallels between land and spectrum, he made reference to the finite and scarce nature of both. Furthermore, he noted that technological changes can have similar influences on both, affecting the efficiency with which land and spectrum can be utilized, expanding the amount of both considered usable and productive as well as altering uses to which both should economically be devoted. While White recognized that a 'clean slate' approach to spectrum reform is impossible in the light of current management policies, he proposed a number of steps in order to move toward a system of spectrum property rights. These included assigning existing rights to incumbent holders in perpetuity, permitting license trading and establishing national registries for spectrum ownership. In addition, he proposed the auctioning of under-utilized bands, compensating incumbents or moving them to alternative bands.

In 2001, one of the most outspoken supporters of the property rights model of spectrum management, Thomas Hazlett, published his essay on airwave allocation policy [42]. In it, he strongly criticized the FCC's rejection of Coase's original proposals and made a comprehensive argument for the establishment of property rights in spectrum. He discussed the 'wireless craze', the explosion in demand for wireless technology and services as well as the fade in demand for broadcast television services, driven by alternatives including cable and satellite services. Rather than allowing for the reallocation of spectrum from incumbent broadcasters to new entrants, Hazlett outlined the tendency of a command-and-control approach to protect incumbents and reject new entrants. This argument was reinforced with numerous examples taken from dates between the first days of regulation in the US and the present day. He went on to examine the spectrum auction 'faux pas', the fact that auctions do not assign property rights in spectrum but rather licenses to use FCC-approved devices to emit radio waves. In this he noted that licenses are analogous to operating permits as opposed to titles in real property. In addition, he used examples of *spectrum tragedies* to argue against the notion of spectrum commons. The 'tragedy of the commons' describes the situation where a resource is destroyed due to overuse. The opposite situation, the 'tragedy of the uncommons' involves overprotection of a resource, giving rise to underuse. In making the case for spectrum property rights, Hazlett illustrated how protection against such tragedies can be provided through the use of well defined ownership rights.

Adopting DeVany's property rights framework, Kwerel and Williams in 2002 addressed in some detail the issues of interference in space and frequency [43]. In frequency, the issue of adjacent channel spillover was examined. While this may result from a transmitter emitting radio energy outside the licensed bandwidth, it may also arise due to inadequate filtering in receivers operating in the adjacent band or from a combination of both. Under these conditions, the authors argued that a natural demarcation of 'trespass' may not be easily defined. However, they suggested that such issues may be resolved through Coasian bargaining between different licensees and regulatory safeguards are not required. A system based on that used to control out-of-area and out-of-band emissions in the personal communications service (PCS) band at the time was proposed.

An extension of DeVany's original system of spectrum propery rights was proposed in 2005 by Matheson [44]. In his paper, Matheson outlined rights in terms of 'electrospace', a 7-dimensional space encompassing time, frequency, space and angle of arrival. In space, the dimensions of latitude, longitude and altitude are included while the dimensions of azimuth and elevation angle make up the angle of arrival. Two straightforward rules for spectrum property rights were proposed. Firstly, the right to transmit within certain power restrictions in licensed space and secondly, the responsibility to keep signal levels below a given level outside of this space.

In his 2005 essay [45], Hazlett focussed upon the issue of *spectrum tragedies* originally introduced in 2001. In discussing the tragedy of the commons, he argued that the lack of well established ownership rights give rise to overuse and destructive interference. In contrast, the tragedy of the anticommons arises when ownership rights are well defined but are so fragmented that efficient aggregation is difficult, resulting in underuse. Protection against both dangers can be provided, in his opinion, by liberalization of property rights through the allocation of exclusively-assigned, flexible-use spectrum (EAFUS).

Taking a step back from the ardent calls for spectrum property rights in 2006, Hatfield and Weiser outlined some of the major challenges associated with defining an enforceable set of ownership rights in spectrum [13]. In their paper, while the authors recognized property-like rights as the best way to allocate spectrum to its highest and best uses, they outlined some of the key contributions to the property rights argument since Coase and argued that these proposals did not sufficiently appreciate the challenges involved. In particular, they identified the issues of geographic and adjacent channel spillover as obstacles to the definition of property rights. Reliable measurement of when these situations arise may pose significant difficulties, while the use of predictive propagation models may invite rent-seeking by incumbents who perceive new entrants as a threat. The authors examined a number of such issues and suggested that solutions are still required before the move to a property rights regime can be successful.

In one of his most recent publications regarding spectrum policy, Hazlett attacks the tripartite categorization of spectrum management alternatives [46]. He argues that the separation of models between command-and-control, exclusive-use and commons confuses access regimes with property regimes. While an access regime dictates how consumers and producers use resources, a property regime determines how control over organizing choices is defined. Rather than separating models in the manner of the SPTF and Ofcom, Hazlett argues that an underlying system of property rights is sufficient to enable each of the usage models posited.

The potential benefits of a system of spectrum property rights and a secondary market for the trading of those rights are well understood. However, as Hatfield and Weiser point out, the development of an enforceable set of such rights is not an easy task due to the unpredictable nature of electromagnetic radiation and the subjective nature of radio receivers. At the opposite side of the debate, a number of commentators have proposed a much different approach for spectrum management. Relying largely on emerging 'smart' radio technology, the spectrum commons proposal would permit many heterogeneous systems and users to share the same spectrum band while avoiding the creation of harmful interference. In the next section, I examine this proposal and outline a number of the key arguments in its favour.

2.3.3 The Commons Argument

Arguably the most important contribution to the spectrum policy reform debate in favour of a commons-based model was provided in 1998 by Yochai Benkler [47]. In his essay 'Overcoming Agoraphobia: Building the commons of the digitally networked environment', Benkler warned against the dangers of a spectrum policy based on outdated assumptions about interference and noise. Recognizing the emergence of property rights as the key regulatory alternative to command-and-control, he questioned the wisdom of such an approach, arguing that it is based on the concept of spectrum as a scarce resource which needs to be managed. This concept is, in his opinion, rendered obsolete by technological advances in digital information processing and wireless communications. Rather than simply choosing between a licensed, command-and-control model and one based on privatisation and property rights, Benkler analysed a third alternative; regulating wireless transmissions as a public commons, similar to the approach typically adopted for highway systems or computer networks.

In examining the choice between licensed and unlicensed approaches, he argued that it was unknown whether a market in equipment, based on unlicensed spectrum, or a spectrum market based on privatisation would be more efficient. However, he gave some indications that an equipment market would have significant advantages and suggested that, at the least, both approaches should be allowed to develop. In particular, Benkler argued that complete privatisation of spectrum would severely curtail the development of the unlicensed approach. While he was in favour of the development of both licensed and unlicensed approaches, he posited a number of key arguments in preference of unlicensed regulation. Among these was the argument that in a system based on owned infrastructure, the information which flows over that infrastructure may be determined by the owner. In an unowned infrastructure, the end user determines what is communicated. In a societal context and in terms of democratic values, Benkler also contended that an information infrastructure should be free of centralized control by any body, government or commercial.

Finally, Benkler presented three key measures to 'negate the potential institutional and technological lock-in effects' of an auctioning policy. The first measure suggested that the constraints placed upon unlicensed devices be revisited in order to avoid warping the development of devices operating in an unlicensed environment around the needs of incumbent licensees. Secondly, he recommended the constraint of auctioning policies in order to allow a more informed choice to be made between the devotion of spectrum to private use and use as a commons. Thirdly, he requested that auctioned licenses come with warnings about renewal uncertainty to leave open the possibility of reallocation as a commons.

In the same year as Benkler's paper, a system of open spectrum access was proposed by Noam [48]. Under his proposal, spectrum would be license-free with users accessing spectrum bands on a pay-as-you-go basis. This would be achieved using access tokens, electronic money transmitted together with content. Access prices would vary according to congestion, leading to spot and futures markets. In opposing spectrum auctions and licensing, Noam argued that they restrict free (electronic) speech and deteriorate into revenue tools. In addition, he claimed that auctions encourage oligopolies by posing a barrier to entry, especially affecting new entrants and unproven technologies. However, Noam accepted that auctions were better suited to the state of technology at that time, suggesting that they be continued but that licenses be granted with limited duration to preserve future flexibility. Furthermore, he proposed that spectrum resale and flexible use be permitted and that innovation in spectrum usage schemes be encouraged through expansion of the unlicensed concept and dedication of frequency bands to the open-access model.

Continuing the argument for spectrum commons, Lessig in 2001 addressed the issue in his book 'The Future of Ideas' [49]. In it, he asked whether control of spectrum as a resource is necessary. Instead, he suggests that, rather than regulating access to spectrum, the devices used to do so should be certified. As the internet depends upon the ethernet protocol, he argued that spectrum resources should be shared through coordination protocols. Comparing the commons regime with the property regime, Lessig accepts that the danger lies in overuse. However, while a property regime can produce great competition, he claims that the market costs of negotiating and securing rights to access spectrum under this approach could become prohibitive. Like Benkler and Noam before him, Lessig suggested that both regimes be allowed to develop side-by-side in order to stimulate innovation. By selling spectrum before alternative uses can develop, he asserts that you place the resources required for those uses in the hands of those with strongest incentives to stop them.

In 2002, Werbach made the case for open spectrum [50]. In doing so, he cited a number of spectrum 'myths' and made four key proposals to promote the development of the 'most pro-innovation, pro-investment, deregulatory and democratic spectrum policy regime'. Among the spectrum myths discussed, he addressed the idea of spectrum scarcity, stating that it was simply a result of the current regulatory regime. He also questioned the use of auctions to put spectrum in the marketplace and claimed that massive capital investment should not be required to exploit the spectrum. The first of his proposals to promote the development of open spectrum was to develop rules encouraging more effective cooperation between unlicensed spectrum users. Secondly, he proposed that more spectrum be set aside for unlicensed uses. In addition he suggested that underlay techniques be permitted across licensed bands and experimentation in unlicensed wireless technology be promoted.

Focussing on the technical-economic aspect of the spectrum policy reform debate, Benkler in 2002 [51] viewed the choice between property rights and open spectrum as a trade-off between network capacity and its rate of growth on the one hand and the efficiency with which that capacity is allocated among competing users on the other. He argued that a property rights model would involve investment which is centralized at the core of the network, with cheaper end-user devices. Contrastingly, an open spectrum model would focus investment on end-user devices. As a result, the free availability of bandwidth and the higher computational intensity of open spectrum systems would support greater capacity and permit that capacity to grow over time. However, Benkler accepted that it is too early to choose decisively between the alternative approaches and proposes a period of experimentation involving both. In this way, experiences gained could be used to inform more long-term strategies.

In the same year, Reed [52] made the argument for a commons approach to spectrum management on the basis of research into the capacity of networks. Citing examples from Shepard at Massachusetts Institute of Technology (MIT) and Gupta and Kumar at University of Illinois, Urbana Champaign, he argued that spectrum capacity can be managed such that it increases with greater numbers of users. This is achieved where spectrum users are organized into a cooperative network rather than an uncoordinated set of point-to-point channels. Accordingly, in Reeds estimation, spectrum is unlike any conventional property and so should not be managed using a market-based approach. Rather, an architecture along the lines of that underlying the internet is required, facilitating cooperative spectrum use while allowing the absorption of unanticipated innovation.

The use of spectrum auctions was strongly criticized by Buck [53] in his paper 'Replacing Spectrum Auctions with a Spectrum Commons'. He argued that auctions pose a barrier to entry for highly innovative, mid-sized companies and that they make it more expensive for rural and poor users to participate in modern media. In addition he claimed that they retain government in providing centralized allocation and bureaucratic enforcement of monopoly rights to spectrum. Instead, he proposed a system of regulating spectrum as a common property regime. This approach is preferable to a private property regime in his opinion, as collective management allows the transaction costs of deals ensuring complimentary spectrum usage to be avoided. He also suggested that a commons is a preferable approach for an indivisible resource, arguing that new technology makes it possible for multiple users to share the same spread of frequencies without interference. In proposing a spectrum commons approach, he suggested a number of 'meta-rules' for such a commons including the need for clearly defined boundaries and users as well as monitoring mechanisms, graduated sanctions for users who violate operational rules and conflict resolution mechanisms.

In 2003, Werbach heralded the coming of a 'Radio Revolution' [54]. In quite a high-level overview, he outlined the coming transition from static networks to more dynamic systems with smart devices replacing hard-wired broadcast networks. These smart devices would make use of dynamic wireless technologies including SDR, mesh-networking and space-time coding and would prompt a move from a market for centralized infrastructure and proprietary services to one for consumer devices, software and ancillary services. Echoing proposals made in 2002, he called for policy makers to allocate more dedicated unlicensed spectrum, enable shared unlicensed underlay devices and opportunistic spectrum sharing as well as ensure the promotion of experimentation and research into new, dynamic wireless systems.

Moving towards a practical system for enabling shared access to a spectrum commons, Lehr and Crowcroft in 2005 outlined a number of key features required for a spectrum sharing protocol or etiquette [36]. They first characterized the future unlicensed environment as comprising multiple, heterogeneous devices with lots of potential operators and users with a relative abundance of available spectrum due to the removal of inefficient legacy regulations. They then presented a set of constraints required to enable such a flexible, decentralized and open access environment. The first of these constraints addressed the need for devices to have both transmit and receive capabilities. Transmit-only devices are not permitted as they cannot support a feedback loop and receive-only devices have no interference rights as they have no way to signal their presence. A second proposed requirement was the need for power limits on devices to help mitigate interference. In addition to transmit power limits, the requirement for some system of limiting aggregate power levels was identified. A further constraint involved the need for a signalling capability, such as a common control channel. However, privacy concerns associated with this requirement were noted. Other requirements included mechanisms for contention resolution, enforcement and privacy protection as well as reallocation of spectrum for alternative uses if needed.

Along similar lines and Lehr and Crowcroft, Weiser and Hatfield in 2005 addressed the issue of policing a spectrum commons [55]. They looked at a number of self-regulation approaches which could be adopted including social norms, free market solutions and technical architectures. Under social norm regulation, parties interact repeatedly and behaviour is controlled as parties' reputations are key in those interactions. However, where parties do not interact repeatedly and reputational sanctions are not available, social norms tend to be less effective and legal enforcement is required. Free market solutions involve a market ordering that creates incentives for and against certain types of behaviour. These succeed where parties can easily contact each other to work out mutually acceptable arrangements, however they can fail where bad actors are not interested in cooperating with a collective solution which is in the interests of the community. While Weiser and Hatfield accept that technical architectures can be effective together with certification systems, they note that protocols are easily circumvented, especially in the case of software and, specifically, software defined radio. Rather than depending upon one solution to ensure policing of a spectrum commons, they suggest that a combination of approaches are required, including oversight by a regulator such as the FCC. They propose that the regulator follow both reactive approaches such as device certification and proactive approaches including the definition of spectrum etiquette rules and the introduction of database registration requirements.

2.3.4 Resolving the Debate

While the spectrum policy debate has become quite polarized over time, some commentators have addressed both sides and attempted to provide some resolution. One example of this approach was provided in 2003 by Faulhaber and Farber, former chief economist and former chief technologist with the FCC respectively [19].

Faulhaber and Farber identified critiques of the command-and-control approach to spectrum management in the context of the economist and the engineer. The economist criticizes the inefficient resource allocation that arises due to centralized control and promotes the use of market forces through a system of property rights. The engineer, on the other hand, criticizes the incompatibility of a rigid license system with new wireless technologies such as UWB, SDR and mesh networks. In order to facilitate these technologies, the engineer proposes the commons model of spectrum management. In assessing both proposals, the authors note that a choice between the two depends upon two key factors; scarcity and transaction costs. Where resource scarcity exists, there is a danger of overuse and a 'tragedy of the commons' type scenario. However, where scarcity is not a significant issue, a property rights system may incur unnecessary transaction costs. Taking a long-term view, Faulhaber and Farber suggest that spectrum scarcity will inevitably become an issue due to rapidly increasing demand and thus a pure spectrum commons approach will not work. Instead, they propose the use of property rights regimes which permit spectrum sharing, either through non-interfering underlay approaches such as UWB or through negotiated sharing of exclusively-owned spectrum. Furthermore, they argue that a spectrum commons approach can be supported by a property rights system through the purchase of spectrum blocks for this purpose by the government. They go on to propose a process for transition to a property rights scheme. This would involve the auctioning of all technically usable spectrum with incentives for existing license holders to take part. Following this 'big bang' auction, the authors expect an active secondary market in spectrum to arise.

A similar comparison between the property rights and commons approaches was made in 2004 by Cave and Webb in the UK [56]. Key points made in their comparison include the view that spectrum commons are unlikely to alleviate congestion in the short term. Accordingly, they propose that unlicensed, spectrum commons approaches to spectrum management should only be applied to spectrum bands where there is a low probability of congestion. The authors accept that this approach requires the likelihood of congestion to be predicted and would prefer this to be performed by the market. This would be possible where a band manager buys spectrum under auction and chooses to turn it into a private commons.

Also in 2004, Goodman took a neutral stance in addressing the spectrum policy reform debate and suggested that both a pure property rights and a commons approach were strongly utopian in nature [57]. She proposed that, in spite of the oppositional stance of the two theories, there was no reason why a mixed approach to spectrum management involving both could not be taken. Furthermore, she suggested that on both sides of the debate, a recognition exists that this dual mode of spectrum management is desirable. In discussing the appropriate mix of both approaches, Goodman cites the unproven nature of the technologies forming the basis for the spectrum commons argument. Due to the uncertainty that exists regarding these technologies, in her opinion, it is undesirable for the commons model to become the primary approach. However, she also accepts that a transparent and predictable system of spectrum property rights has yet to be developed. Accordingly, Goodman sees a significant role for the regulator in a mixed regime of spectrum management for the foreseeable future.

The future direction of spectrum policy reform is as yet unclear. However, regardless of whether a property rights approach, a commons-based approach or indeed a mix of the two is adopted, what is certain is that future spectrum regimes will seek to overcome the strict limitations of command-and-control and will permit greater flexibility of spectrum use. With this flexibility will come significant opportunity for emerging DySPAN technologies. Some of these opportunities are outlined in the next section.

2.3.5 DySPAN Opportunities

The introduction of greater flexibility with spectrum policy reform can open the door for the deployment of innovative reconfigurable wireless systems. In particular, systems which are not tied to specific operating frequencies or spectrum bands will provide key advantages. The term *Dynamic Spectrum Access Network (DySPAN)* is used to describe these systems. These DySPAN systems will play a key role in efficiently utilizing radio spectrum through the exploitation of these increasingly flexible spectrum management regimes.

With the adoption of a property rights system of spectrum management, adaptive wireless systems would allow network owners to choose spectrum rights on the basis of price and propagation characteristics instead of purely technical requirements. By avoiding the need to become locked into one particular set of operating frequencies, such systems would permit owners to buy and sell spectrum rights according to price fluctuations and market demand. In addition, aggregation of spectrum rights would be greatly simplified where licenses for different spectrum bands could be used over different geographic regions. Under these conditions, adaptive systems would choose operating frequencies on the basis of their geographic locations. Flexible wireless systems could also be leveraged to opportunistically access spectrum on a non-interfering basis. This can be made possible through the introduction of property rights easements, discussed in Section 2.3.1. In this way, secondary users could access spectrum belonging to a primary user under the condition that no harmful interference is caused.

To a certain extent, adaptive and reconfigurable wireless networks form the basis for the argument in favour of spectrum commons. Through the use of spectrum etiquettes or policies, such networks permit a range of frequencies to be shared between a number of heterogeneous systems without the creation of harmful interference. In this way, very high levels of efficiency in the way spectrum is used can be achieved and the high capital costs typically associated with spectrum access can be avoided.

2.4 Summary

Around the world, regulators are acknowledging the inefficiencies associated with a command-and-control approach to spectrum regulation. In order to capitalize on the growing value of radio frequency spectrum, these regulators are actively evaluating a number of alternative, flexible regimes which have been proposed in a spectrum policy reform debate spanning the past 50 years.

By examining some of the key arguments of this spectrum policy reform debate, it can be seen that the issues involved in moving away from a command-and-control based approach are complex and highly contentious. While the arguments have become polarized between those advocating a property rights approach and those proposing adoption of a spectrum commons, a straight choice between either involves significant drawbacks.

Although the introduction of property rights in spectrum would leverage the power of the market to allocate spectrum resources to their most productive uses, no well-defined system of rights has been proposed which deals effectively with the issues of interference and rights enforcement. In addition, a pure system of exclusive-use property rights may preclude the deployment of a range of emerging wireless technologies with significant potential such as SDR and UWB.

On the other hand, the arguments in favour of a system of spectrum commons depend heavily on the ability of emerging wireless technologies to overcome the complex issues of interference avoidance and reliable service provision while ensuring fair access to spectrum. As these technologies are as yet unproven, the decision to allocate wide swathes of spectrum for commons use would involve a significant gamble. However, as wireless technology develops, non-interfering, shared access to a spectrum commons on a non-exclusive basis may become a reality. Current decisions made regarding spectrum policy should be wary of excluding this possibility.

Regardless of what form future spectrum management regimes may take, the increased flexibility of those regime can provide significant opportunities for the deployment of innovative DySPAN systems. The potential advantages of these advanced wireless systems are considerable. However, the introduction of such flexibility while ensuring system robustness and reliability is one of the most significant challenges facing wireless system designers today. In the following chapter, I look at some of the technologies which may form the basis for these systems and address some of the key challenges involved in their design. In particular, I examine the challenge of network rendezvous and coordination and discuss the reasons why, as systems become more flexible, these challenges become more significant.

3. RENDEZVOUS AND COORDINATION IN DYSPAN SYSTEMS

3.1 Introduction

Dramatic growth of wireless communications technology over the past two decades has driven a significant increase in the demand for radio frequency spectrum to support new, innovative systems and services. However, serious inefficiencies in the way spectrum is managed have given rise to a situation of apparent spectrum scarcity. The resulting inability to make spectrum available for new allocations and assignments has had a stifling effect upon many potential new systems and service providers. At the same time, a number of empirical studies from around the world have shown that an abundance of spectrum lies unused at any given time and place. In an attempt to rectify this situation, telecommunications regulators are currently examining new and flexible approaches to spectrum management.

This introduction of less restrictive spectrum management policies promises a number of significant opportunities for the deployment of highly adaptive, reconfigurable wireless systems. These systems, in turn, promise new levels of spectrum usage efficiency by sharing spectrum resources while avoiding the creation of harmful interference. At the heart of these intelligent systems are networks of devices capable of dynamically changing operating frequencies and spectrum bands as required while maintaining communication links and thus, network connectivity. Such networks of devices are termed Dynamic Spectrum Access Network (DySPAN)s.

Significant advances in digital signal processing and software-defined radio (SDR) over the past decade have brought the concept of DySPAN systems much closer to a reality. However, there still exist a number of complex challenges which need to be overcome before robust DySPAN systems can be realised. Not least among these is the challenge of rendezvous and coordination.

Currently, one of the major roles of a telecommunications regulator is the mitigation of harmful interference between wireless systems. Under the command-and-control method of spectrum management, this was achieved through the allocation of spectrum bands to specific wireless technologies, the further assignment within those bands of frequency ranges to individual operators and then the tight regulation of radio equipment used by those operators. A direct consequence of this form of regulation was the confinement of operators to specific, fixed frequency ranges. Accordingly, wireless systems deployed by operators were designed to operate at very specific frequencies within these ranges.

With the introduction of more flexible approaches to spectrum management, regulators are attempting to move away from the tight strictures of command-and-control. More relaxed regulations will afford operators greater choice in wireless technologies employed and operating frequencies used. However, with improved flexibility will come the need for wireless systems to self-organize and agree upon parameters of operation including spectrum bands and operating frequencies. It is this self-organizing ability which comprises the challenge of DySPAN rendezvous and coordination. The key purpose of this chapter is to examine this challenge.

Section 3.2 begins by discussing a number of existing wireless technologies and examining the approaches used in each to achieve rendezvous and coordination. In appraising these existing systems, it will be seen that the significance of network coordination increases with greater system flexibility and reconfigurability. Some of the existing solutions to DySPAN coordination are investigated in Section 3.3 and Section 3.4 concludes the chapter.

3.2 The Challenge of Rendezvous and Coordination

DySPAN technology offers a solution to current spectrum usage inefficiencies based on the ability to dynamically adapt operating frequencies to share spectrum resources while avoiding the creation of harmful interference. A number of significant challenges must be overcome before this solution can be realized however. One of these key challenges is that of *frequency rendezvous*. In traditional wireless communications networks, devices typically have á priori knowledge of the initial operating frequencies to be used. This means that upon commencing operation, nodes within the network may have a predetermined frequency, or list of frequencies which can searched in an attempt to established a wireless communications link with their peers. In a DySPAN system, the frequency of operation may not be known initially; establishing a common communications channel may be dependent on the available spectrum and on other systems which may be using it. The potential channel may therefore lie within a much greater frequency range and may also change during the operating lifetime of the network. The challenge of rendezvous in this case involves not only synchronization with, but also the detection and identification of signals of peer devices in the network.

I will examine the challenge of frequency rendezvous and network coordination by first looking at approaches taken within a number of existing wireless systems.

3.2.1 Static Control Channels - Global System for Mobile (GSM)

A popular approach for achieving network rendezvous in cellular systems is the use of fixed frequency control channels. Under the command-and-control method of spectrum management, regulators assign fixed bands of spectrum to individual operators. Within these bands, static control channels can be deployed. Equipped with a prior knowledge of the operating frequencies and bandwidths of these control channels, network devices can perform time and frequency synchronization, obtain network configuration data and join the network.

Global System for Mobile (GSM) is the world's most popular second generation cellular technology. Developed in the mid-1980s by a special working group of the European Conference of Post and Telecommunications (CEPT), GSM was introduced to the European market in 1991 and by 2001 had over 350 million subscribers worldwide [4].

Like many conventional networks, GSM uses fixed frequency control channels which are known in advance by all subscriber devices. Due to this static configuration, network rendezvous is achieved in a straightforward manner. Channels of 200 KHz are defined within two 25 MHz bands, centred at 902.5 MHz and 947.5 MHz. frequency-division duplexing (FDD) is used with base-subscriber transmissions taking place in the upper band and subscriber-base transmissions occurring in the lower band. Forward and reverse link channel pairs are separated by 45 MHz and are identified using absolute radio frequency channel numbers (ARFCN)s. Time Division Multiple Access (TDMA) is used within each channel to permit sharing between up to 8 subscribers. A physical channel is thus described using an ARFCN and a unique timeslot (TS).

Thirty four specific ARFCNs are defined as broadcast channels, used for periodic control signalling by base stations. Within the forward link of each broadcast channel (BCH), TS 0 is reserved for control signalling, while TS 1-7 are used for regular data traffic. The control data broadcast is determined by a repetitive 51-frame sequence known as a control multiframe. The GSM control multiframe is illustrated in Fig. 3.1.

Within the 51-frame sequence, frames 0,10,20,30 and 40 are used for frequency

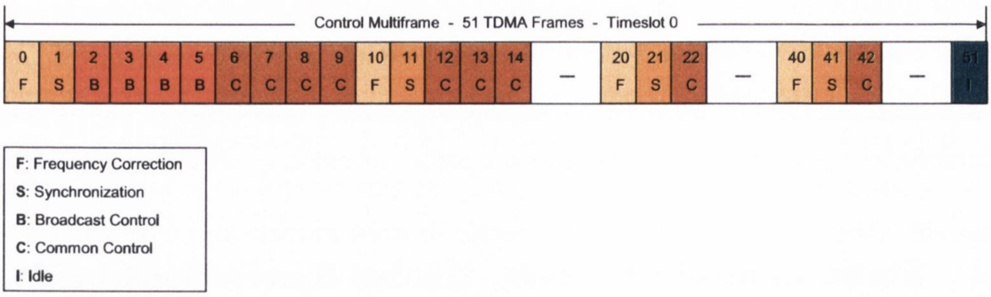


Fig. 3.1: GSM Control Multiframe. Reproduced from [4].

correction, allowing subscribers to synchronize their local clocks to the frequency of the base station. Synchronization bursts follow each frequency correction burst in frames 1,11,21,31 and 41. Synchronization bursts contain a *frame number* and a *base station identity code* and are used to adjust subscriber timing according to the distance from the base station. Frames 2-5 are used to broadcast control information including cell and network identification, control channel configuration, channels used within the cell and congestion. The remaining broadcast timeslots are used for paging and access grants on the forward link and for random access on the reverse link.

Thus by scanning a known control channel, a GSM subscriber can achieve time and frequency synchronization and receive control messages about the network configuration prior to network entry. In this way, the use of periodic signalling on fixed frequency control channels provides a straightforward technique for achieving network rendezvous.

3.2.2 In-Band Control Signalling - WiMax

An alternative approach for achieving network rendezvous is the use of in-band signalling. In this case control signals are not broadcast only on fixed frequency control channels but are rather transmitted together with data traffic on all used channels. This is the approach adopted for Worldwide Interoperability for Microwave Access (WiMAX), a broadband solution for wireless metropolitan area networks based on the Institute of Electrical and Electronics Engineers (IEEE) 802.16 family of standards [10].

Although the IEEE 802.16 family of standards describe a wide range of PHY and MAC layer options for fixed and mobile access in both the 2-11 GHz and the 10-66 GHz ranges, these options have been reduced to a set of specific profiles for implementation

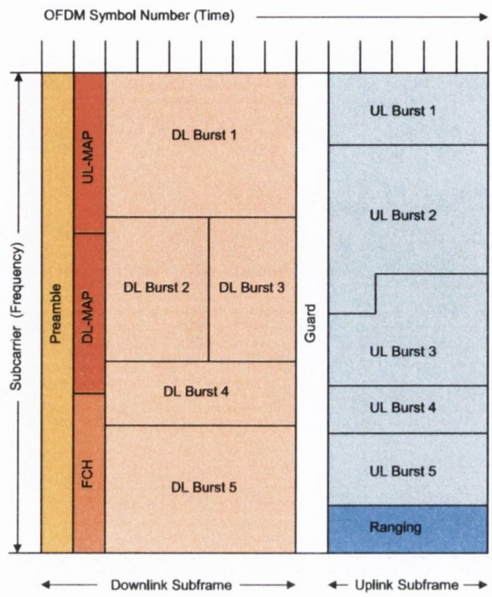


Fig. 3.2: WiMAX frame structure. Reproduced from [5].

by the WiMAX Forum. Profiles are defined for fixed and mobile access using a range of operating frequencies, channel bandwidths and duplexing modes. Network rendezvous is achieved within each profile through use of in-band signalling.

WiMAX signals are Orthogonal Frequency Division Multiplexing (OFDM)-based and equivalent uplink and downlink frame structures are specified for both time-division duplexing (TDD) and FDD implementations. With TDD implementations, uplink and downlink subframes are transmitted sequentially within a single channel, while FDD operation specifies simultaneous transmission on separate uplink and downlink channels. The TDD subframe structures are outlined in Fig. 3.2. Each frame begins with a preamble, used for time and frequency synchronization. This is followed by a frame control header (FCH) which includes information on frame configuration, usable OFDM subcarriers, modulation and coding schemes as well as the structure of the MAP messages used to specify uplink and downlink bandwidth allocations for individual subscribers. This is followed by the uplink and downlink MAP messages themselves. WiMAX uses a wide range of modulation and coding schemes which may be tailored to suit channel conditions for individual subscribers, however control signals are transmitted using a single, highly reliable scheme such as BPSK with 1/2 rate coding and repetition coding.

This downlink frame structure effectively facilitates subscribers performing network rendezvous. Upon commencing operation, a subscriber scans each of the known

WiMAX channels in turn for frame preambles. Upon detection of a preamble, timing and frequency synchronization is performed, after which control messages may be received and used to configure the device prior to network entry. Subscribers then enter the network using the contention-based ranging channel of the uplink subframe.

3.2.3 Dynamic Spectrum Access Networks (DySPANs)

Network rendezvous using both in-band control signalling and fixed frequency control channels depends upon the use of known channels which may be scanned for control information. DySPAN systems achieve highly efficient spectrum use by detecting and occupying spectrum white space - frequency bands which are unoccupied by other networks at given times and places. As the availability of this white space spectrum fluctuates over time, the channels used by a DySPAN system may not be known in advance and can change unpredictably over time as other primary and secondary networks occupy and vacate them. Under these conditions, more complex techniques are required to perform network rendezvous.

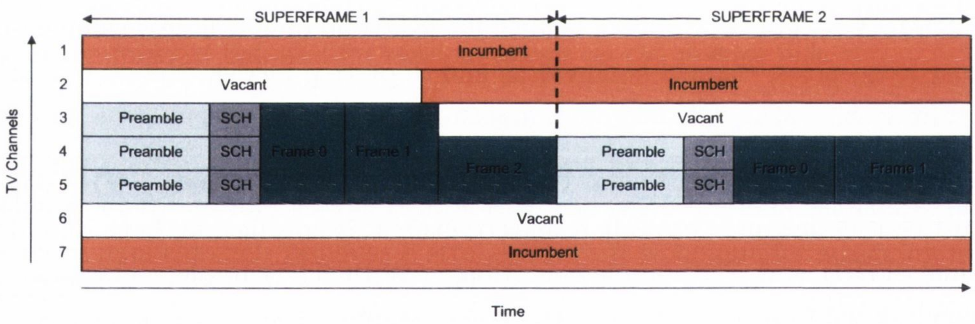


Fig. 3.3: IEEE 802.22 Superframe structure. Reproduced from [6].

The first networking standard based on the use of DySPAN technology is currently under development by the IEEE 802.22 working group on wireless regional area networks [58]. The standard seeks to outline the PHY, MAC and air interface for use by license-exempt devices on a non-interfering basis in broadcast TV spectrum between 41 and 910 MHz. A fixed point-to-multipoint (P-MP) topology is specified with a minimum peak downstream rate of 1.5 Mbps per subscriber. A critical requirement for the standard is the protection of legacy networks operating in the same spectrum bands including broadcast TV networks as well as other services such as wireless microphones. In order to provide legacy network protection, a system of distributed sensing is proposed whereby spectrum sensing is performed by each subscriber device and observations within a cell are pooled by the base station in order to reach spectrum occupancy decisions.

The draft standard specifies use of OFDM-based modulation for both the uplink and downlink and network rendezvous is facilitated through use of a specified superframe structure, illustrated in Fig. 3.3. At the start of each superframe is a preamble which is used for frame detection and synchronization. The preamble is followed by a superframe control header (SCH) which provides all information needed to associate with the basestation and enter the network. A key challenge for 802.22 devices commencing operation however, is the detection of those channels currently in use by the network.

Upon starting up, an 802.22 subscriber will perform a scan of the TV channels in order to build a spectrum occupancy map and identify vacant channels. Each of these channels may potentially be used by the network and so each is scanned for superframe preambles. Upon detection of a superframe, synchronization is performed and the SCH is used to obtain control information for the network. Once network rendezvous is achieved, the spectrum occupancy map is provided to the base station for use in the distributed sensing process.

Network rendezvous is also complicated by the use of channel bonding in the 802.22 draft standard. Channel bonding is used to achieve the high data rates required by the 802.22 specifications and involves the simultaneous use of up to three unoccupied TV channels, providing an overall bandwidth of 18 MHz for 6 MHz channels. In performing network rendezvous however, a subscriber does not have prior knowledge of the number of bonded channels in use by the network. For this reason, the superframe preamble and SCH used for network rendezvous are transmitted independently upon each channel used (see Fig. 3.3). Subscriber devices may thus detect transmitted superframes and receive SCH control messages by scanning individual channels.

3.2.4 Summary

Looking at a number of the mechanisms used for frequency rendezvous and network coordination in existing wireless systems, it can be seen that each depends upon prior knowledge about operating frequencies, channel schemes, signal bandwidths and/or waveform parameters in use within that system. As flexibility in these operating parameters is introduced, the challenge of rendezvous and coordination becomes more significant. The power of DySPAN systems stems from the ability to introduce exactly this form of flexibility. Thus, in order to facilitate rendezvous and coordination in DySPAN systems, new mechanisms are required.

In the next section, I examine a number of proposed techniques and address their strengths and weaknesses.

3.3 Existing Approaches to DySPAN Rendezvous and Coordination

Spectrum availability for DySPAN systems may depend upon the occupancy of other systems operating in the same spectrum band, both higher-priority primary networks and other equal-priority secondary networks. Under these conditions, a static channel may not be allocated and so a fixed frequency control channel such as that used in GSM networks may not be used to achieve network rendezvous and coordination. In-band control signalling such as that used in WiMAX and proposed IEEE 802.22 networks offers an alternative approach to that of the fixed frequency control channel by including control traffic together with data traffic in uplink and downlink frames. However, this approach relies on the use of known channels which can be individually scanned for frames containing control data. In the case of IEEE 802.22, these channels are determined by the main wireless system present in the same spectrum band, terrestrial broadcast TV. Under more general dynamic spectrum access conditions however, a wide range of heterogeneous networks may be required to utilize the same spectrum band. These networks may use a range of differing channel schemes and may need to dynamically adapt channel bandwidths according to system requirements. Thus, in order to achieve highly efficient spectrum use, DySPAN systems must take advantage of any unoccupied spectrum which can be reliably detected and must not be constrained by fixed channel schemes and carrier frequencies. A solution to the challenge of frequency rendezvous and network coordination must therefore facilitate device discovery, network creation and network entry while supporting high degrees of flexibility in the carrier frequencies, signal bandwidths and waveforms utilized by the network.

A significant advantage of such a highly flexible mechanism for rendezvous in DySPAN systems would be the ability to apply the same approach to a number of different heterogeneous networks. DySPAN systems may comprise a number of highly adaptable heterogeneous devices, each capable of adopting a wide range of operating parameters including carrier frequencies and signal bandwidths as well as waveform-specific parameters. Such devices are not confined to a single network but may join a range of networks, both dynamic and static, through careful choice of operating parameters. A common network approach for rendezvous and coordination would permit devices to quickly detect the presence of all compatible networks in a given location, choose that which is most suited to its requirements and perform rendezvous.

One suggested approach for facilitating the levels of co-ordination required is the use of a static common control channel over which systems could negotiate access to available spectrum [59, 60, 61]. However, the common control channel approach has a number of significant drawbacks.

The first of these is the assumption of continuously available spectrum on which to host the control channel. In a DySPAN environment, the spectrum available for use may change dynamically due to the occupancy of other systems. Under these conditions, it may not be possible to allocate a fixed control channel and an alternative mechanism for coordination is required. Secondly, in order to access the common control channel, all DySPAN systems must agree upon and support a predefined set of waveforms, parameters, frame structures and access protocols to be used. By employing a less restrictive and complex mechanism for coordination, it may be possible to permit a greater range of wireless system types to take part and access the available spectrum. Furthermore, a common control channel poses a performance bottleneck and single point of failure for all networks employing it.

An alternative approach [62, 63] involves the use of local control channels which are dynamically assigned within cognitive node clusters. Within a node cluster, spectrum availability may be considered uniform and a control channel may be allocated. However, the successful creation and maintenance of these node clusters involves considerable additional network complexity and overhead.

Cordeiro and Challapali [64] propose the use of a *rendezvous channel (RC)* in order to coordinate multi-channel DySPAN systems. This channel is dynamically chosen in a distributed fashion and a backup channel system is used to provide robustness. However, the cognitive medium access control (MAC) protocol proposed relies upon the use of a known channel scheme as a beaconing and channel scanning system is employed for initial choice of the RC.

A system using frequency domain decision statistics is suggested by Horine and Turgut [65]. The approach involves transmission of an attention signal with an easily identified spectrum in order to achieve link rendezvous. Listening nodes scan the spectrum band of interest, using fast Fourier transform (FFT) processing to perform frequency domain detection of the attention signal. The authors propose the use of a double-sideband signal, amplitude modulated with a set of discrete tones at specific relative amplitudes and offset frequencies. These particular tones are used for identification. While this low-complexity approach would facilitate rendezvous between heterogeneous DySPAN devices without the need for á priori knowledge about a wide range of operating parameters, it suffers from a number of drawbacks. The first of these is an intolerance to noise in general and frequency-selective fading in particular. Any distortion of the specified tones may result in a missed detection. Furthermore, the use of a dedicated beaconing signal requires a beaconing node to transmit at the same time and operating frequency being scanned by a listening node. Once a communications link is established, no mechanism is specified to support rendezvous by a third or subsequent devices. Polson [66] likens this use of beaconing to two men searching for each other with flashlights, a mile apart on a moonless, dark night in the middle of a desert.

3.4 Summary

In this chapter I have examined the challenge of frequency rendezvous and network coordination for DySPAN systems. By examining a number of mechanisms used to overcome this challenge in current networks, I have shown that current approaches typically rely upon prior knowledge of operating frequencies, signal bandwidths, channel schemes and/or waveform-specific parameters. DySPAN systems promise very high levels of spectrum-use efficiency through sharing spectrum resources with other networks while avoiding the creation of harmful interference. In order to do this, they must be capable of dynamically adapting some of these operating parameters which are typically fixed in conventional systems. With the introduction of this flexibility comes the challenge of DySPAN rendezvous and coordination.

The first requirement for a DySPAN rendezvous and coordination mechanism is a degree of independence from the dynamic parameters of the system. By developing a technique which can be employed while offering significant flexibility in operating parameters, the power of the system to adapt and reconfigure can be preserved. Any coordination technique will, by definition, require some features of the system to remain constant. However, it may be possible to keep these particular features constant while allowing some fundamental parameters of the system to be dynamically adapted.

DySPAN systems are likely to operate in spectrum bands which are shared with other heterogeneous wireless systems. This issue further complicates the process of rendezvous and coordination. Rather than simply detecting and synchronizing with a signal of interest in one of a number of known channels, DySPAN devices must detect a signal of interest (SOI) received at any operating frequency within that shared spectrum band. Furthermore, they must be capable of uniquely identifying that SOI as being transmitted by a member of a network with which they can join. Following identification, they must synchronize with the SOI in frequency and time in order to establish a communications link.

In addition to these challenges, a technique for DySPAN rendezvous and coordination must involve relatively low complexity, yet must permit rendezvous to be achieved within a minimum timeframe and with a considerable degree of robustness.

The development of an ideal technique which successfully meets each of these criteria poses a significant challenge. However, DySPAN systems are enabled by the considerable power and flexibility of software-defined radio (SDR) and today's digital signal processing capabilities, which place a range of powerful tools at our disposal. One such tool is *cyclostationary signal analysis*. In the next chapter, I examine cyclostationary signals, a number of the ways in which they can be processed and analysed and I discuss ways in which they can be leveraged to overcome the challenge of frequency rendezvous and network coordination for DySPAN systems.

4. CYCLOSTATIONARY SIGNAL ANALYSIS

4.1 Introduction

In the previous chapter, the challenge of rendezvous and coordination in Dynamic Spectrum Access Networks (DySPANs) was outlined. It was seen that the challenge becomes more significant with the introduction of flexibility in the fundamental operating parameters of a wireless system. As the power of DySPAN systems stems from precisely this type of flexibility, new techniques for achieving rendezvous and coordination are required.

One tool with considerable potential for use in the development of a rendezvous mechanism for DySPAN systems is *cyclostationary signal analysis*. Many of the communications signals in use today may be modelled as cyclostationary processes due to the presence of implicit periodicities. These periodicities are caused by the coupling of stationary message signals with periodic sinusoidal carriers, pulse trains or repeating codes as well as processes such as sampling and multiplexing. Using non-linear transformations, the cyclostationary properties of a signal can be detected and leveraged to accomplish key tasks including signal detection [67, 68], classification [69, 70], synchronization [71, 72] and equalization [73, 74].

In this chapter I introduce cyclostationary signal analysis and examine some of the ways in which the technique may be employed in emerging DySPAN systems. Section 4.2 addresses the concepts of stationarity and cyclostationarity and presents the key functions used to examine cyclostationary signals. In Section 4.3, some of the ways in which cyclostationary signal analysis is employed in communication systems today are examined. Some potential applications of cyclostationary signal analysis in DySPAN systems are discussed in Section 4.4. Section 4.5 concludes the chapter.

4.2 Cyclostationary Signals

4.2.1 Stationarity and Cyclostationarity

Much of classical signal processing theory is based upon the use of a stationary signal model, in which the second and higher order statistics of the signal are deemed to be constant over time. However, inherent periodicities which underlie many of the naturally occurring and man-made signals typically encountered cause the statistics of those signals to vary periodically with time. These signals are more appropriately modelled as *cyclostationary*.

A signal is cyclostationary with order n if and only if there exists some nth-order nonlinear transformation of that signal which will generate finite-strength additive sine-wave components [75]. A signal, $x(t)$, is said to exhibit *second order* cyclostationarity if its mean and autocorrelation are periodic with some period, T_0 [76]:

$$\mu_x(t + T_0) = \mu_x(t) \tag{4.1}$$

$$R_x(t + T_0, \tau) = R_x(t, \tau) \tag{4.2}$$

Here the mean, $\mu_x(t)$ and the autocorrelation, $R_x(t, \tau)$ are defined as:

$$\mu_x(t) = E[x(t)] \tag{4.3}$$

$$R_x(t, \tau) = E[x(t)x^*(t - \tau)] \tag{4.4}$$

where $E[x(t)]$ denotes expected value of $x(t)$.

This definition of signal cyclostationarity can be illustrated by way of an example, reproduced here from [77]. Fig. 4.1 illustrates a random bipolar rectangular pulse sequence, with keying period T_0 and lag illustrated as τ.

In deriving the autocorrelation of a process on the basis of the probabilistic definition (as in Eq. 4.4), a stationary or cyclostationary model may be adopted depending upon the definition of the ensemble used. An ensemble is an imaginary set of an infinite number of instances of the process under consideration. In the case of the bipolar rectangular pulse sequence with period T_0 and amplitude -1 or 1 illustrated in Fig. 4.1, all members of the ensemble will have the same period and amplitude but will have different random data sequences.

In order to adopt a cyclostationary model, the temporal relation between members of the ensemble is key. Particularly, if members of the ensemble are synchronous

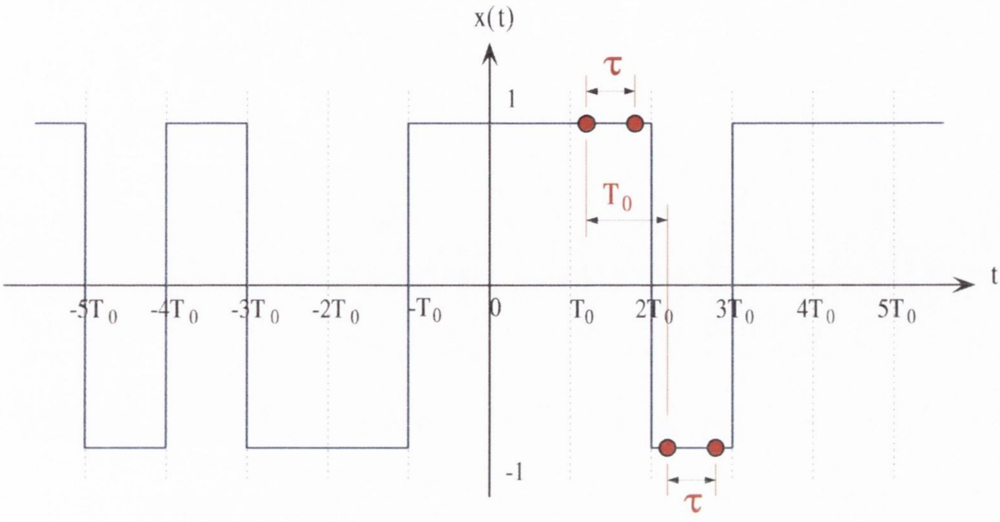


Fig. 4.1: Autocorrelation of a bipolar rectangular square pulse sequence.

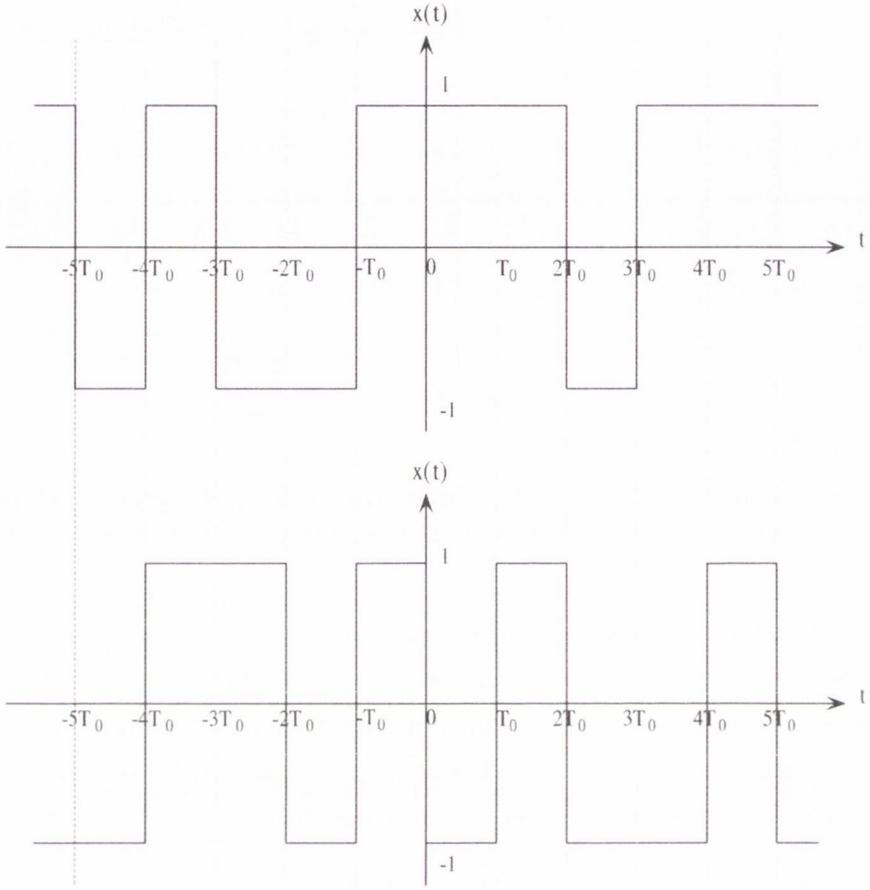
(symbol transitions occur at the same time) then the cyclostationarity of the process is preserved. However, if members of the ensemble are asynchronous (there exist random phase differences between members), phase randomizations are introduced, the innate periodicity of the process is lost and it becomes stationary. This issue of synchronous ensemble members is illustrated in Fig. 4.2 and Fig. 4.3.

Fig. 4.2(a) shows two members of an ensemble with synchronous symbol transitions. In this case, cyclostationarity of the signal is preserved. The two-parameter autocorrelation illustrated in Fig. 4.2(b) shows the time-variant properties of the autocorrelation function. From this function, it can be seen that the autocorrelation is periodic with period dependent upon the lag τ.

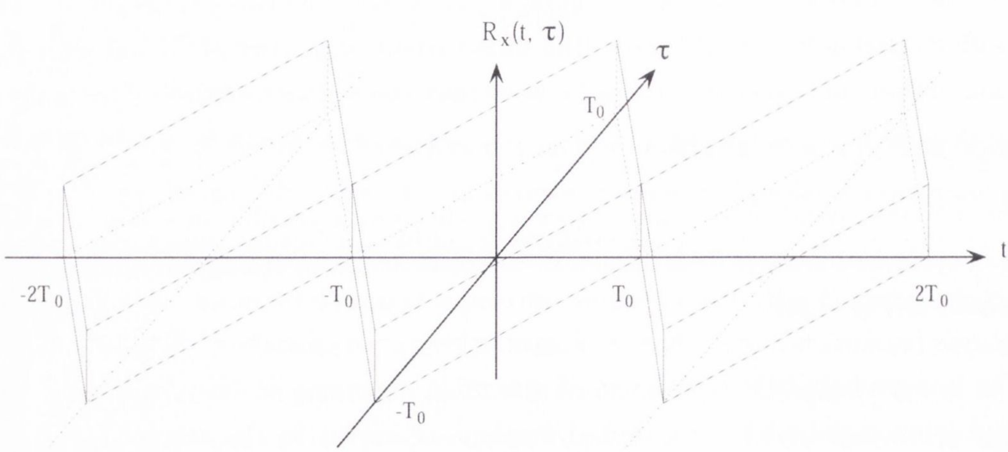
On the other hand, Fig. 4.3(a) shows asynchronous ensemble members, leading to a loss of cyclostationarity. This results in the time-invariant triangular autocorrelation illustrated in Fig. 4.3(b).

The non-probabilistic equivalent of ensemble averaging is time averaging, where a signal is averaged with time-shifted versions of itself. In the case of synchronous averaging, these time shifts comprise an integer number of symbols and so symbol transitions remain concurrent and signal cyclostationarity is preserved. However, with asynchronous averaging, random phase shifts are introduced, removing the innate periodicity of the signal and making it stationary.

As the autocorrelation of a cyclostationary signal is periodic in time, it accepts a

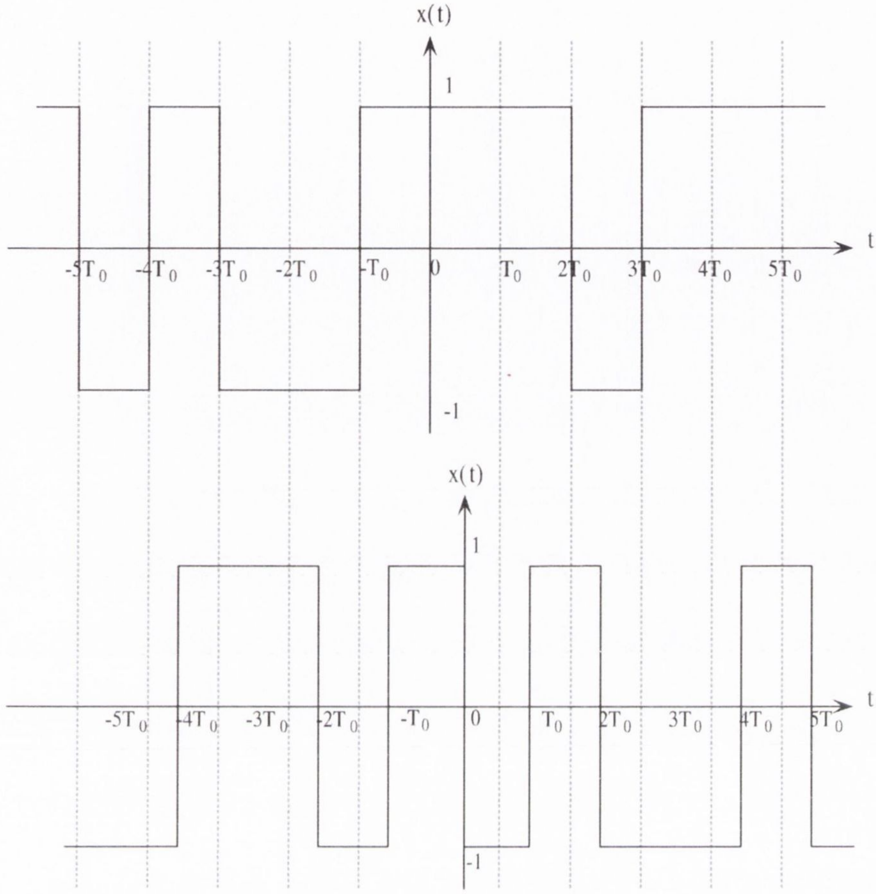


(a) Synchronous ensemble members, leading to preservation of cyclostationarity.

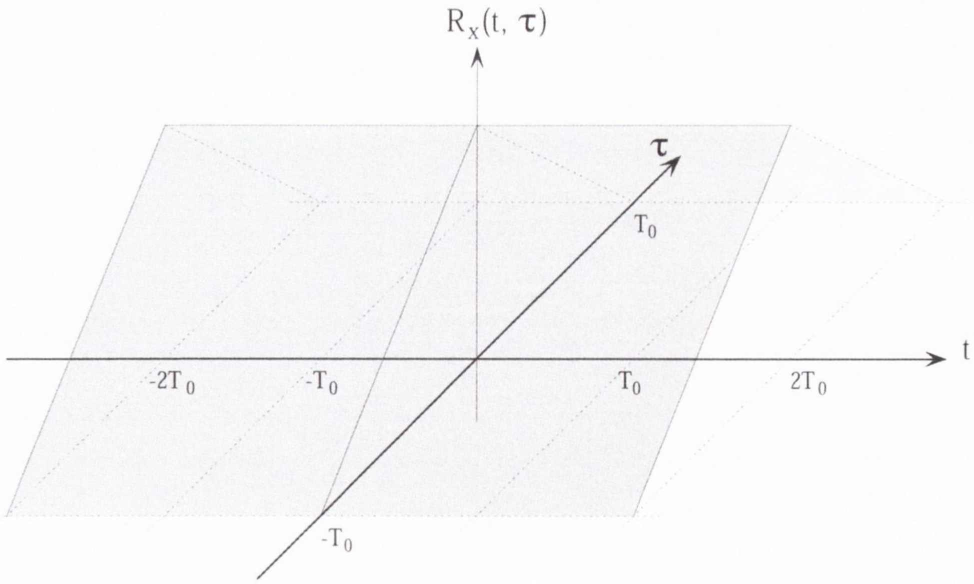


(b) Autocorrelation of cyclostationary rectangular pulse sequence

Fig. 4.2: Cyclostationary modelling of a bipolar rectangular pulse sequence.



(a) Asynchronous ensemble members, leading to loss of cyclostationarity.



(b) Autocorrelation of stationary rectangular pulse sequence

Fig. 4.3: Stationary modelling of a bipolar rectangular pulse sequence.

Fourier series expansion [76]:

$$R_x(t,\tau) = \sum_{\{\alpha\}} R_x^\alpha(\tau)e^{i2\pi\alpha t} \quad (4.5)$$

where $\{\alpha\}$ includes all values of α in the principal domain $(-\frac{1}{2}, \frac{1}{2}]$ for which the corresponding Fourier coefficient is not identically zero as a function of τ. The Fourier coefficients, R_x^α will be non-zero only at values of α which equal a period of the autocorrelation function. If $R_x(t,\tau)$ is non-periodic, all coefficients of the expansion will be zero except for R_x^0. These coefficients therefore represent the cyclostationarity of a signal in the time domain and are known as the *cyclic autocorrelation function (CAF)*:

$$\begin{aligned} R_x^\alpha &= E[R_x(t,\tau)e^{-i2\pi\alpha t}] & (4.6) \\ &= E[x(t)x^*(t-\tau)e^{-i2\pi\alpha t}] & (4.7) \end{aligned}$$

The identity α is known as the *cyclic frequency*. The set of values of α for which $R_x^\alpha \neq 0$ is known as the cycle spectrum.

While the CAF may be used to examine signal cyclostationarity in the time domain, it also reveals the impact of that cyclostationarity in the frequency domain. From Eq. 4.7, it can be seen that $x(t)e^{-i2\pi\alpha t}$ is the signal $x(t)$ shifted in the frequency domain by α. Therefore, the cyclic autocorrelation of $x(t)$ is simply the cross-correlation between the signal and a frequency-shifted version of itself. If a signal $x(t)$ is cyclostationary with cyclic frequency α, there exists a non-zero correlation between that signal and a version of itself, shifted in frequency by α. This is known as *spectral correlation* and is the frequency domain manifestation of cyclostationarity. Spectral correlation and the *spectrum correlation function (SCF)* used to analyse it are examined in the next section.

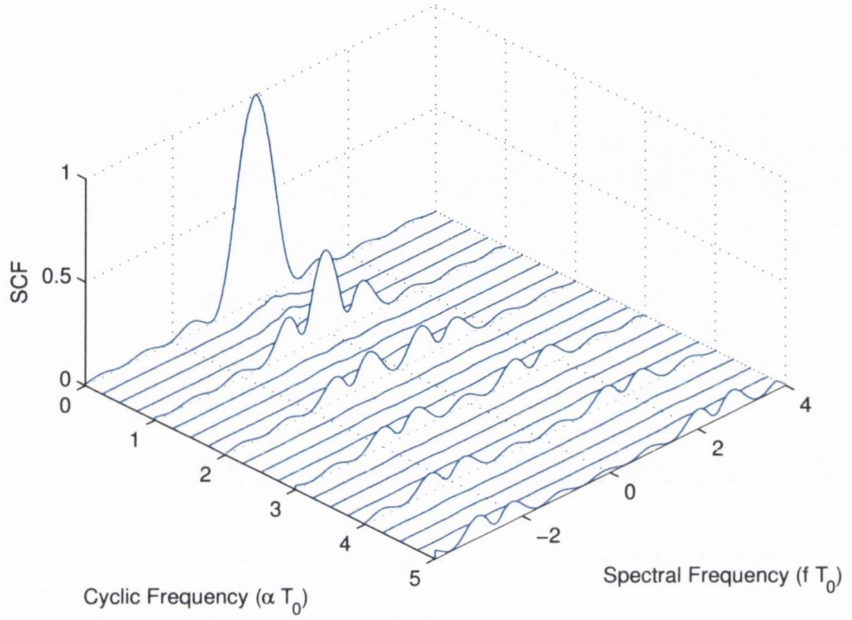
4.2.2 Frequency-Domain Representation : Spectral Correlation

In the frequency domain, signal cyclostationarity manifests as a correlation pattern in the spectrum of the signal. These correlation patterns may be examined using the Fourier transform of the CAF, the spectrum correlation function (SCF) [76]:

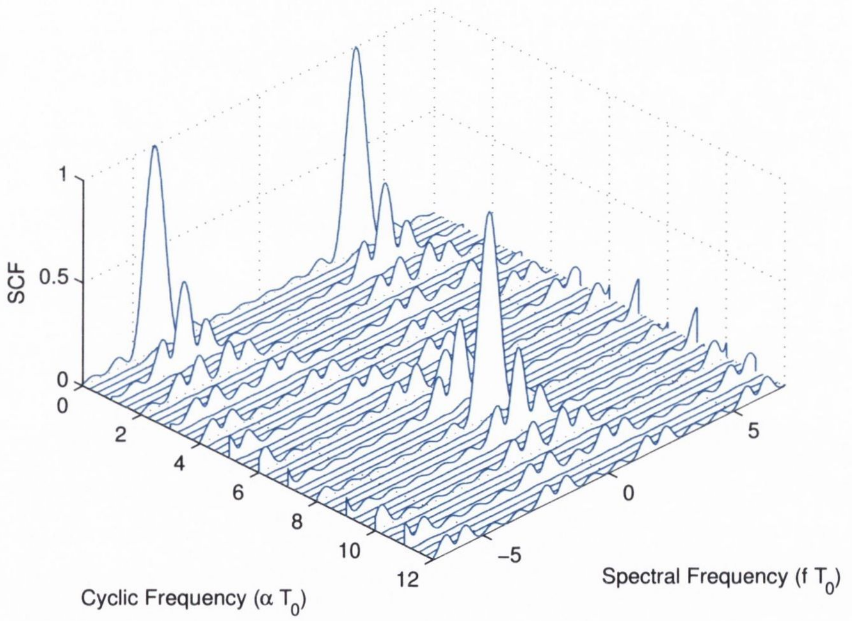
$$S_x^\alpha(f) = \int_{-\infty}^{\infty} R_x^\alpha(\tau)e^{i2\pi f\tau}d\tau \quad (4.8)$$

For cyclic frequency $\alpha = 0$, the CAF and SCF reduce to the conventional autocorrelation function and power spectral density respectively, related by the well-known

Wiener-Khinchin theorem [78].



(a) SCF of a baseband BPSK signal



(b) SCF of a passband BPSK signal

Fig. 4.4: Spectral correlation functions of baseband and passband BPSK signals.

Many of the communications signals in use today exhibit cyclostationarity due to the processes used in their generation. While a message sequence in itself may be stationary, innate periodicities are introduced through coupling with sinusoidal carriers, repeating pulse sequences or repeating codes. Cyclostationary features are also created by processes such as sampling, multiplexing and, in the case of Orthogonal Frequency Division Multiplexing (OFDM), the use of a cyclic prefix. One of the key benefits of cyclostationary signal analysis is the ability to use these features to derive useful information about the processes which cause them.

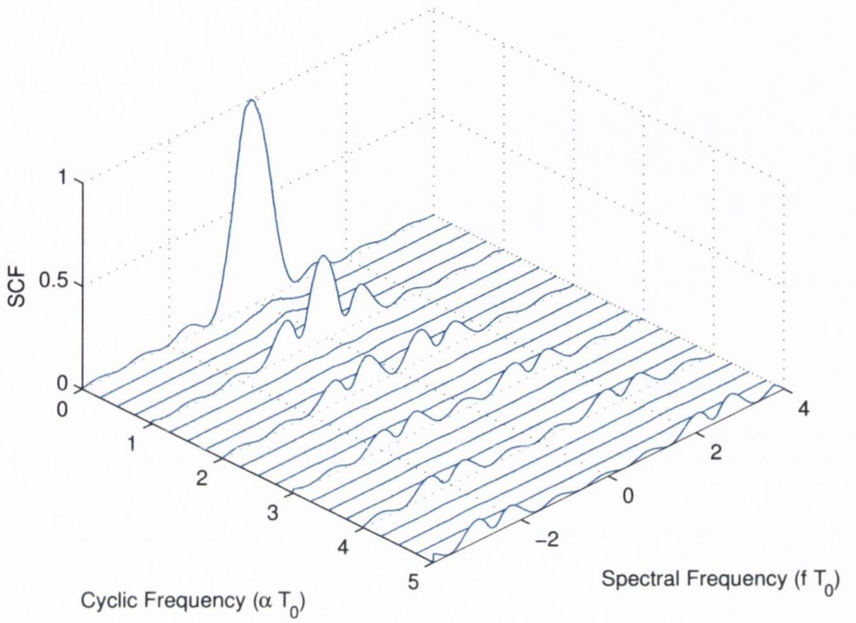
Fig. 4.4 shows the SCFs associated with baseband and passband binary phase shift keying (BPSK) signals. Examining the SCF for baseband BPSK in Fig. 4.4(a), we can see the power spectral density (PSD) of the signal at cyclic frequency $\alpha = 0$. The rectangular pulse shape of the time-domain signal gives rise to the $sinc^2(x)$ shape seen in the frequency domain. In this example, the baud rate of the signal is 1. Accordingly, a cyclostationary feature associated with this baud rate can be seen at the cyclic frequency $\alpha = 1$. Harmonics of the baud rate also give rise to cyclostationary features, these can be seen at integer multiples of the base cyclic frequency $\alpha = 2, 3, 4 \ldots$

In addition to features associated with the signal baud rate, features arising due to the carrier frequency of a passband BPSK signal can be seen in Fig. 4.4(b). In this example, a carrier frequency of $F_c = 4T_0$ is used. The resulting cyclostationary feature can be seen at $\alpha = 2F_c = 8T_0$.

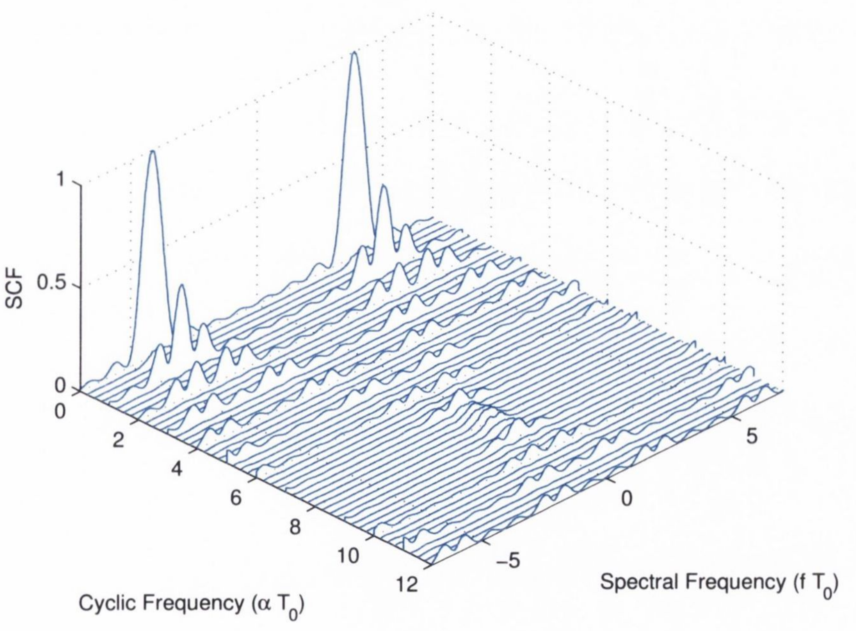
Through examination of the patterns of spectral correlation present in a signal, a great deal of information can be derived about that signal and the processes used to generate it. In the case of a BPSK signal, we have seen that these cyclostationary features can be used to determine both the baud rate and the carrier frequency. In this way, cyclostationary signal analysis can be used to achieve blind receiver synchronization [71, 72].

The SCFs for baseband and passband BPSK can be compared with those for quadrature phase shift keying (QPSK) in Fig. 4.5. While the baseband features of both signals can be seen to be identical, the SCF of the passband QPSK exhibits no carrier frequency-related features. This can be explained by the fact that BPSK is a real signal, with constellation points [-1,1], while QPSK is a complex signal with constellation points [1+i, 1-i, -1+i, -1-i].

As a real signal, baseband BPSK exhibits reflective symmetry about the zero frequency axis. However, being complex, baseband QPSK does not exhibit this symmetry. For passband signals, positive and negative frequency components are reflected about the zero frequency axis. The baseband symmetry of BPSK means that significant correlation exists between positive and negative frequency components separated by twice the carrier frequency. As QPSK does not exhibit this reflective symmetry, compo-



(a) SCF of a baseband QPSK signal



(b) SCF of a passband QPSK signal

Fig. 4.5: Spectral correlation functions of baseband and passband QPSK signals.

nents separated by $2F_c$ are uncorrelated and cyclostationary features due to the carrier frequency do not occur.

Although the power spectrum for BPSK and QPSK signals are very similar, it can be seen that their spectral correlation properties are quite different. These differences can be observed using cyclostationary signal analysis and so this approach can be used to differentiate the two. In the same way, many of the modulation schemes employed in communications signals exhibit distinct spectral correlation properties which can be determined through cyclostationary signal analysis and used to perform signal classification [69, 70].

4.2.3 Measurement of Spectral Correlation

Much of the initial work demonstrating the power of cyclostationary signal analysis when applied to wireless communications was carried out by Gardner and his colleagues [75, 79, 80, 81]. In [82], the issue of spectral correlation measurement was addressed.

In discussing the measurement of spectral correlation, Gardner showed that estimation of the spectrum correlation function (SCF) for a time series exhibiting cyclostationarity can be performed using both time-smoothed and frequency-smoothed approaches. The time-smoothing approach involves use of the time-smoothed cyclic cross periodogram (TS-CCP), which has been shown to be a consistent, asymptotically unbiased and complex normally distributed estimator for the cyclic spectrum [83]:

$$\widehat{S}_x^{\alpha}(f) = \lim_{\Delta f \to 0} \lim_{\Delta t \to \infty} \frac{1}{\Delta t} \int_{-\Delta t/2}^{\Delta t/2} \Delta f X_{1/\Delta f}(t, f + \alpha/2) X^*_{1/\Delta f}(t, f - \alpha/2) dt \tag{4.9}$$

where $X_{1/\Delta f}(t, v)$ is the complex envelope of the narrow band-pass component of $x(t)$ with centre frequency v and approximate bandwidth Δf:

$$X_{1/\Delta f}(t, v) = \int_{t-1/2\Delta f}^{t+1/2\Delta f} x(u) e^{-i2\pi v u} du \tag{4.10}$$

Gardner showed that this approach is completely equivalent to the frequency-smoothed approach, using the frequency-smoothed cyclic cross periodogram (FS-CCP):

$$\widehat{S}_x^{\alpha}(f) = \lim_{\Delta f \to 0} \lim_{\Delta t \to \infty} \frac{1}{\Delta f} \int_{f-\Delta f/2}^{f+\Delta f/2} \frac{1}{\Delta t} X_{\Delta t}(t, v + \alpha/2) X^*_{\Delta t}(t, v - \alpha/2) dv \tag{4.11}$$

Here, $X_{\Delta t}(t, f)$ is defined by 4.10 with $1/\Delta f$ replaced with Δt.

By illustrating the equivalence of the time and frequency-smoothed approaches for spectral correlation measurement, Gardner provided a unifying theoretical framework for cyclic spectrum estimation. A key aspect of this framework addresses the reliability with which spectral correlation estimates may be made using either approach. Specifically, Gardner showed that in order to minimize random effects and increase estimate reliability, the temporal-spectral resolution product must greatly exceed unity:

$$\Delta t \Delta f >> 1 \tag{4.12}$$

Here Δt and Δf are the *temporal resolution* and *spectral resolution* respectively. Due to use of the Fourier transform, the spectral resolution capability, Δf^0 of a cyclic periodogram measurement is on the order of the reciprocal of duration $1/T$ of the series which is transformed:

$$\Delta f^0 \cong 1/T \tag{4.13}$$

The temporal resolution capability, Δt^0 is determined by the length of the time integral, T:

$$\Delta t^0 = T \tag{4.14}$$

Combining these, it can be seen that the temporal-spectral resolution product is approximately unity for any given value of T:

$$\Delta t^0 \Delta f^0 \cong 1 \tag{4.15}$$

However, in performing spectral correlation measurement, the process of smoothing will involve a reduction in one of these two resolution capabilities. In order to ensure that random effects are minimized, substantial smoothing is required. Thus, for time-smoothing,

$$\Delta t >> 1/\Delta f \tag{4.16}$$

and for frequency-smoothing

$$\Delta f >> 1/\Delta t \tag{4.17}$$

Thus, for both approaches, the temporal-spectral resolution product must greatly exceed unity:

$$\Delta t \Delta f >> 1 \tag{4.18}$$

This relationship between the temporal and spectral resolutions of a cyclic spectrum estimate has a significant bearing upon the observation time required to reliably estimate a given cyclostationary features. Specifically, as the spectral resolution needed to resolve a feature decreases, the overall observation time required to perform reliable estimation increases and vica-versa. The significance of this trade-off in the context of DySPAN rendezvous and coordination is addressed in the next chapter.

While the TS-CCP and FS-CCP provide estimates of the cyclic spectrum for a time series, it is often useful to examine the *spectral coherence* exhibited by a series. This is achieved through use of the autocoherence function (AF):

$$C_x^{\alpha}(f) = \frac{S_x^{\alpha}(f)}{[S_x^0(f+\alpha/2)S_x^0(f-\alpha/2)]^{1/2}} \tag{4.19}$$

The AF is constrained to the range [0,1] and is the time-averaged correlation coefficient for frequency components of $x(t)$ separated by α.

A recognized limitation of cyclostationary signal analysis is the computational complexity which is typically entailed. This complexity arises due to the large number of correlation computations required in order to estimate the cyclic spectrum across a large region of the bifrequency (f-α) plane. This complexity is increased by the need to oversample the signal of interest (SOI) in order to perform cyclostationary analysis. In order to successfully analyse the spectral redundancies exhibited by cyclostationary signals, these signals must be sampled at a rate greater than Nyquist. If a signal's bandwidth is no greater than the Nyquist bandwidth $(-\frac{1}{2T}, \frac{1}{2T})$, there is no duplication of information within the signal. In this case there can be no spectral correlation and therefore no cyclostationarity.

One approach for reducing the computational complexity required for cyclostationary signal analysis involves reducing the bifrequency plane search space. If the cyclic features of a signal can be estimated in advance, there may be no need to estimate the full cyclic spectrum of that signal. By choosing a small range of spectral and cyclic frequencies, the computation required for analysis can be significantly reduced.

While computational complexity is still a key issue, it has become less of a barrier over the past decade as a result of significant increases in the processing power available across a range of platforms. Furthermore, the development of computationally efficient algorithms for cyclic spectral analysis has also served to reduce the complexity associated with cyclic spectral analysis. Using the TS-CCP as a basis, Roberts et al [84] describe a number of such algorithms. Their approaches take advantage of the highly efficient fast Fourier transform (FFT) algorithm in order to perform spectral analysis and to reduce the complexity associated with the time-smoothing process.

4.3 Applications of Cyclostationary Signal Analysis

4.3.1 Overview

Periodic phenomena give rise to cyclostationary signals in a diverse range of areas including telecommunications, telemetry, radar, sonar, mechanics, radio astronomy and econometrics. Within these areas, cyclostationary signal analysis has been successfully applied to overcome a broad range of challenges. Comprehensive surveys of the use of cyclostationary signal analysis in these areas can be found at [85] and [86].

In this section however, I focus on the use of cyclostationary signal analysis in wireless communications systems. Specifically, I address the areas of signal detection, classification, synchronization and equalization as well as cyclic Wiener or frequency shift (FRESH) filtering. The advantages of leveraging signal cyclostationarity in these contexts are outlined and key research contributions are discussed.

4.3.2 Signal Detection and Classification

In the area of signal detection for wireless communication systems, three broad categories of detectors can be identified. These are non-coherent energy detectors, feature detectors and coherent detectors such as matched filters.

Radiometric or energy detectors require little or no prior information about the signal to be detected, however they suffer from a number of recognized drawbacks. In particular, radiometric approaches typically exhibit sensitivity to noise and interference uncertainty which severely limits their performance. Energy detectors are also very limited in the amount of information which can be obtained about a detected signal of interest (SOI). Other than registering the presence of a signal, this approach cannot be used reliably to measure or exploit timing or phase properties of the SOI or to determine operating parameters such as carrier frequency, signal bandwidth or modulation scheme.

In contrast, coherent detectors such as matched filters use prior knowledge of an SOI to achieve detection performance above and beyond that provided by non-coherent approaches. However, these detectors are typically tailored to specific signal types and cannot be applied generally. While coherent approaches can be successfully applied for signal classification, a unique matched filter is typically required for each signal type to be classified.

Between the two extremes of energy detection and matched filtering, general cyclostationary feature detectors may be employed with limited prior knowledge about the SOI and yet can be used to determine and exploit specific signal properties to achieve improved detection performance over equivalent radiometric approaches. This flexibility of cyclic-feature detection stems from the wealth of information which can be derived from the cyclic spectrum of a communications signal.

It has been shown that cyclic feature detectors may be used successfully to detect low-powered signals in the presence of noise or interferers and to differentiate between and classify interfering signals. This is made possible by the discriminatory capabilities of the cyclic spectrum. Signal features which overlap in the power spectrum due to interference often occur at discrete cyclic frequencies and so can be independently identified and used for detection and classification. Similarly, while signal features may be obscured by noise in the power spectrum, this noise is frequently uncorrelated at cyclic frequencies above zero and so cyclic features of the signal may be identified using the cyclic spectrum.

These key advantages of cyclic feature detectors are examined by Gardner in [67], where a unifying framework for feature detection is developed. Using this framework of the spectral correlation theory of cyclostationary signals, Gardner shows that relationships between a wide range of signal detectors can be established and direct comparisons can be drawn. The main drawbacks associated with radiometric approaches to signal detection are outlined and the performance advantages of cyclic feature detectors are illustrated using receiver operating characteristic (ROC) performance comparisons.

The advantages of cyclic feature detectors are further examined in [68]. Here, comparisons are made between four detector types for spread-spectrum phase shift keyed (PSK) signals. The detectors compared are the optimum radiometer, the optimum radiometer featuring noise level estimation and maximum signal-to-noise ratio (SNR) feature detectors for chip-rate and doubled carrier-frequency related features. ROC performance is used to show that the cyclic feature detectors outperform both radiometric approaches.

More recently, Tandra and Sahai [87] have performed performance comparisons for each of the detector categories listed above. In particular, the authors define *SNR walls* as fundamental sensitivity limits which exist for all detectors in wireless environments due to natural model uncertainties. These SNR walls are derived for each category of detection algorithm and used for comparison. It is shown that the SNR wall for cyclic feature detectors outperforms that for energy detectors but falls short of that for coherent detection using a matched filter.

In the area of signal classification, the benefits of cyclostationary signal analysis are well recognised. While many of the signals used in wireless communications have similar power spectral densities, their cyclic features are frequently very different. This was seen in the case of BPSK and QPSK signals in the previous section. Cyclic features associated with a much wider range of analog and digital modulation types are examined in [80, 81] and [88]. By taking advantage of these unique cyclic features, a classifier can achieve high levels of performance at low SNR values while using relaxed information on the specific signal parameters being detected.

Classifiers employing neural networks and cyclic feature detectors are proposed in [69] and [70]. Fehske et al propose the use of the α-profile defined as:

$$profile(\alpha) = \max_f [C_x^\alpha] \tag{4.20}$$

where C_x^α is the AF described in Section 4.2.3. In this way the amount of cyclic spectrum data which must be processed by the neural network can be significantly reduced. This approach is extended to include the use of the spectral frequency profile defined as:

$$profile(f) = \max_\alpha [C_x^\alpha] \tag{4.21}$$

by Wu et al.

Taking a similar approach, Kim et al [89] propose the use of the α-profile for signal classification. However, rather than employing a neural network, the authors propose the use of a hidden Markov model.

4.3.3 Synchronization and Equalization

In the area of phase and frequency synchronization of communication signals, Gardner showed that all synchronization schemes can be recognized to exploit the second or higher-order cyclostationary features of signals [90]. Synchronization involves matching the phase and frequency of an oscillator or clock to a periodicity contained in a signal. As cyclostationary signal analysis involves the study of innate signal periodicities, all synchronization approaches can be characterized in terms of the CAF or SCF. In this way, cyclostationary signal analysis provides a unifying framework for signal synchronization.

Gini and Giannakis [71] developed algorithms for joint estimation of frequency offset and symbol timing in flat-fading channels using second-order cyclostationarity. The nondata-aided approaches proposed involve the use of nonlinear signal combinations to reveal periodic components containing synchronization parameters, a recognized approach for the analysis of cyclostationary signals. While Gini and Giannakis note that this approach underlies algorithms proposed by a number of authors, they attempt to unify and improve upon these proposals within a cyclostationary signal analysis framework.

Bölcskei [72] extended the blind synchronization algorithms proposed by Gini and Giannakis for single carrier systems to multi-carrier OFDM systems in 2001. In his paper, Bölcskei examines many of the ways in which cyclostationarity can arise in OFDM signals and illustrates how this cyclostationarity can be exploited to achieve blind frequency offset and symbol timing synchronization.

An overview of the use of cyclostationary signal analysis for blind channel identification and equalization is provided by Ding [91]. The author shows that channel identification can be achieved without the need for pilot signals or transmitter assistance by sampling the channel output at a rate greater than the baud rate and exploiting the signal cyclostationarity to recover the magnitude and phase of the channel transfer function. This approach was extended to include multi-carrier OFDM systems by Heath and Giannakis [74] in 1999.

More efficient approaches to channel identification and equalization using transmitter-induced cyclostationarity were explored by Gardner [79] and Tsatsanis and Giannakis [73].

4.3.4 Cyclic Wiener/Frequency Shift (FRESH) Filtering

Signal cyclostationarity manifests in the frequency domain as correlation patterns in the signal spectrum. These correlation patterns provide a degree of redundancy in spectral components of the signal. Cyclic Wiener or frequency shift (FRESH) filtering takes advantage of this spectral redundancy in cyclostationary signals in order to overcome a range of challenges including the separation of temporally and spectrally overlapping signals and the removal of narrow in-band interferers.

The theory and application of FRESH filtering is developed by Gardner in [75]. Examples of the use of FRESH filtering are provided and include the separation of overlapping amplitude modulation (AM), BPSK and QPSK signals. A more detailed examination of the practical use of FRESH filtering for interference rejection is provided by Adlard [77].

4.4 Cyclostationary Signal Analysis and DySPAN Systems

4.4.1 Overview

In the previous section it was seen that cyclostationary signal analysis provides a powerful and highly flexible tool which can be leveraged to overcome many of the challenges typically associated with wireless communication systems. A specific advantage of this form of signal analysis is that it may be applied with limited prior knowledge about the parameters of the signals being examined. This means that it can be used as a general technique for the analysis of a broad range of signal types.

A key advantage of cyclostationary signal analysis when compared with alternative approaches lies in the wealth of information which can be derived by analysing the cyclic features of a signal. As well as providing a robust technique for signal detection, cyclostationary signal analysis permits key signal properties including modulation type and frequency and phase information to be determined and exploited. These capabilities have motivated the use of cyclostationary signal analysis in applications as diverse as signal detection, classification, synchronization and channel identification and equalization as well as interference rejection through cyclic Wiener filtering.

DySPAN systems achieve very high levels of spectrum use efficiency by dynamically adapting their parameters of operation in response to their operating environments. These increasing levels of flexibility are enabled by emerging software-defined radio (SDR) technologies. However, before DySPAN systems can be realised, a number of significant challenges must be overcome. Among these are the challenges of low-power signal detection, modulation classification and waveform recognition, synchronization and network rendezvous and coordination.

4.4.2 Proposed Applications

In order to achieve spectrum efficiency while avoiding the creation of harmful interference, DySPAN systems must develop an acute awareness of their radio-frequency environment. Low-power signal detection, modulation classification and waveform recognition is required to determine spectrum occupancy and thus the availability of spectrum *white spaces*. As well as determining the nature of other spectrum users, reconfigurable devices must discern the nature of signals being used by peer devices in order to establish communication links using that available spectrum. Above the level of individual point-to-point links, robust techniques are required to achieve network-wide coordination and to facilitate network rendezvous and link maintenance.

Considering the broad range of challenges associated with DySPAN systems, cyclostationary signal analysis would appear to be a tool highly suited to addressing these issues. Indeed, a number of authors have proposed the use of this approach in overcoming many of the key obstacles. In particular, the challenge of low-power signal detection has been identified as an area in which cyclostationary signal analysis may play a significant role.

In order to opportunistically use white space spectrum while avoiding the creation of harmful interference, DySPAN systems must detect the presence of other spectrum users with a high degree of reliability. Due to the hidden terminal problem and the possibility of fading at the detector, very low detection thresholds must be adopted to provide adequate interference protection. For example, the use of DySPAN systems has recently been proposed in the 700 MHz band used for broadcast television in the United States. In any given location, one or more TV channels may be unused and can be exploited by secondary systems for provision of services such as wireless internet. However, in order to avoid the creation of harmful interference, these secondary systems must reliably detect those channels which are in use. Typical digital TV receivers can provide error-free reception to a sensitivity on the order of -83 dBm. However, in order to account for the possibility of fading, detectors adopted in secondary DySPAN systems require a sensitivity of at least -113 dBm [92].

Coherent detection methods such as matched filtering can be used to provide maximum SNR detection however, as previously discussed, these approaches are typically tailored to specific signal types. DySPAN systems may need to share spectrum resources with more than one wireless system. Under these circumstances, a matched filter detector is required for each signal type which may be present. Cyclostationary signal analysis on the other hand provides a robust method of signal detection which can be applied generally to a broad range of signal types.

The use of cyclostationary signal analysis in the context of low-power signal detection has been proposed by a number of authors. Cabric [93] suggests the use of cyclic feature detectors as a non-coherent detection approach which overcomes a number of the limitations associated with energy detectors. Tkachenko [94] examines real-world detection results using cyclic feature detectors implemented upon an field programmable gate array (FPGA)-based platform and Shankar [95] examines the performance of feature detectors for digital TV signals.

A second DySPAN challenge to which cyclostationary signal analysis has been applied is modulation classification and waveform recognition. Many of the waveforms used in communications signals today exhibit unique cyclic features generated as a by-product of the processes used in their generation. These features can be detected using general detector architectures and used to uniquely identify those waveforms. In this way, a DySPAN device can classify other spectrum users and determine the nature of communication waveforms being used by peer devices. This approach has been proposed by Öner and Jondral for air interface recognition [96] and extraction of channel allocation information [97]. As previously discussed, Fehske [69], Kim [89] and Wu [70] have assessed the performance of cyclic feature detectors for modulation classification when combined with neural networks and hidden Markov models.

It has been shown that cyclostationary signal analysis may be successfully employed to overcome the DySPAN-related issues of low-power signal detection and classification. However, our interest lies in the challenge of network rendezvous and coordination in DySPAN systems. In the next section, I examine the potential of cyclostationary signal analysis for addressing this issue.

4.4.3 DySPAN Rendezvous and Coordination

In Chapter 3, rendezvous and coordination was identified as a key challenge which needs to be overcome before DySPAN systems can be successfully developed and deployed. DySPAN systems achieve high levels of spectrum use efficiency by identifying spectrum resources which are unused at specific times and places. By adapting their operating parameters, these systems can take advantage of such *white space* spectrum to establish communication links and form a network. However, with increasingly flexible operating parameters comes an increase in the challenge of rendezvous and coordination. Conventional rendezvous schemes typically rely upon prior knowledge of peer operating parameters. When those parameters are not fixed but may be dynamically adapted, these conventional schemes cannot be employed and new mechanisms are required.

In order for devices within a DySPAN system to achieve rendezvous and coordinate to form a network, a number of key tasks must be accomplished. Firstly, peer devices and compatible networks within transmission range must be detected and identified. This can be achieved by scanning one or more frequency bands for transmitted signals. Upon detection of a signal, a device must identify the transmitter as a peer, acquire that signal and successfully demodulate it in order to obtain control information and establish a communications link. While this process is essential for the initial establishment of communication links within a network, it may also be needed to maintain those links following an unexpected change in operating parameters. In the case of opportunistic DySPAN systems, such a change can occur upon the detection of a high priority spectrum user in the same band.

This chapter has examined cyclostationary signal analysis as a powerful tool for overcoming a number of challenges associated with wireless communication systems. It has been seen that the cyclic features present in many of the communications signals used today can be exploited to achieve key tasks associated with DySPAN systems including low-power signal detection and modulation classification. However, cyclostationary signal analysis is also a tool with significant potential use in overcoming the challenge of DySPAN rendezvous and coordination.

A key attraction of cyclostationary signal analysis is the ability to adopt one general signal processing technique in order to achieve multiple goals. Using this single approach, it could be possible for a DySPAN device to overcome each of the challenges associated with DySPAN rendezvous and coordination, namely peer detection, identification and signal acquisition.

However, there are a number of drawbacks associated with cyclostationary signal processing which significantly limit the potential this approach holds. The first of these drawbacks is the computational complexity associated with full cyclic spectrum signal analysis. The cyclic features which occur inherently in communications signals are typically tied to the operating parameters of those signals. These include the carrier frequency, baud rate, modulation type, pulse shape, in the case of OFDM-based systems, cyclic prefix length. Changes in these operating parameters will result in changes in the spectral and cyclic frequencies of the features associated with them. Thus, in order to reliably detect inherent signal features, a receiver must search the full cyclic spectrum of the signal. A second drawback typically associated with the use of cyclostationary signal analysis is the need for oversampling in the receiver. In order to detect and analyse inherent signal features, a sampling rate greater than Nyquist is needed. In this way, the excess bandwidth permits spectral redundancies to be identified and cyclic features to be detected.

A third drawback arises due to the small spectral resolution typically required to resolve inherent cyclic features of a signal. In Section 4.2.3 it was seen that the signal observation time required for reliable analysis of cyclic features is directly related to the spectral resolution needed to resolve those features. Specifically, in order to eliminate random effects in estimating cyclic features, the temporal-spectral resolution product must greatly exceed unity:

$$\Delta t \Delta f >> 1 \tag{4.22}$$

Thus, as a small spectral resolution is typically required to resolve inherent signal features, a relatively long signal observation time is required for reliable estimation of those features.

Before cyclostationary signal processing can be successfully employed to address the challenge of DySPAN rendezvous and coordination, these key limitations must be overcome.

4.5 Summary

This chapter has examined cyclostationary signal analysis, a powerful general signal processing technique which can be applied to overcome a wide range of challenges commonly associated with wireless communications systems. I have identified a number of the challenges which have been successfully overcome using this approach including signal detection and classification, synchronization and channel equalization and interference rejection through cyclic Wiener or FRESH filtering. In addition, I have discussed cyclostationary signal analysis in the context of emerging DySPAN systems. Specifically, the challenges of low-power signal detection, modulation classification and waveform recognition have been considered and some proposed solutions to these issues involving cyclostationary signal analysis have been explored.

Following on from the previous chapter, I have discussed the exploitation of signal cyclostationarity in the context of DySPAN rendezvous and coordination. While the approach has significant potential as a tool for achieving peer detection, identification and link establishment in DySPAN systems, a number of significant drawbacks associated with its use were identified. In particular, it was noted that cyclostationary signal analysis typically involves significant computational complexity, requires receiver oversampling of the SOI and can require long signal observation times for reliable estimation of inherent cyclic features.

In the next chapter, I look at an approach for overcoming these key limitations through the intentional generation of cyclic features or *cyclostationary signatures* in multi-carrier communication systems. Techniques are presented for the generation, detection and analysis of these signatures and their use in overcoming the challenge of DySPAN rendezvous and coordination is discussed.

5. CYCLOSTATIONARY SIGNATURES

5.1 Introduction

Cyclostationary signal analysis provides a powerful non-coherent technique for the general analysis of a broad range of waveforms. The ability to determine key signal properties without the need for phase-related information makes the technique highly attractive in the context of rendezvous and coordination for DySPANs. Using signal cyclostationarity, it is possible for receiving devices to detect a signal of interest, estimate key parameters of that signal and successfully perform synchronization and demodulation in order to obtain control information about the network. In this way the challenges of device discovery and waveform synchronization for network creation, entry and maintenance can be overcome.

Much of the power of cyclostationary signal analysis lies in the direct relationship that exists between the inherent cyclostationary features of a signal and the key parameters of that signal (such as carrier frequency, symbol rate or cyclic prefix length). However, there are significant drawbacks associated with the use of these inherent cyclostationary features to accomplish network rendezvous and coordination due to this direct relationship. One such drawback is the inability to manipulate inherent cyclostationary features without directly impacting system performance. For example, by altering the symbol rate of a PSK signal, the cyclic frequency of the associated cyclostationary feature can be changed, however this is achieved at the cost of a fundamental change in the operation of the wireless system. Similarly, a second drawback arises in the case of a reconfigurable wireless system where operating parameters may be dynamically chosen in order to suit environmental conditions at a given time and place. As these parameters may not be known in advance by a receiving device, the properties of inherent signal cyclostationary features can not be accurately known. Thus, in order to detect such features, cyclostationary analysis must be performed over the range of possible cyclic frequencies, requiring a high degree of computational complexity. A third limitation associated with the use of inherent cyclostationary features for network rendezvous and coordination is the typically long observation time required for reliable detection and analysis of such features. In Chapter 4, it was seen that the reliability of a spectrum correlation function (SCF) estimate is dependent upon the spectral resolution Δf and the temporal resolution Δt of the detector. In order to obtain a substantial reduction in random effects in estimates calculated using a spectrally or temporally smoothed approach, the temporal-spectral resolution product must greatly exceed unity

$$\Delta t \Delta f >> 1 \tag{5.1}$$

In order to resolve inherent cyclostationary features of a signal, small values of Δf are typically required. As a result, large values of Δt, the observation time, are needed for reliable detection. In addition to these limitations, the drawbacks of high computational complexity and the need for oversampling were outlined in the previous chapter.

One possible alternative to the use of inherent signal cyclostationarity to achieve rendezvous and coordination is the use of *cyclostationary signatures*. I define a cyclostationary signature as a feature which may be *intentionally* embedded in the physical properties of a digital communications signal, easily manipulated, detected using cyclostationary analysis and used as a unique identifier. Using such an intentionally embedded feature, the key limitations of inherent features can be overcome. By creating a cyclostationary signature which is not tied to a fundamental signal parameter, it becomes possible to manipulate that feature without impacting overall system performance. This freedom to manipulate the embedded feature facilitates the creation of uniquely identifying signatures and allows them to be tailored to the requirements of the system. Embedded signatures can be generated at a specific cyclic frequency and need not change as waveform parameters are adjusted. This permits a receiving device to detect a signature by analysing only that specific cyclic frequency, greatly reducing the computational complexity required. Embedded features can be generated such that a relatively large frequency resolution, Δf, is needed for detection. Accordingly, a shorter observation time Δt, is required for reliable detection. Finally, the use of intentionally embedded cyclostationary signatures can overcome the need for sampling in the receiver at a rate higher than that required for demodulation of the signal of interest (SOI) and thus further reduce the computational complexity involved.

Having identified the potential benefits of intentionally embedded cyclostationary signatures, a technique is required for the generation of such features in data-carrying waveforms. This chapter presents such a technique developed for Orthogonal Frequency Division Multiplexing (OFDM)-based waveforms. As well as addressing the generation of signatures, techniques for detecting and analysing those embedded signatures are presented.

The chapter is structured as follows. Section 5.2 provides a brief overview of OFDM and examines the key advantages provided by this flexible transmission scheme in the context of dynamic spectrum access. A technique for generating cyclostationary signatures in OFDM-based waveforms is presented in Section 5.3. Section 5.4 looks at the ways in which cyclostationary signatures can be used to facilitate rendezvous and coordination in DySPANs. The detection and analysis of intentionally embedded features is discussed in Section 5.5. The issue of frequency-selective fading is addressed in Section 5.6 and Section 5.7 concludes the chapter.

5.2 Technology for Dynamic Spectrum Access Networks: OFDM

Orthogonal Frequency Division Multiplexing (OFDM) is a multi-carrier transmission scheme which has significant advantages for high data rate communications in non line-of-sight (NLOS) applications. The scheme involves the conversion of a high rate data stream into a number of parallel low rate streams which are then mapped onto closely spaced orthogonal subcarriers. Fig. 5.1 illustrates three such subcarriers. Note that each subcarrier peak occurs at the null of the neighbouring carriers. By performing this conversion, a number of benefits are realized.

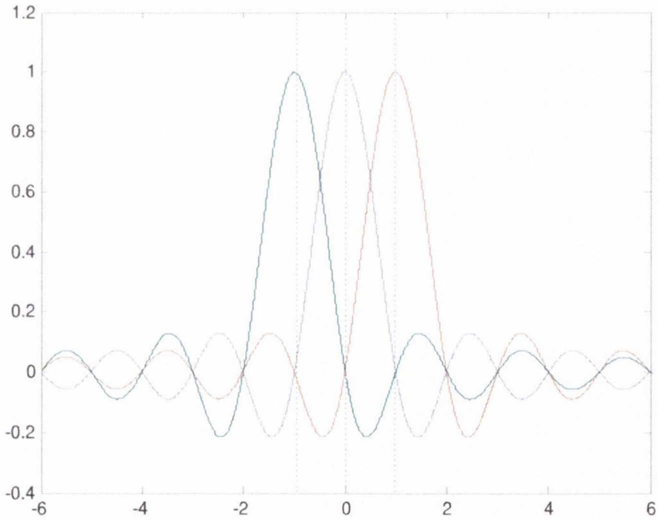


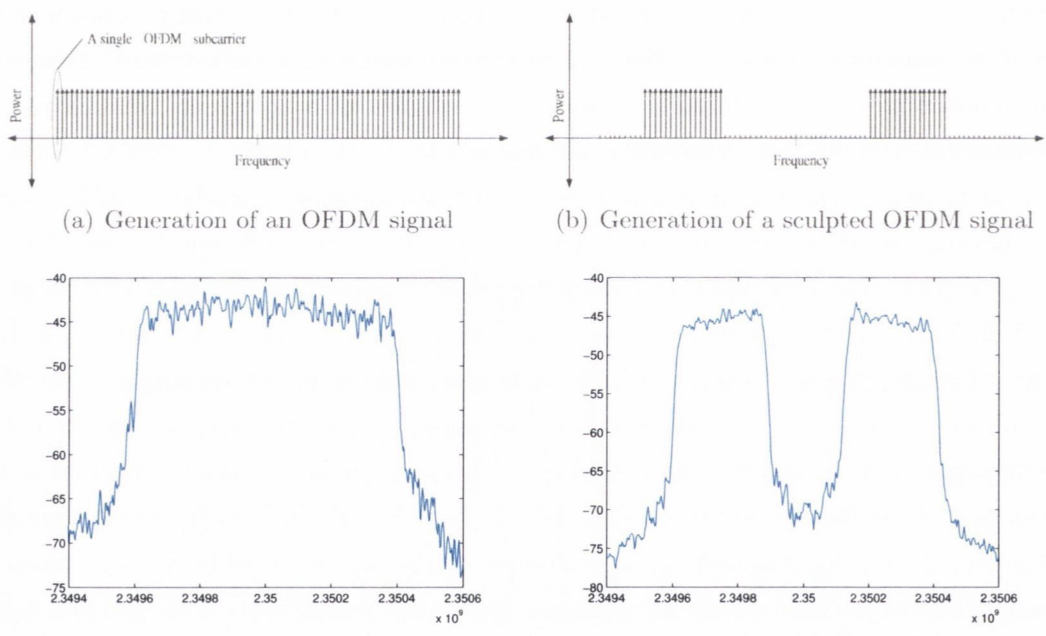
Fig. 5.1: Orthogonal Frequency Division Multiplexing (OFDM) subcarriers

First, the decrease in symbol rate on each carrier provides a reduced sensitivity to inter-symbol interference. In multipath environments this robustness may be improved through use of a cyclic prefix on each symbol transmitted. The cyclic prefix effectively collects multipath components which arrive within a given period, preventing the occurence of inter-symbol interference (ISI).

A second benefit arises from the flat fading that is experienced at each narrowband carrier. In high bandwidth single carrier transmission schemes, signals are distorted by frequency selective fading which requires complex equalization. By using parallel narrowband carriers, the fading may be treated as flat and may be equalized using much less complex structures.

A third significant benefit of OFDM as a transmission scheme is the availability of an efficient implementation in the form of the inverse fast Fourier transform (IFFT).

Each of these advantages have contributed to the adoption of OFDM as the transmission scheme of choice for a number of recent standards including Institute of Electrical and Electronics Engineers (IEEE) 802.11 [9], IEEE 802.16 [10], Digital Audio Broadcasting (DAB) [11], Terrestrial Digital Video Broadcasting (DVB-T) [12] and the first proposed wireless standard based on dynamic spectrum access cognitive radios, IEEE 802.22 [58].



(a) Generation of an OFDM signal

(b) Generation of a sculpted OFDM signal

(c) PSD of an OFDM signal

(d) PSD of a sculpted OFDM signal

Fig. 5.2: Sculpting the spectrum of an OFDM signal through subcarrier manipulation.

When applied to Dynamic Spectrum Access Network (DySPAN) systems, OFDM provides a considerable advantage over alternative transmission schemes due to the flexible nature of its power spectrum. In using the inverse fast Fourier transform (IFFT) to generate an OFDM symbol, a vector of bins is used to represent the parallel carriers in the frequency domain. By altering the contents of these bins, the frequency domain properties of the resultant OFDM symbol are directly impacted. It has been shown that this approach may be used effectively for both interference avoidance [98] and bandwidth matching [99] in DySPAN applications. Fig. 5.2 illustrates the manner in which the spectrum of an OFDM signal can be 'sculpted'. This is achieved simply by altering the power of data symbols transmitted on specific subcarriers.

Another considerable benefit of using OFDM is the spectral occupancy and channel condition information which may be obtained through the use of a fast Fourier transform (FFT) process in the receiver. As an IFFT is used to create the OFDM symbol transmitted, an FFT is performed upon received symbols in order to extract the modulated data. In cases where data transmission is not taking place or where a number of carriers are not in use, the corresponding FFT bins may be used to obtain power spectral density (PSD) information for the channel.

For these reasons, OFDM is likely to play a significant role in future DySPAN systems. Coupled with the use of intentionally embedded cyclostationary signatures, OFDM-based waveforms provide a highly flexible physical layer solution for DySPANs which effectively addresses the challenge of network rendezvous and coordination. In the next section, a low-complexity technique is presented for the generation of artificial cyclic features in OFDM-based waveforms.

5.3 Signature Generation

In Chapter 4, it was seen that second order cyclostationarity manifests as a correlation pattern in the spectrum of a signal. This spectral correlation completely describes the cyclostationarity of the signal and may be examined using the SCF. In considering the creation of an intentionally embedded cyclostationary signature, one approach would be to artificially create such a spectrum correlation in the signal of interest.

As discussed in the previous section, OFDM is a transmission scheme with key advantages for high data rate communications in NLOS environments. In the context of DySPAN systems, OFDM provides significant advantages due to the ability to manipulate the spectral shape of the signal. An OFDM signal is comprised of closely spaced orthogonal subcarriers, each of which may carry an independent data symbol. By controlling the data symbols carried by the individual subcarriers, the spectrum of the OFDM signal can be directly influenced. This spectrum sculpting ability of OFDM signals provides a unique opportunity for the generation of cyclostationary signatures by creating spectral correlation patterns.

OFDM signals may be represented as a composite of N statistically independent subchannel quadrature amplitude modulation (QAM) signals [100]:

$$w(t) = \sum_k \sum_{n=0}^{N-1} \gamma_{n,k} e^{j(2\pi/T_s)nt} q(t - kT) \tag{5.2}$$

where $w(t)$ is the complex envelope of an OFDM signal with a cyclic prefix, $\gamma_{n,k}$ is the independent and identically distributed (IID) message symbol transmitted on subcarrier n during OFDM symbol k, N is the number of subcarriers and $q(t)$ is a square shaping pulse of duration T. T_s is the source symbol length and T_g is the cyclic prefix length such that $T = T_s + T_g$.

Due to the statistical independence of the subchannel QAM signals, the problem of cyclostationary analysis of OFDM may be reduced to the analysis of these QAM signals. In the absence of a cyclic prefix, subcarrier orthogonality causes destruction of the individual QAM signal cyclostationarity. However, the use of a cyclic prefix causes a loss of subcarrier orthogonality and permits inherent QAM signal features to be detected [100]. Features arising due to use of the cyclic prefix are examined in [100] and the spectral correlation of the complex envelope $w(t)$ of an OFDM signal is derived as:

$$S_w^\alpha(f) = \begin{cases} \frac{\delta_\gamma^2}{T} \sum_{n=0}^{N-1} Q(f - \frac{n}{T_s} + \frac{\alpha}{2}) \cdot Q^*(f - \frac{n}{T_s} - \frac{\alpha}{2}), & \alpha = \frac{k}{T} \\ 0, & \alpha \neq \frac{k}{T} \end{cases} \tag{5.3}$$

where

$$Q(f) = \frac{sin(\pi f T)}{\pi f} \tag{5.4}$$

is the Fourier transform of the square shaping pulse $q(t)$.

The SCF for an OFDM signal with cyclic prefix $T_g = \frac{T_s}{4}$ and $N = 16$ is illustrated in Fig. 5.3. Inherent cyclostationary features are shown for cyclic frequencies $\frac{1}{T}$, $\frac{2}{T}$ and $\frac{3}{T}$.

These inherent features of OFDM signals may be used to perform tasks such as synchronization [72] and blind channel identification [74] however, as discussed in Section 5.1, they are unsuitable for use in the context of DySPAN rendezvous and coordination.

In order to embed unique signatures using cyclostationary features, it must be possible to directly control and manipulate the properties of those features. In the case of these inherent features, this involves altering T_g, the cyclic prefix length. As the cyclic prefix length is a key parameter determining the performance of an OFDM-based system, any alteration has a significant overall system impact. Furthermore, low

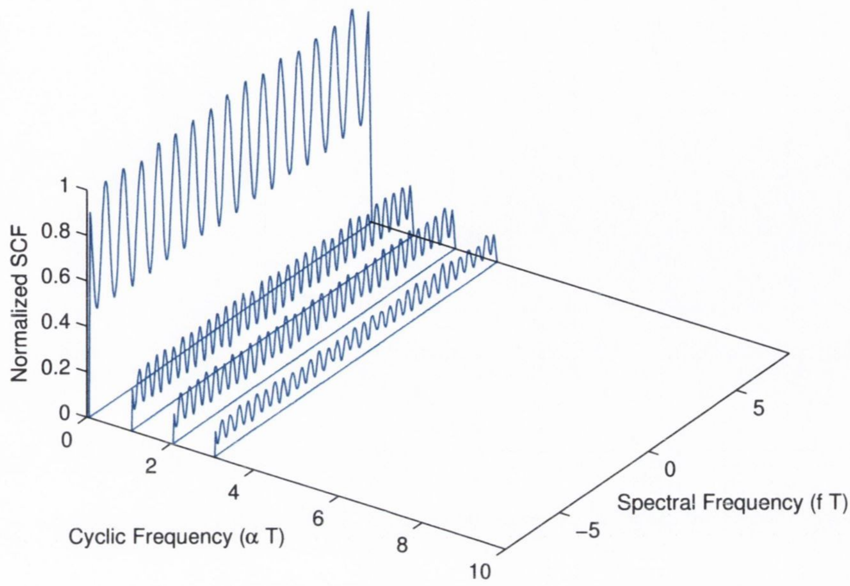


Fig. 5.3: Normalized SCF for OFDM with cyclic prefix showing inherent cyclostationary features.

computational complexity and rapid signal detection are key requirements for coordination. As the power of inherent OFDM features are low relative to that of the signal, reliable detection of these features requires the use of complex receiver architectures and long signal observation times.

In order to generate a distinctive *cyclostationary signature*, a correlation pattern must be created in the spectrum of the signal. OFDM spectrum sculpting permits such a correlation pattern to be intentionally created by manipulating the message symbols $\gamma_{n,k}$, assigned to individual subcarriers. By mapping a set of subcarriers onto a second set as:

$$\gamma_{n,k} = \gamma_{n+p,k}, \qquad n \in M \tag{5.5}$$

where M is the set of subcarrier values to be mapped and p is the number of subcarriers between mapped symbols, message symbols are redundantly transmitted on more than one subcarrier, a correlation pattern is created and a cyclostationary feature is embedded in the signal. Fig. 5.4 illustrates this process of subcarrier set mapping.

This introduction of a statistical dependence between certain subcarriers of an OFDM signal results in the spectral correlation:

$$S_w^\alpha(f) = \begin{cases} \frac{\delta_\gamma^2}{T}\sum_{n=0}^{N-1} Q(f - \frac{n}{T_s} + \frac{\alpha}{2}) \cdot Q^*(f - \frac{n}{T_s} - \frac{\alpha}{2}), & \alpha = \frac{k}{T} \\ \frac{\delta_\gamma^2}{T}\sum_{n=0}^{N-1} Q(f - \frac{n}{T_s} + \frac{\alpha}{2}) \cdot Q^*(f - \frac{n+p}{T_s} - \frac{\alpha}{2}), & \alpha = \frac{p}{T_s} \pm \frac{k}{T}, n \in M \\ 0, & \alpha \neq \frac{k}{T}, \frac{p}{T_s} \pm \frac{k}{T} \end{cases} \quad (5.6)$$

where M is the set of mapped subcarriers. The SCF for an OFDM signal containing an embedded cyclostationary signature is illustrated in Fig. 5.5 where $p = 6$, $N = 16$, $T_g = T_s/4$ and a single subcarrier is mapped. The strong feature which is associated with the cyclostationary signature can be seen at cyclic frequency $\alpha = \frac{p}{T_s} = \frac{7.5}{T}$.

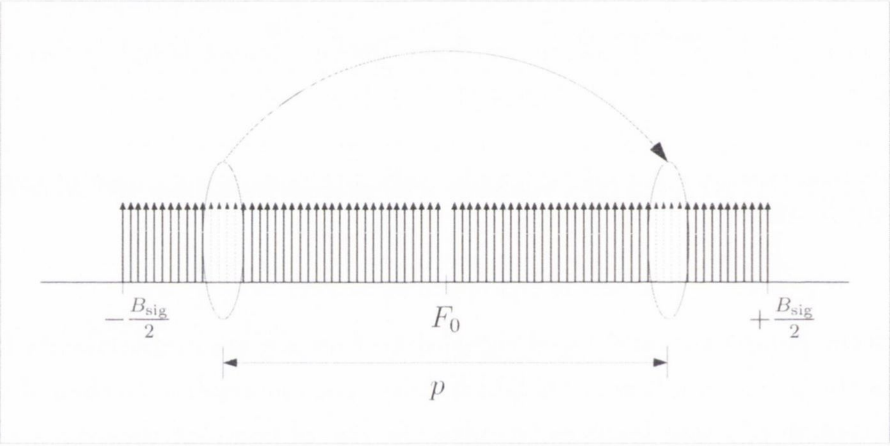


Fig. 5.4: Generation of a Cyclostationary Signature using OFDM Subcarrier Set Mapping.

A number of key advantages may be realized through the use of OFDM subcarrier set mapping to generate cyclostationary signatures for rendezvous and coordination in DySPANs.

Firstly, subcarrier set mapping permits cyclostationary signatures to be embedded in data-carrying waveforms without adding significant complexity to existing transmitter designs. OFDM signal generation may be efficiently implemented using an inverse discrete Fourier transform (IDFT). As illustrated in Fig. 5.4, cyclostationary signatures may be incorporated in existing transceiver architectures simply by mapping one set of subcarriers to another. Here, F_0 is the carrier frequency, B_{sig} is the signal bandwidth and p is the subcarrier set separation. A spectral correlation is created by simultaneously transmitting data symbols on more than one subcarrier. By mapping a set of subcarriers in this way, a larger correlation pattern is created.

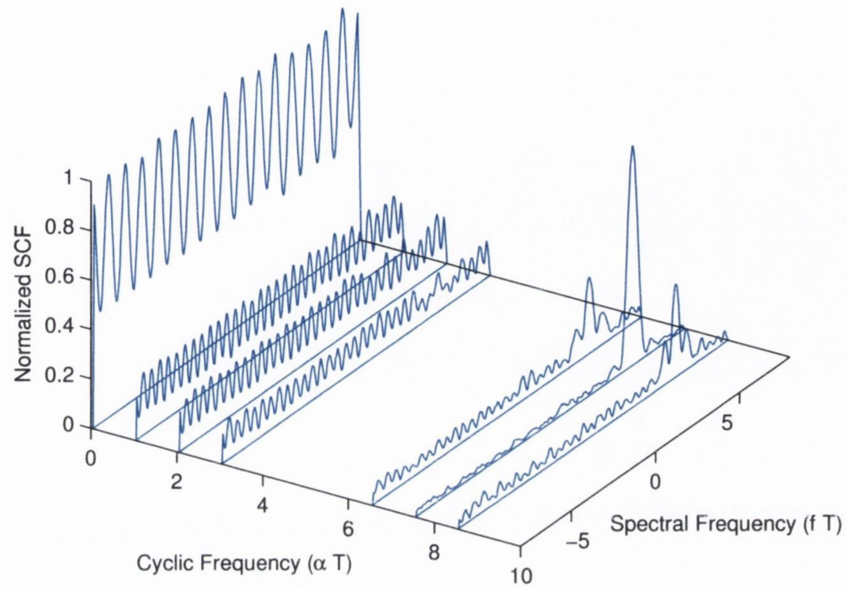


Fig. 5.5: Normalized SCF for OFDM with cyclic prefix and embedded cyclostationary signature.

A second key advantage of the use of subcarrier set mapping lies in the observation times and receiver complexity required for reliable signature detection. Cyclostationary signatures may be reliably detected using a spectral resolution Δf equal to the OFDM subcarrier spacing. However, successful detection of inherent features such as those arising due to the use of a cyclic prefix requires use of a smaller spectral resolution. As SCF estimate reliability depends upon the spectral-temporal resolution product $\Delta f \Delta t$ (see Equation 5.1), longer observation times are required for reliable detection of inherent OFDM features than those needed for cyclostationary signatures.

Reduced receiver complexity may be achieved as the key feature associated with a cyclostationary signature occurs at a single cyclic frequency, $\alpha = \frac{p}{T_s}$. Successful detection and analysis of the signature may thus be performed using estimation of the SCF at this cyclic frequency alone using a low complexity single-cycle estimator.

An important strength of cyclostationary signatures generated using OFDM subcarrier set mapping is the flexibility with which they may be manipulated. Cyclostationary features generated in this way may be directly manipulated in both the cyclic and spectral frequency domains through careful choice of mapped subcarrier sets. The cyclic frequency of a cyclostationary signature is determined by the OFDM source symbol duration T_s and the number of subcarriers between mapped sets p as

$$\alpha_{sig} = \frac{p}{T_s} \tag{5.7}$$

Thus by altering the spacing between mapped sets, p may be chosen and the cyclic frequency of the resulting cyclostationary signature determined. This approach permits unique signatures to be generated through the creation of cyclostationary features at different cyclic frequencies.

The spectral frequency of an embedded cyclostationary signature is determined by the carrier frequency of the signal and the properties of the subcarrier sets used in its generation. For example, mapping of one subcarrier set onto a second set, equidistant from the carrier frequency (as in Fig. 5.4) results in a cyclostationary feature which is centred upon that carrier frequency. Fig. 5.6 illustrates such a feature, showing the spectral frequency of the signature for $N = 256$ and a signature generated using a mapped set of 3 subcarriers. The significance of the spectral frequency properties of a signature for DySPAN rendezvous is discussed in more detail in Section 5.4.

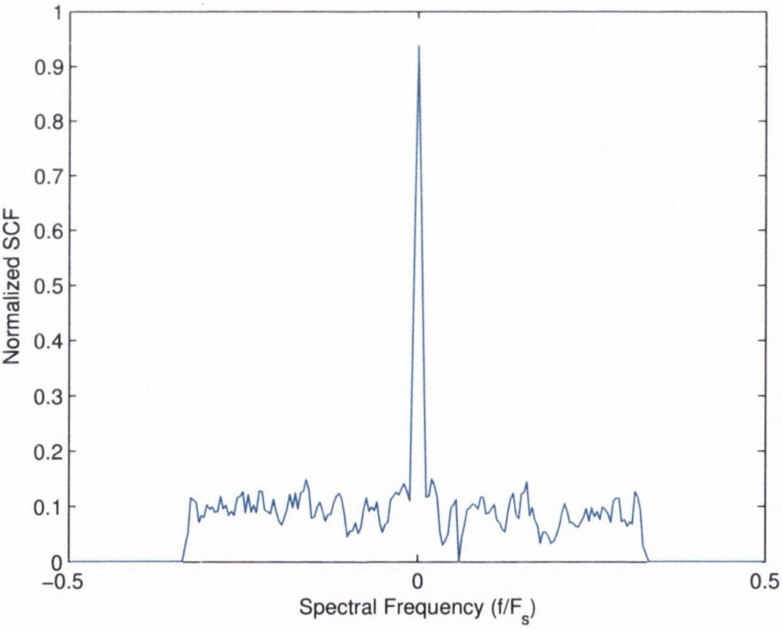


Fig. 5.6: Spectral frequency at α_{sig}, the signature cyclic frequency.

A final advantage of the use of OFDM subcarrier set mapping is the continuous presence of the cyclostationary signature in the transmitted signal due to the consistent mapping of carriers for every generated OFDM symbol. This permits cyclostationary signal detection to be performed using any received portion of the signal. This is in contrast to approaches involving cyclostationarity induced only in specific elements of a signal, such as the preamble-based technique outlined in [101].

A major consideration in the design of an OFDM transceiver using embedded cyclostationary signatures is the overhead incurred as a result of the subcarrier mapping used. The number of subcarriers available for data transmission is reduced by the number used to carry mapped data symbols, causing a reduction in the overall data rate which may be supported. However, there exists an important trade off between the number of subcarriers used in a mapped set and the detection performance which may be achieved. This trade off is examined using results of both simulations and experiments in Chapters 6 and 8 respectively.

5.4 Cyclostationary Signatures in Dynamic Spectrum Access Networks

In the context of DySPAN rendezvous and coordination, cyclostationary signatures can be leveraged to achieve a number of critical tasks. These include

- Detection of signals of interest
- Network identification
- Frequency acquisition

In the following sections the importance of these tasks is discussed and ways in which cyclostationary signatures can be used to accomplish them are examined.

5.4.1 Signal Detection

In order to achieve rendezvous with peer nodes of a DySPAN, the first critical task to be fulfilled is that of detection of a signal of interest. In Chapter 4, the advantages of using cyclostationary signal analysis for signal detection were discussed. While radiometric approaches permit the general detection of a wide range of signal types, they are typically susceptible to noise uncertainty in the receiver. This sensitivity is greatly reduced through the use of a cyclostationary feature-based detector. Matched-filter based approaches for signal detection also overcome the issue of noise uncertainty, however they are often tailored to a single signal type and cannot be applied to a wide range of signal types in the same way as cyclostationary feature-based detectors.

The use of intentionally embedded cyclostationary signatures permits the advantages of cyclostationary feature detection to be realized while also providing the flexibility to generate unique features, uncoupled from key signal parameters and tailored to the needs of the wireless system. Cyclostationary signatures generated using OFDM subcarrier mapping can be embedded within data-carrying waveforms and so may be present in any portion of an intercepted signal. Due to this continuous presence of the embedded signature, a node wishing to rendezvous with an existing network may detect a signature by intercepting and analysing a signal transmitted by any member of that network.

As shown in Fig. 5.5, a cyclostationary signature may be added to a signal in such a way as to cause a distinctive peak at a single value of the cyclic frequency, α in the SCF of the signal. The presence of the cyclostationary feature at a single specific cyclic frequency permits the use of a low-complexity single-cycle detector in order to detect and analyse the signature. This is the approach adopted in Chapters 6 and 8 where results of simulations and experiments using embedded cyclostationary signatures are presented.

5.4.2 Network Identification

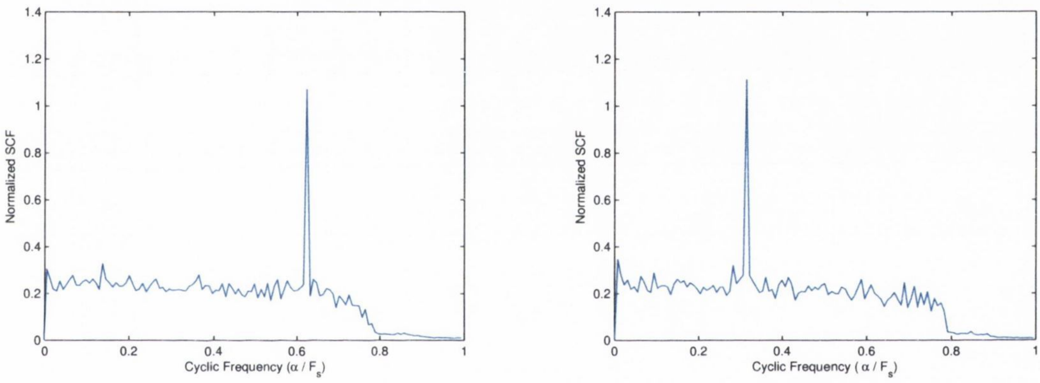
An important property of cyclostationary signatures is the ability to create unique identifiers by choosing the cyclic frequency, α, of the embedded feature. In the context of DySPAN rendezvous and coordination, these unique signatures can be used to perform network identification. A single signature can be chosen for a given network such that all transmissions by members of that network contain that signature. In this way, a device wishing to detect the network and perform rendezvous can search for that particular signature. As the signature is present in all transmissions, network detection and identification can be achieved using an intercepted signal from any member of that network.

Network identification is of particular value in the case of a device which is capable of operating within two or more wireless network types. A key strength of the highly reconfigurable radio devices used for DySPAN operation is the ability to dynamically change operating parameters. Such a device can adapt parameters used according to the specific network which it wishes to join at a given time and place. In the case where two or more DySPANs may be detected, the device must identify those networks and choose that which is most suited to its requirements. If each network uses a predetermined unique cyclostationary signature, this type of network identification is possible.

As discussed in Section 5.3, the cyclic frequency of a cyclostationary signature is determined by choice of p, the spacing between mapped subcarrier sets. Using different values of p, unique signatures may be generated and used for network identification. This approach is illustrated in Fig. 5.7 which shows the α-profiles of two signals containing unique signatures generated at different cyclic frequencies using OFDM subcarrier mapping. Recall that the α-profile of a signal is defined as:

$$\text{profile}(\alpha) = \max_f [C_x^\alpha] \qquad (5.8)$$

where C_x^α is the autocoherence function (AF) and f is the spectral frequency.



(a) Signature at cyclic frequency α_1 (b) Signature at cyclic frequency α_2

Fig. 5.7: Unique cyclostationary signatures at two different cyclic frequencies.

The use of cyclostationary signatures for network identification in this way requires an assignment mechanism to ensure that unique signatures are assigned to networks operating at a given time and place and within a given spectrum band. In the case where networks require authorization to operate within a spectrum band, signature assignment may be performed in a centralized manner by the authorizing agent. Such assignment could take place for example in the case of a spectrum commons where devices require certification prior to operation. In the absence of a centralized authority however, signature assignment must be performed in a distributed manner by the networks themselves.

Chapters 6 and 8 further examine the use of unique cyclostationary signatures for network identification using simulation and experimental results.

5.4.3 Frequency Acquisition

The task of frequency acquisition is a challenge which arises due to the uniquely flexible nature of DySPANs. In a conventional wireless system, operating frequencies are typically known in advance or they can be easily determined using fixed frequency control channels. In DySPAN systems this may not be the case as operating frequencies can depend upon the spectrum resources available at a given time and place. Therefore, upon commencing operation, a DySPAN device must be capable of identifying those frequencies currently in use by its peer nodes and performing rendezvous and synchronization. As well as facilitating signal detection and network identification, embedded cyclostationary signatures can play a significant role in this process of frequency acquisition.

As discussed in Section 5.3, the spectral frequency of a cyclostationary signature embedded in an OFDM-based signal is determined by the carrier frequency of that signal and the subcarrier sets used to generate it. If the relationship between the carrier frequency of the signal and the spectral properties of the signature is known in advance, a detected signature may be used by a device to estimate the signal carrier frequency and perform acquisition. An embedded signature centred at the carrier frequency of the signal is illustrated in Fig. 5.6.

Although a wide range of frequency synchronization techniques exist for OFDM-based systems, few of these techniques are suited to the unique challenge of acquisition for DySPAN networks. Within a conventional wireless network, the carrier frequency of the signal of interest typically lies in a narrow range at one of a number of discrete locations. In the case of DySPAN networks however, operating frequencies are determined by spectrum availability and so may lie within a very wide frequency range relative to the bandwidth of the signal. By combining the use of cyclostationary signatures with an existing synchronization technique, a powerful mechanism for DySPAN frequency acquisition can be achieved.

OFDM-based transmission schemes are highly sensitive to frequency offset errors due to the use of multiple closely spaced carriers. The orthogonality of these carriers is preserved as each occurs at a null in the spectrum of those adjacent to it. In the event of a frequency offset, the location of the carriers is shifted from these null positions and adjacent channel interference (ACI) significantly reduces system performance [102]. Due to this sensitivity, OFDM systems typically employ a two-stage approach to carrier frequency synchronization - a coarse carrier frequency acquisition stage and a separate fine carrier frequency tracking stage [103] [104]. Techniques employed include the use of training symbols [105], null symbols [106], cyclic prefix correlation [107] as well as cyclostationary analysis [108]. Moose [109] proposed the use of a preamble consisting of two repeated symbols. By comparing phase shifts between these symbols in the receiver, a frequency acquisition range of +/- half a subcarrier spacing can be achieved. Schmidl and Cox [105] extended this approach to use a single symbol with a half-symbol repetition to provide an acquisition range of +/- 1 subcarrier spacing. This is used in tandem with a symbol containing a pseudo-noise (PN) sequence. Following fractional frequency offset correction using the half-symbol repetition, integer offset correction is achieved using this PN sequence symbol. In this way, an acquisition range of the signal bandwidth can be achieved.

In Chapters 6 and 8 both simulation and experimental results are used to show that cyclostationary signatures may be used to achieve carrier frequency estimation to within a single subcarrier spacing of the true value. By combining the use of cyclostationary signatures in this way with the fractional frequency offset correction approach of Schmidl and Cox, rapid frequency synchronization with a detected signal of interest is possible.

A key advantage of the use of signatures for frequency acquisition is the ability to extend the range of acquisition beyond the bandwidth of the signal of interest. DySPAN devices typically use agile radio frequency (RF) front-ends within which the transmit and receive bandwidth can be dynamically adjusted. In performing detection of a cyclostationary signature, a wide receive bandwidth can be chosen. Any signals containing signatures within that received bandwidth can be detected, following which the receive bandwidth can be adapted to that of the detected signal and frequency synchronization performed. In this way the range of acquisition can be extended to the maximum receive bandwidth of the RF front-end in use. Of course, this approach may only be taken provided that high-powered signals adjacent to the SOI do not cause dynamic range and front-end overload issues.

5.5 Signature Detection and Analysis

In the previous sections I examined techniques for the generation of embedded cyclostationary signatures in OFDM-based signals and discussed a number of the possible ways in which cyclostationary signatures can be used in DySPAN systems. In this section the issue of cyclostationary signature detection is addressed and a suitable detector design is proposed.

In Chapter 4 it was seen that a key issue in the use of cyclostationary signal analysis is the computational complexity associated with the calculation of a complete SCF function [84]. This complexity arises due to the large numbers of complex convolution operations required. One advantage of the use of cyclostationary signatures of the type illustrated in Fig. 5.5 is the fact that the principal signature features are confined to a narrow range of the cyclic frequency, α. This presence of a signature at a single cyclic frequency permits the design of a low-complexity single-cycle detector.

The time-smoothed cyclic cross periodogram (TS-CCP), $\widehat{S}_x^\alpha[k]$, was presented in Chapter 4 as a consistent, asymptotically unbiased and complex normally distributed estimator for the cyclic cross spectrum [83]:

$$\widehat{S}_x^\alpha[k] = \frac{1}{L}\sum_{l=0}^{L-1} X_l[k]X_l^*[k-\alpha]W[k] \tag{5.9}$$

where $W[k]$ denotes a smoothing spectral window and $X_l[k]$ is the Fourier transform of the received signal $x[n]$,

$$X_l[k] = \sum_{n=0}^{N-1} x[n]\exp^{\frac{-j2\pi nk}{N}} \tag{5.10}$$

Estimates are calculated using L windows of length N where N is the duration of a single OFDM symbol. Following SCF estimation using the TS-CCP, the SCF coefficient, the AF [76] may be used to normalize results in the range [0,1]:

$$C_x^\alpha[k] = \frac{S_x^\alpha[k]}{(S_x^0[k+\alpha/2]S_x^0[k-\alpha/2])^{1/2}} \tag{5.11}$$

Using the TS-CCP, the AF may be estimated at individual values of the cyclic frequency, α. The TS-CCP can be used in this way to detect a cyclostationary signature at a single cyclic frequency.

In designing a detector for embedded cyclostationary features, it is possible to employ either a time-smoothing or frequency-smoothing based approach. The choice between the two depends largely upon the requirements of the designer. The motivation for use of a time-smoothing based approach in this dissertation was provided to a large degree by the need to implement a practical signature detector upon a highly reconfigurable general purpose processor (GPP)-based software radio platform. The details of this implementation can be found in Chapter 7. A time-smoothing based design involves the calculation of a number of short Fourier transforms which are averaged over time. This approach permits the processing requirements of the algorithm to be quite evenly distributed in time. In contrast, a frequency-smoothing based approach involves the capture of a large set of data samples, the calculation of a large Fourier transform and the subsequent frequency smoothing. As this approach requires a highly bursty processing profile, it can result in the introduction of latency and is less suited to GPP-based platforms.

Existing OFDM receiver designs typically involve the use of a Fourier transform in order to demodulate a received signal. In designing an estimator based on the TS-CCP, using a Fourier transform, it is possible to incorporate the use of cyclostationary signatures using minor modifications to existing OFDM receiver designs.

Gardner showed that optimum cyclostationary feature detection is performed through correlation of the cyclic periodogram with the ideal spectral correlation function [67]:

$$y_\alpha(t) = \int_{-\infty}^{\infty} S_s^\alpha(f) * \tilde{S}_x^\alpha(f) df e^{i2\alpha\pi t} \tag{5.12}$$

where $\tilde{S}_x^\alpha(f)$ is the cyclic periodogram following notch filtering to remove strong narrowband interference.

Cyclostationary features generated through OFDM subcarrier set mapping may be successfully detected using spectral resolution Δf, equal to the OFDM subcarrier spacing. Using this approach, the ideal spectral correlation function may be approximated using a simple rectangular window of width $M.\Delta f$, where M is the number of subcarriers in the mapped set. In this way, a low-complexity single-cycle signature detector may be implemented as:

$$y_\alpha = \max_{0 \le k \le N-1} \sum_{m=0}^{M-1} W[m] \widehat{C}_x^\alpha [k-m] \tag{5.13}$$

where $W[m]$ is a rectangular window.

Fig. 5.8 illustrates a cyclostationary signature detector based on the use of the time-smoothed cyclic cross periodogram.

5.6 Multipath Fading

5.6.1 Overview

Cyclostationary signatures offer a highly flexible tool for overcoming the issue of rendezvous and coordination in DySPAN systems. However, a limitation of cyclostationary signatures is their sensitivity to frequency-selective fading. A deep fade occurring at the frequency of a mapped subcarrier set may severely distort the signature and deteriorate detection performance.

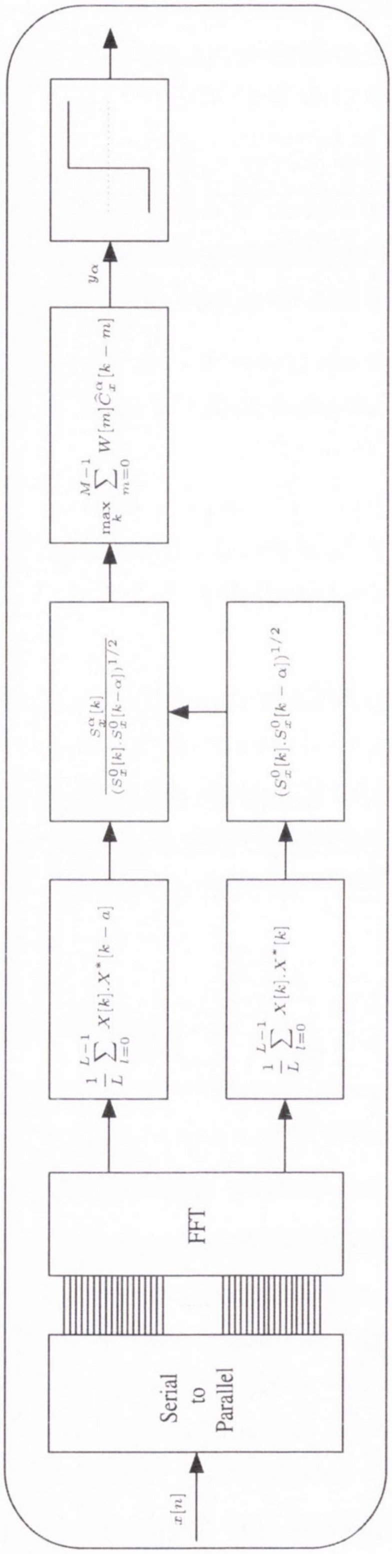
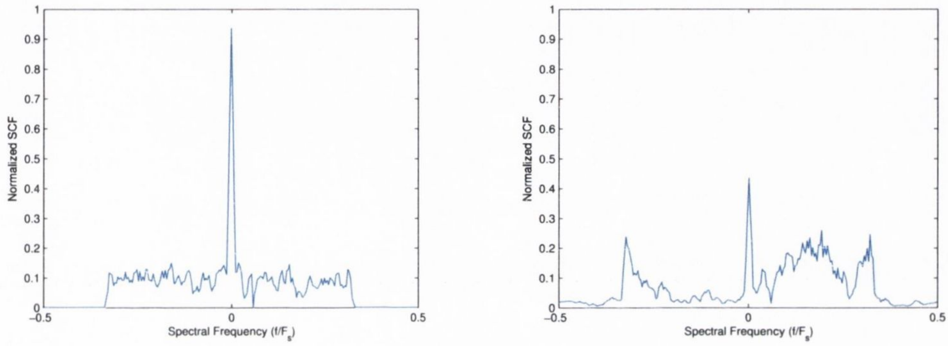


Fig. 5.8: Cyclostationary signature detection using the time-smoothed cyclic cross periodogram.

Frequency-selective fading arises in a wireless channel due to reception of multiple versions of the same signal, known as multipath. Reflections of the transmitted signal arrive at different times at the receiver and the resulting delay spread in the received signal causes a reduction in the coherence bandwidth of the channel and hence, frequency-selective fading.



(a) (b)

Fig. 5.9: Distortion of cyclostationary signature caused by multipath Rayleigh fading.

Fig. 5.9 illustrates the effect of multipath fading on a single cyclostationary signature. Fig. 5.9(a) shows the spectral frequency at the cyclic frequency of the signature for a signal in an additive white Gaussian noise (AWGN) channel and Fig. 5.9(b) shows the distorting effects of a multipath Rayleigh fading channel.

5.6.2 Signatures for Multipath Fading Environments

In order to overcome this limitation, it is necessary to increase the frequency diversity of the cyclostationary features used as a signature. Such frequency diversity can be achieved through the use of multiple OFDM subcarrier mappings to increase the number of features which are generated.

Fig. 5.10 illustrates the way in which a multiple-feature signature may be generated using multiple mapped subcarrier sets. The SCF of a signal containing two independent cyclostationary features is illustrated in Fig. 5.11 for a cyclic prefix $T_g = \frac{T_s}{4}$ and $N = 32$. Through use of a constant mapping separation, p, each feature is generated at the same cyclic frequency, α and the optimum single-cycle feature detector may be approximated by:

$$y_\alpha = \max_{0 \leq k \leq N-1} \sum_{m=0}^{M-1} H[m] \widehat{C}_x^\alpha [k-m] \tag{5.14}$$

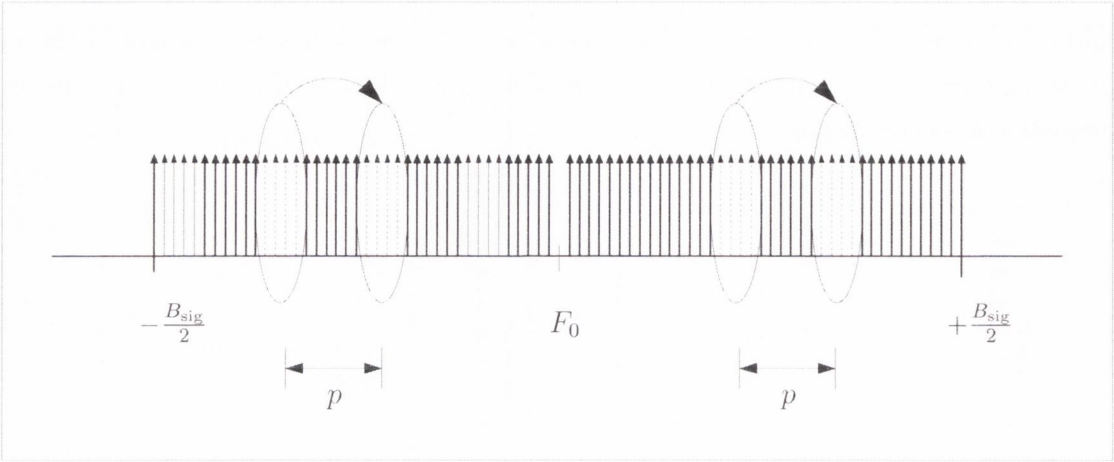


Fig. 5.10: Generation of a multiple-feature cyclostationary signature.

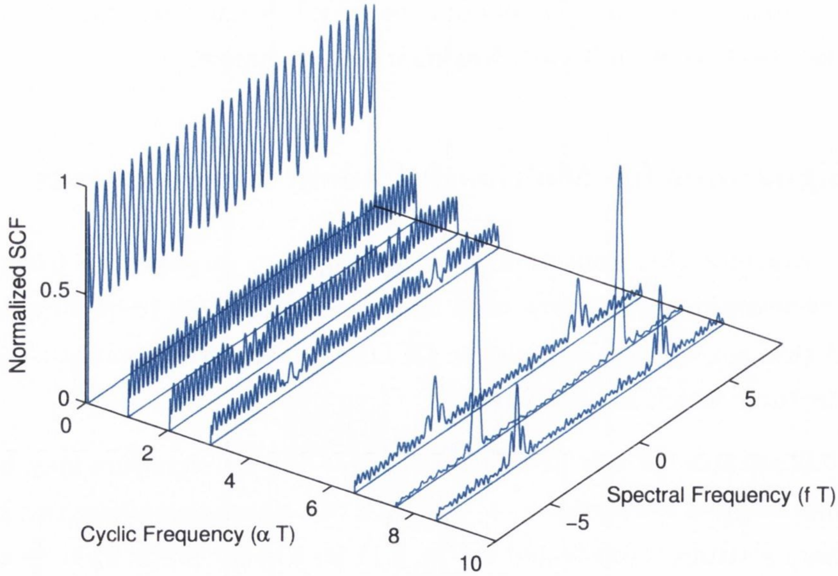


Fig. 5.11: Normalized SCF for OFDM signal containing two independent embedded features.

As features due to each mapped set may be approximated using a rectangular window, the ideal spectral correlation function for multiple-feature signatures may be approximated by $H[k]$, a periodic pulse train. In the case where the number of unique features is not known in advance, the single feature detector (Equation 5.13) may be used and the features detected independently. It should be noted that unique multiple-feature signatures may still be generated through choice of set spacing p to generate a signature at discrete cyclic frequency α_{sig}. Thus multiple-feature signatures may be used for cognitive network identification.

Although the use of multiple subcarrier mappings effectively increases the robustness of the resulting signature, this comes at the cost of increased overhead due to the increased number of subcarriers which must be used to carry mapped data symbols. This trade-off between system overhead and signature robustness in the use of multiple-feature signatures to overcome multipath fading is examined in more detail in Chapter 6.

5.7 Summary

This chapter has introduced the idea of a cyclostationary signature, a feature intentionally embedded in a data-carrying waveform to facilitate rendezvous and coordination in DySPAN systems. While many of the signals used today in wireless communications contain inherent cyclostationary features, there are a number of key limitations associated with their use in the context of DySPAN systems. These limitations have been outlined and ways in which they can be overcome through the use of intentionally embedded cyclostationary signatures have been discussed.

A highly flexible, low-complexity approach for embedding a signature in an OFDM-based waveform has been presented using the technique of subcarrier set mapping. Some of challenges which can be overcome through the use of embedded signatures have been discussed. Specifically, the issues of signal detection, network identification and frequency acquisition for rendezvous in DySPAN systems have been addressed. A low-complexity single-cycle signature detector has been proposed using a time-smoothed cyclic cross periodogram.

Cyclostationary signatures generated using OFDM subcarrier set mapping may be distorted by frequency-selective fading under multipath channel conditions. For this reason, the use of a more robust signature containing multiple independent cyclostationary features has been proposed. By increasing the frequency diversity of the signature in this way, the challenge of frequency-selective fading can be overcome.

The novel approach of using intentionally embedded cyclic features to facilitate DySPAN rendezvous and coordination was first proposed by the author at the first International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN) in Dublin, Ireland in 2007. In the same session, a similar approach was proposed by Maeda et al to achieve waveform recognition in OFDM-based networks [101]. The approach proposed by this dissertation involves subcarrier mapping to reduce system overhead and to overcome the key limitations of cyclostationary signal analysis. In contrast, the approach proposed by Maeda uses a predefined periodic sequence which is transmitted upon a dedicated set of subcarriers. In this way, the number of possible unique signatures is increased at the cost of greater signalling overhead. Furthermore, this approach requires the use of small frequency resolutions in the detector and hence long signal observation times. However, in spite of the differences in the proposed techniques, the presence of two proposals using embedded cyclic features for OFDM-based systems at the first conference dedicated to DySPAN research underlines the wide-ranging utility of this approach for DySPAN systems.

The use of cyclostationary signatures to overcome the challenge of rendezvous and coordination in OFDM-based DySPAN systems is examined in more detail using simulations in the next chapter. Chapter 7 outlines the implementation of an OFDM transceiver using cyclostationary signatures upon a highly reconfigurable platform for DySPAN experimentation. The results of experiments carried out using the implemented transceiver are presented in Chapter 8 and are used to further examine the utility of cyclostationary signatures.

6. SIGNATURE SIMULATIONS

6.1 Introduction

In Chapter 5 it was seen that a cyclostationary signature may be artificially generated and intentionally embedded in a data-carrying Orthogonal Frequency Division Multiplexing (OFDM)-based signal. Potential uses of signatures in OFDM-based Dynamic Spectrum Access Network (DySPAN) systems were discussed and a suggested detector design was examined. While cyclostationary signatures appear to be a valuable tool for the realization of a DySPAN system and merit further investigation, it is necessary to assess the key benefits and restrictions associated with their usage. To this end, a wide range of simulations were carried out using the Mathworks Matlab environment.

The flexibility of OFDM subcarrier mapping as a technique for the generation of cyclostationary signatures was discussed in Section 5.3. By altering the parameters used to generate a signature, the properties of that signature may be directly manipulated. Initial simulations focus on these parameters and assess the trade-off existing between the overhead associated with an embedded signature and the detection performance which may be achieved using that signature. Results are presented in Section 6.2 below.

In the previous chapter it was seen that intentionally embedded cyclostationary features may be used to overcome a number of drawbacks associated with the use of inherent features arising in wireless communication signals. One such drawback is the observation time required for reliable feature detection. In the context of DySPAN rendezvous and coordination, the required observation time dictates the speed with which a signal may be detected and rendezvous achieved using a given detector design. Using simulations, the impact of observation time upon signature detection performance is examined. Further simulations assess the performance of a feature detector for inherent features arising in OFDM-based signal due to the use of a cyclic prefix. By comparing both approaches, the advantages of cyclostationary signatures for DySPAN rendezvous and coordination are illustrated.

A third issue concerning signal detection using embedded cyclostationary signatures is that of detection under frequency-selective channel conditions. An important benefit of OFDM-based signals is the robustness they exhibit under conditions of multi-path fading. This advantage is largely due to the use of a cyclic prefix which is appended to each symbol and is discussed in Chapter 2. In performing initial signal detection and rendezvous, timing information is not available and the cyclic prefix may not be leveraged to overcome the effects of frequency-selective fading. Under these conditions, multiple-feature cyclostationary signatures can be used to provide frequency diversity and robust performance. Simulations are carried out to assess the performance of these robust signatures under a range of channel conditions. Simulation results are presented in Section 6.3 and the trade-off between signature overhead and detection performance are discussed.

It was seen that OFDM-subcarrier mapping may be used to embed cyclostationary features in data-carrying waveforms at discrete cyclic frequencies. Such features form uniquely identifying signatures and permit similar waveforms to be differentiated. In the context of DySPAN rendezvous and network coordination, unique cyclostationary signatures may be used to enable *network identification*. To facilitate network identification, all nodes within a given network embed a common signature in all transmissions. In this way, nodes performing rendezvous can detect this signature and establish that the detected signal was transmitted by a member of a particular network.

Simulations are carried out to examine the suitability of cyclostationary signatures for DySPAN network identification. Results are presented in Section 6.4 and are used to assess identifier performance in the presence of waveforms containing unique signatures. The number of unique signatures which may be used within a given OFDM-based system are determined and observation times required for reliable detection are examined.

Section 6.5 presents simulations carried out to examine the use of cyclostationary signatures in performing signal carrier frequency acquisition. In Chapter 5 it was seen that the detection of signals in the frequency domain using embedded cyclostationary signatures permits key signal properties, including carrier frequency, to be estimated. Although the use of inherent cyclostationary features to perform blind receiver synchronization is well understood [72], the use of intentionally embedded cyclostationary signatures permits some of the limitations of inherent feature detection and analysis to be overcome.

As discussed in Chapter 2, OFDM-based systems exhibit sensitivity to carrier frequency offsets due to the use of closely spaced orthogonal carriers. Even a relatively small frequency offset can give rise to significant adjacent channel interference (ACI) and an associated fall in system performance. In order to overcome this sensitivity, OFDM frequency synchronization typically involves two discrete stages - a coarse frequency acquisition stage and a fine-frequency carrier tracking stage. Using embedded cyclostationary signatures, coarse carrier frequency acquisition can be performed for a detected signal of interest (SOI). Following use of the signature in this way, fine-frequency tracking can be performed to achieve full frequency synchronization.

The extent to which embedded signatures may be used towards OFDM frequency synchronization depends upon the accuracy with which estimations may be made. To this end, simulations using embedded signatures are carried out and the accuracy of carrier frequency estimations are assessed for a range of signal strengths and under conditions of frequency-selective fading.

6.2 Signal Detection

6.2.1 Overview

Correlation values can be magnitude constrained to [0,1] using the correlation coefficient for the spectrum correlation function (SCF), the autocoherence function (AF) [76]:

$$C_x^\alpha(f) = \frac{S_x^\alpha(f)}{[S_x^0(f+\alpha/2)S_x^0(f-\alpha/2)]^{1/2}} \tag{6.1}$$

Cyclostationary features generated through OFDM subcarrier set mapping may be successfully detected using spectral resolution Δf, equal to the OFDM subcarrier spacing. Using this approach, the ideal spectral correlation function may be approximated using a simple square pulse of width $M.\Delta f$, where M is the number of subcarriers in the mapped set. In this way, a low-complexity single-cycle signature detector may be implemented as:

$$y_\alpha = \max_{0\leq k\leq N-1} \sum_{m=0}^{M-1} W[m]\widehat{C}_x^\alpha[k-m] \tag{6.2}$$

where $W[m]$ is a moving average window.

Initial signature detection simulations focus upon the parameters used in generating and detecting embedded signatures. In generating embedded signatures, the impact of mapped OFDM subcarrier set sizes is examined and the signal-to-noise ratio (SNR) performance of the designed detector is assessed. In performing signature detection the issue of signal observation time is addressed and detector performance is examined using receiver operating characteristic (ROC) analyses. Finally, comparisons are drawn between detector performances for intentionally embedded features and inherent, cyclic-prefix related features.

6.2.2 Mapped Subcarrier Set Sizes

In generating a cyclostationary signature using OFDM subcarrier set mapping, a significant trade off exists between the number of subcarriers used to embed the signature and the detection performance which may be achieved. Subcarriers used to carry mapped data may not be used to transmit independent data symbols and so, as the mapped subcarrier set size increases, the overhead of the OFDM system increases and the overall capacity is reduced.

The performance of signatures created using different mapped subcarrier set sizes is examined using simulation. 256-subcarrier OFDM signals are considered with carriers designated as follows: 192 data, 8 pilot, 55 guard, 1 DC (zero-frequency) carrier. Subcarriers are modulated using quadrature phase shift keying (QPSK) message symbols and a 1/16 cyclic prefix was adopted. Signatures with an arbitrarily chosen cyclic frequency, $\alpha = 32/T_s$ are generated using subcarrier set mapping. Gaussian white noise is added to each signal to result in SNR values of between -20 dB and 20 dB. In addition a random timing offset is added according to a uniform distribution over a single OFDM symbol. Detection statistics are recorded for signals containing embedded signatures (y_{sig}) and those in which subcarrier set mapping is not used (y_0). 1000 simulations are carried out for each and mean values are used to generate the detection ratio y_{sig}/y_0. This ratio illustrates the distance between mean detection statistics for signals containing signatures and those without embedded features and may be interpreted as a measure of the confidence with which detection decisions can be made.

Results are illustrated in Fig. 6.1 for observation time, $\Delta t = 30T$ where T is the OFDM symbol duration.

As expected, results illustrate the improvement in detection performance associated with increasing the size of the OFDM subcarrier sets used to embed signatures. As the mapped subcarrier set size is increased, so too is the size of the moving average window used in the signature detector. This moving average window performs smoothing in the frequency domain and has the effect of reducing the mean values of y_0, the detection statistic for signals without embedded signatures. Therefore, as the mapped subcarrier set size is increased, the mean value of y_0 is decreased and the detection ratio y_{sig}/y_0 is increased. This improvement in detector performance with increasing subcarrier set size is examined further in the next section.

The associated overheads for a system using 192 data carriers are outlined in Table 6.1. Although a large improvement in detector performance may be realized by increasing the mapped subcarrier set size from 1 to 3, it can be seen that the relative performance improvement diminishes as set sizes are increased further. As the over-

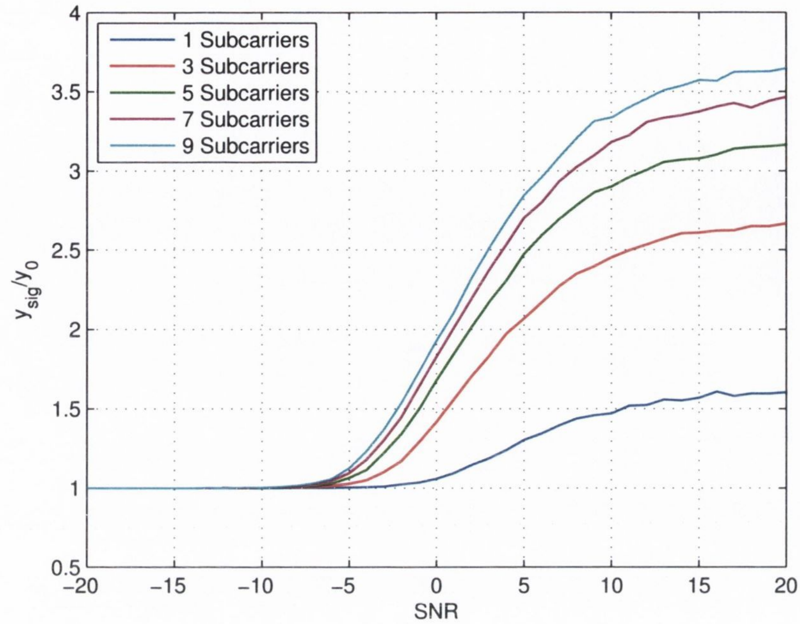


Fig. 6.1: Signature detection ratio performance with increasing mapped subcarrier set sizes over a range of SNR values.

head of the system increases linearly, this would suggest that the optimum subcarrier set size may lie between 3 and 7, depending upon the requirements of the application.

Set Size	% Overhead
1	0.52
3	1.56
5	2.60
7	3.65
9	4.69

Tab. 6.1: Signature Overhead

It can be seen that detector performance deteriorates rapidly with SNR $<$ 0 dB, to the stage where y_{sig} and y_0 are indistinguishable at SNR $<$ -5 dB. This suggests that cyclostationary signatures may not be used successfully to facilitate very low-power signal detection when short signal observation times are adopted. However, in the context of network rendezvous and coordination, network nodes must synchronize with and successfully demodulate detected signals. At SNR levels below which detection may be performed OFDM based systems typically experience very high bit-error rates and rendezvous can not be achieved [110].

6.2.3 Observation Times

A key performance metric for cyclostationary signatures used in the context of DySPAN rendezvous and coordination is the time taken to reliably detect and analyse an embedded signature. Although reliable analysis of inherent signal features typically requires high spectral resolution and long signal observation times, the use of cyclostationary signatures facilitates the use of spectral resolution on the order of OFDM subcarrier spacings and thus relatively short observation times.

The effect of observation times upon signature detection performance is examined using further simulations. 256-subcarrier OFDM signals are considered as before. Signatures are embedded using mapped subcarrier set sizes of 3, 5 and 7 at an arbitrarily chosen cyclic frequency. Gaussian white noise is added for SNR $\approx 5\,\text{dB}$ and a random timing offset is used as in the previous section. Monte Carlo simulations are used to estimate probabilities of detection, P_d and false alarm, P_{fa} as determined over 2000 runs. Simulations are repeated using observation times of between 6 and 16 symbol durations, T, for each subcarrier set size. Fig. 6.2, 6.3 and 6.4 illustrate results for subcarrier set sizes of 3, 5 and 7 respectively.

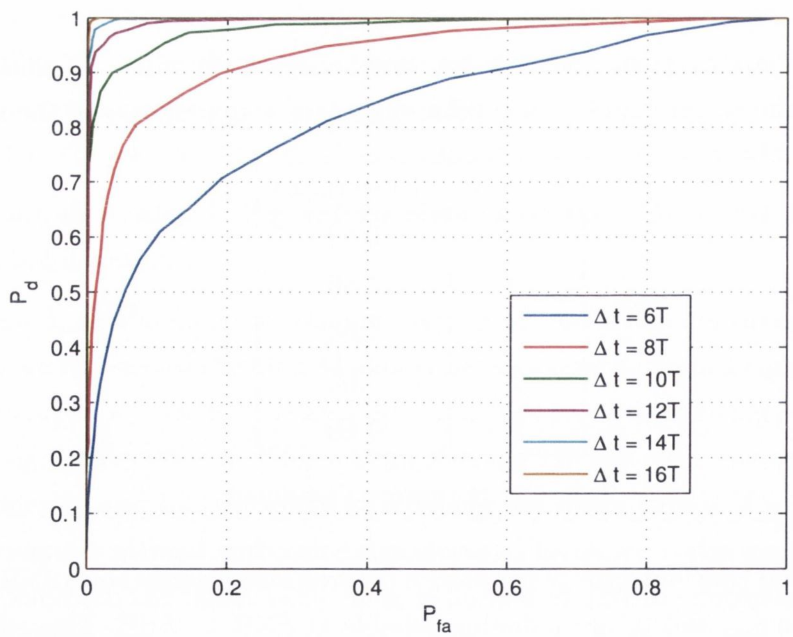


Fig. 6.2: Receiver Operating Characteristic (ROC) performance with increasing observation time for $M = 3$.

It can be seen that detection performance improves considerably with increasing signal observation time. For a signature generated using 3 mapped subcarriers, an

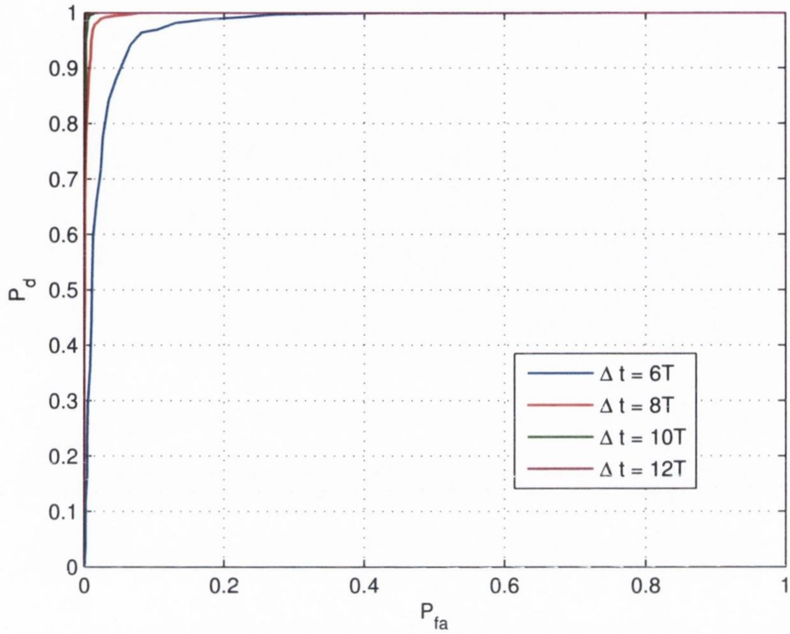


Fig. 6.3: ROC performance with increasing observation time for $M = 5$.

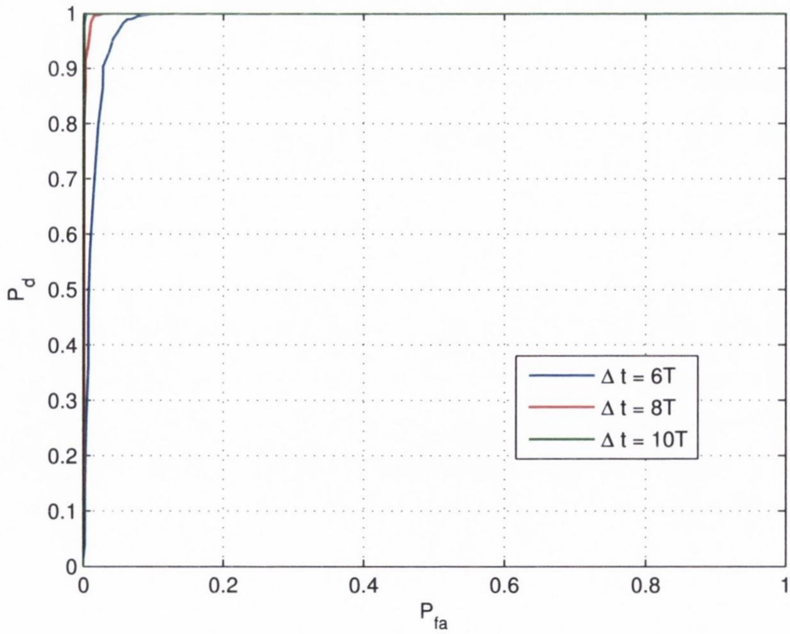


Fig. 6.4: ROC performance with increasing observation time for $M = 7$.

observation time of 16 symbol durations yields a false alarm rate of 1% for an associated detection rate of 99% as determined over 2000 simulations. A significant reduction in required observation time may be achieved by adopting a larger mapped subcarrier set size. Indeed Fig. 6.3 shows that for $M = 5$, just 10 symbol durations are required for comparable performance. As can be seen in Fig. 6.4, this value drops to just 8 symbol durations for $M = 7$.

This reduction in required observation time can be explained using the temporal-spectral resolution product discussed in Chapter 5. Gardner states that the reliability of an SCF estimate calculated using time or frequency-smoothing depends upon the resolution product [82],

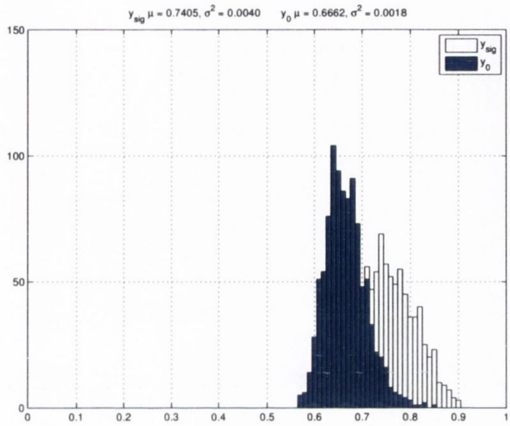
$$\Delta t \Delta f >> 1 \tag{6.3}$$

where Δt and Δf are the temporal and spectral resolutions respectively. The size of the moving average window used in the signature detector is dictated by the size of the subcarrier set mapped in order to generate a signature. Thus by increasing the subcarrier set size, we increase the size of the moving average window. As the moving average window effectively performs frequency smoothing on our SCF estimate, a greater value of Δf is obtained. Accordingly, a smaller temporal resolution, Δt is required for an equivalent estimate reliability.

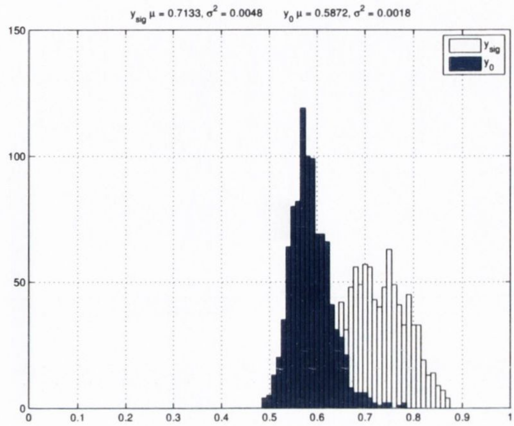
Greater insight into the performance of the signature detector can be obtained through closer inspection of the simulation results. Fig. 6.5, 6.6 and 6.7 illustrate the histograms of y_{sig} and y_0 underlying the ROC analyses shown by Fig. 6.2, 6.3 and 6.4 respectively. In these histograms, an overlap between values of y_{sig} and y_0 indicates that perfect detection results cannot be obtained. Therefore, the greater the distance between the values of y_{sig} and y_0, the better the detection performance which can be achieved.

As the signal observation time used for detection is increased, it can be seen that the mean of the detection statistic for signals without signatures falls significantly. In the case of $M = 3$, mean y_0 falls from 0.6662 for $\Delta t = 6T$ to 0.4259 for $\Delta t = 16T$. Additionally, the associated variance of y_0 falls considerably from 0.0018 to 0.0011, resulting in a greatly reduced false alarm rate for a given threshold. These trends are mirrored by the results for $M = 5$ and $M = 7$.

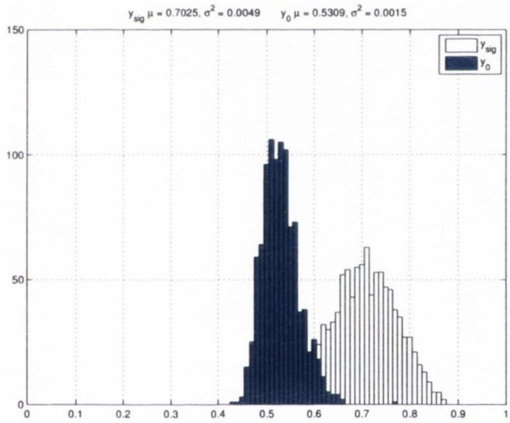
The improvement in detection performance which can be seen with increasing subcarrier set size, M, arises for a number of reasons. The first of these is a reduction in the variance of both y_{sig} and y_0. For example, the variance of y_{sig} for $M = 7$ is just 0.0009 compared to 0.0041 for $M = 3$ with observation time $\Delta t = 16T$. Secondly, it can be seen that mean values for y_0 fall significantly with increased M. For observation time $\Delta t = 16T$, mean y_0 falls from 0.4259 for $M = 3$ to just 0.3563 for $M = 7$. The sum of these effects results in the considerable improvement in overall detection performance seen in Fig. 6.2, 6.3 and 6.4.



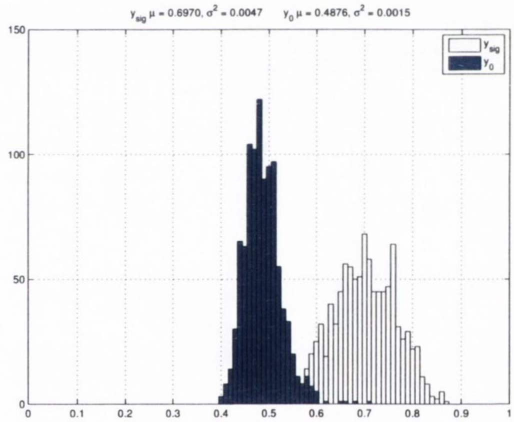
(a) $\Delta t = 6T$



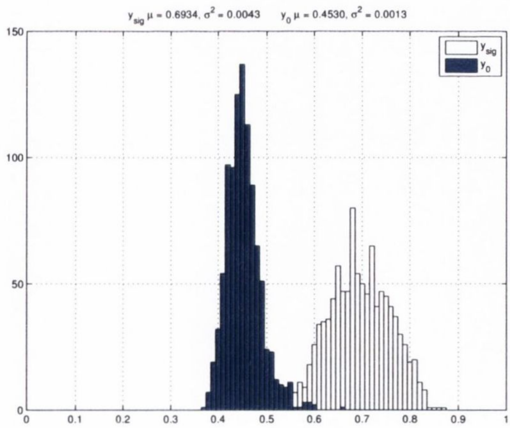
(b) $\Delta t = 8T$



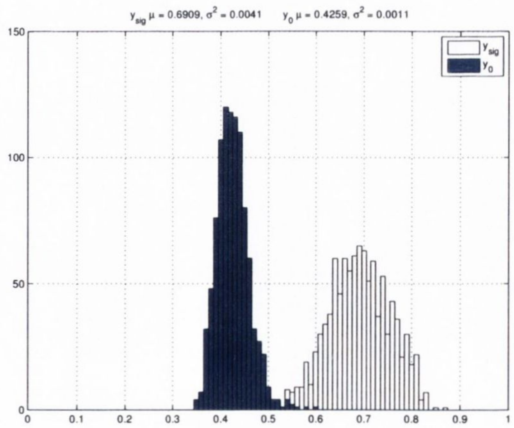
(c) $\Delta t = 10T$



(d) $\Delta t = 12T$

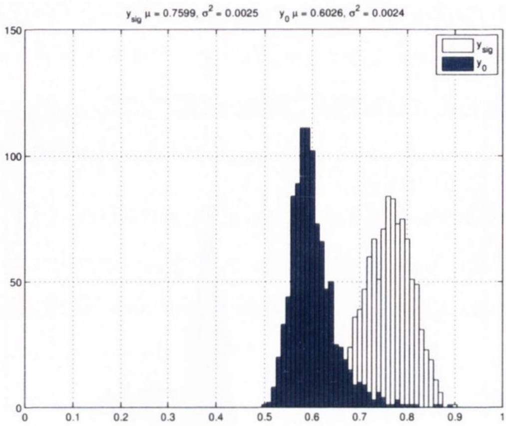


(e) $\Delta t = 14T$

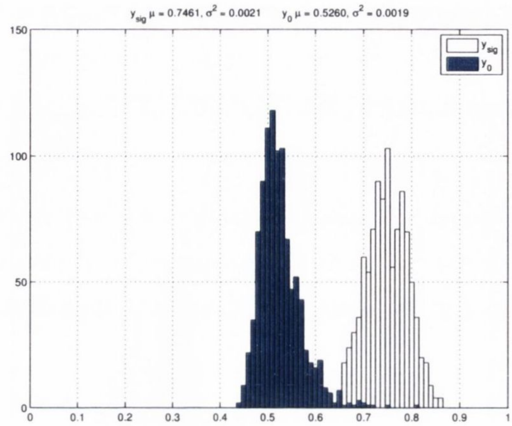


(f) $\Delta t = 16T$

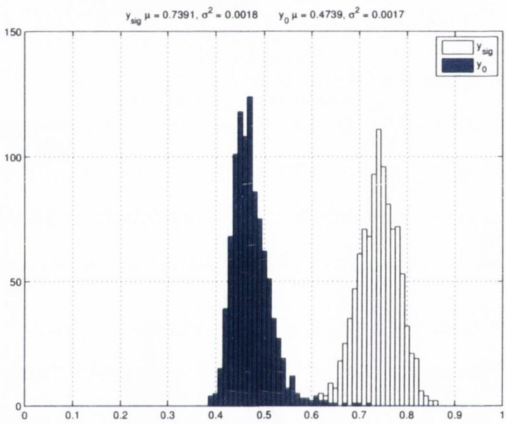
Fig. 6.5: Histograms of y_{sig} and y_0 underlying ROC analyses for $M = 3$.



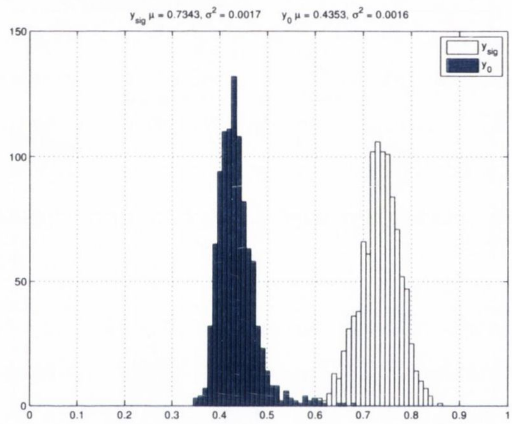
(a) $\Delta t = 6T$



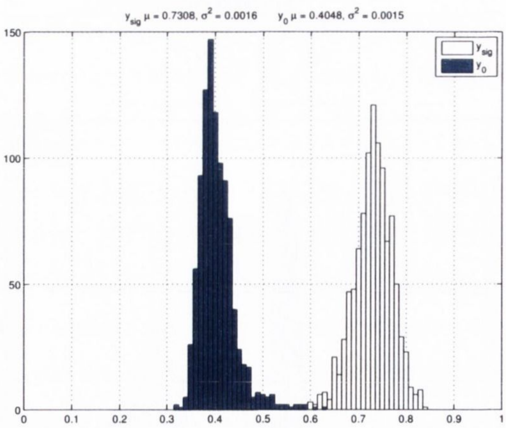
(b) $\Delta t = 8T$



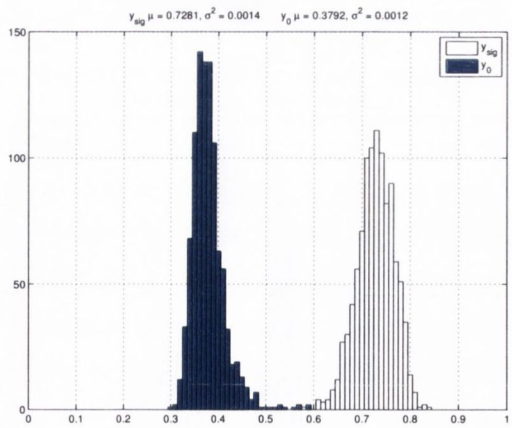
(c) $\Delta t = 10T$



(d) $\Delta t = 12T$

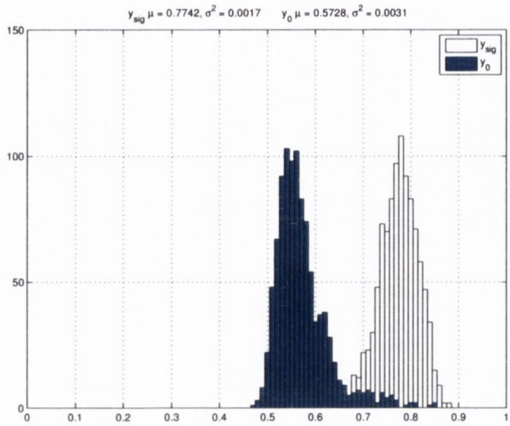


(e) $\Delta t = 14T$

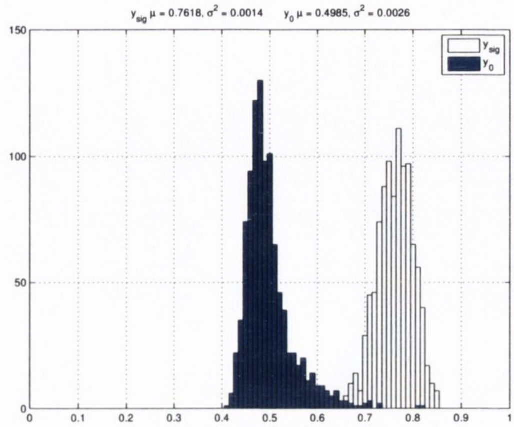


(f) $\Delta t = 16T$

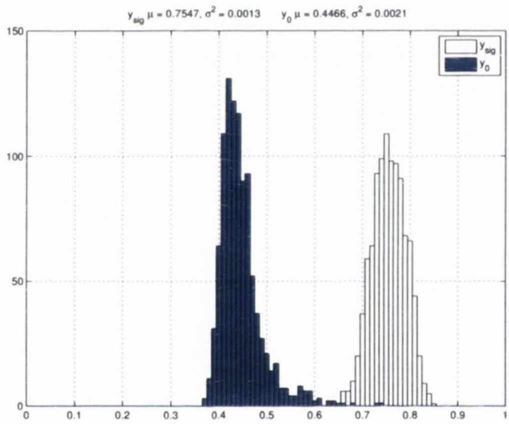
Fig. 6.6: Histograms of y_{sig} and y_0 underlying ROC analyses for $M = 5$.



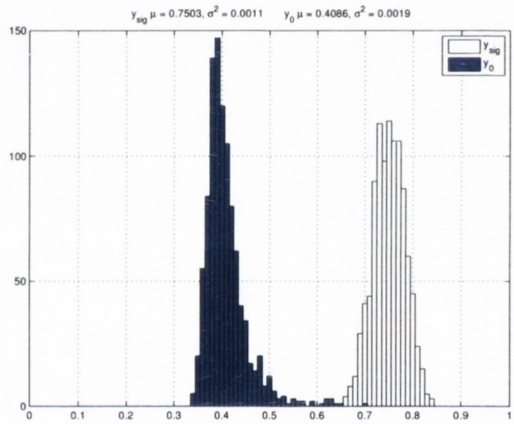
(a) $\Delta t = 6T$



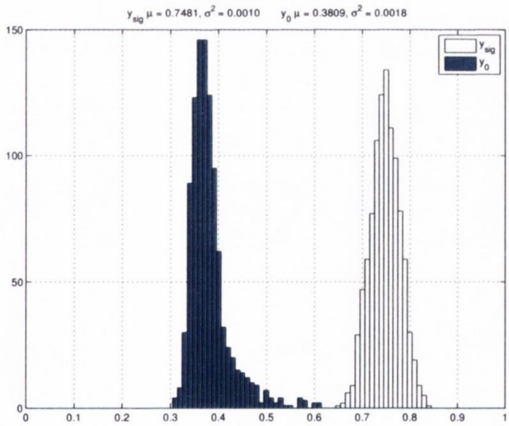
(b) $\Delta t = 8T$



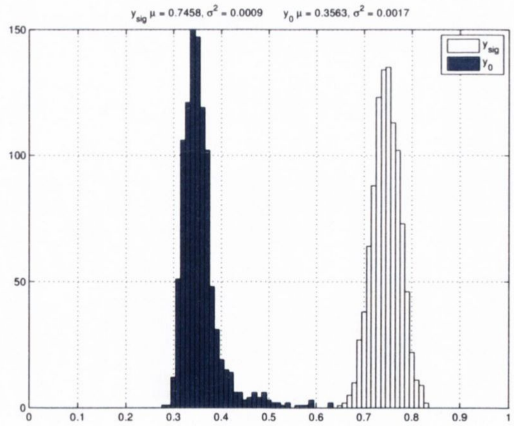
(c) $\Delta t = 10T$



(d) $\Delta t = 12T$



(e) $\Delta t = 14T$



(f) $\Delta t = 16T$

Fig. 6.7: Histograms of y_{sig} and y_0 underlying ROC analyses for $M = 7$.

6.2.4 Inherent Feature Detector Performance Comparison

In Chapter 5, a number of the main drawbacks associated with the use of inherent cyclostationary features for DySPAN rendezvous and coordination were identified. Among these limitations was the inability to manipulate inherent cyclostationary features without directly impacting system performance. By generating artificially embedded cyclostationary signatures, these features can be uncoupled to a degree from the fundamental operating parameters of the system and so can be independently manipulated to suit the requirements of the application.

A further motivation for the creation of artificial cyclostationary signatures is the typically long observation time required to perform detection on the basis of inherent signal features. The issue of observation time arises due to the spectral resolution, Δf required to successfully resolve those features inherent to the signal. As the spectral resolution is increased (smaller Δf), a longer observation time, Δt, is required for an equivalent estimate reliability (see Eq. 6.3). Thus, by embedding features which may be resolved using a lower spectral resolution (larger Δf), the observation time required for reliable detection may be significantly reduced. Additionally, the power of inherent signal features is typically low relative to that of the signal. Accordingly, longer observation times are required in order to reduce the power of uncorrelated spectral components below that of the correlated features. This limitation can once again be overcome using artificially generated features. A direct comparison between inherent signal features and an artificially introduced signature can be seen in Fig. 6.8. The figure shows the spectral frequency of an OFDM signal with a cyclic prefix at cyclic frequencies $\alpha = 0$ (signal power), $\alpha = 1/T$ (inherent features due to the cyclic prefix) and $\alpha = 1/T_s$ (signature embedded using a single mapped OFDM subcarrier).

In order to assess the observation time required to perform signal detection on the basis of inherent cyclostationary features, a simple inherent feature detector is implemented and Monte Carlo simulations are carried out using a similar approach to that used in the previous section. The feature detector is implemented as

$$y_\alpha = \frac{1}{K}\sum_{k=0}^{K-1} \widehat{S}_x^\alpha[k] \tag{6.4}$$

where the estimated SCF is

$$\widehat{S}_x^\alpha[k] = \frac{1}{L}\sum_{l=0}^{L-1} X_l[k]X_l^*[k-\alpha]W[k] \tag{6.5}$$

and $W[k]$ is a smoothing spectral window.

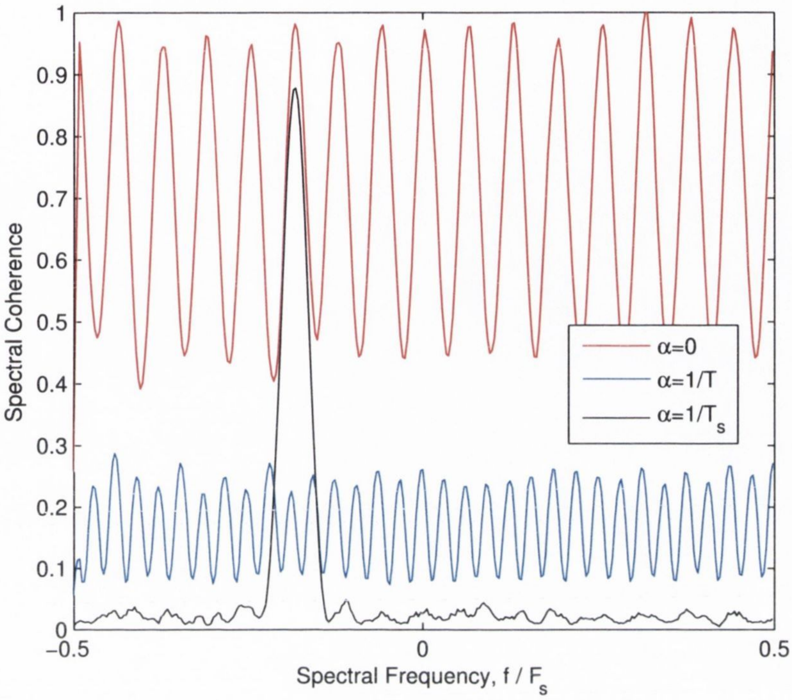


Fig. 6.8: Comparison of inherent and artificially embedded cyclostationary features.

256-subcarrier OFDM with a 1/16 cyclic prefix is considered. Gaussian white noise is added for SNR $\approx$ 5 dB and a random timing offset is used as before. In order to resolve the inherent features arising due to use of the cyclic prefix, a frequency resolution of $\Delta f = 1/10T_s$ is adopted. Simulations are carried out using observation times of between 10 and 60 symbol durations, T. Detection and false alarm rates are calculated over 2000 simulations and used to generate the ROC analysis illustrated in Fig. 6.9.

Results show that a relatively long observation time is required in order to achieve reliable signal detection performance using inherent cyclic prefix-related features. For inherent features arising due to use of the cyclic prefix, a detection rate of 85% can be achieved for an associated false alarm rate of 17% using an observation time of $\Delta t = 60T$. By comparison, similar performance can be achieved with an observation time of just $\Delta t = 8T$ using a cyclostationary signature generated using 3 mapped OFDM subcarriers (see Fig. 6.2).

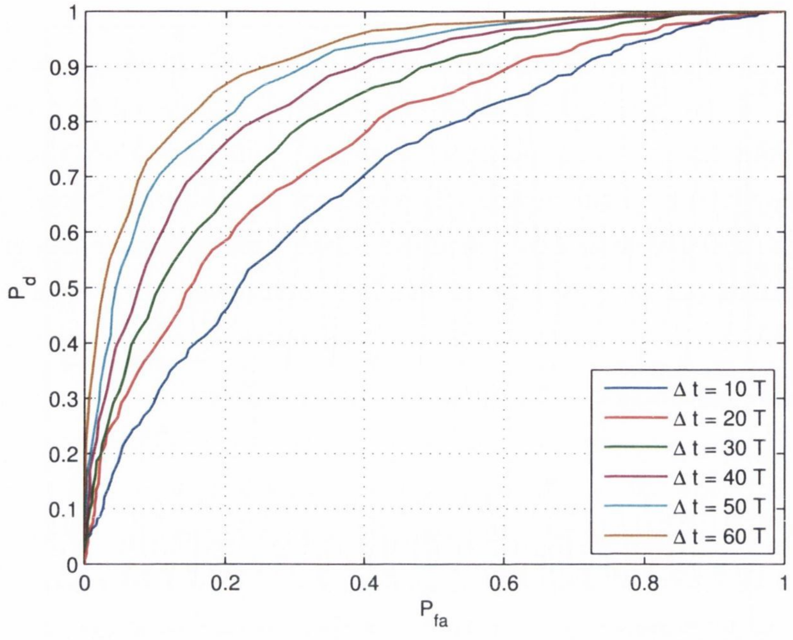


Fig. 6.9: Detection performance for detector using inherent cyclic prefix-related cyclostationary features.

6.2.5 Summary

In performing a range of simulations, a number of key insights have been gained regarding the generation and detection of cyclostationary signatures in OFDM-based waveforms. Firstly, it has been seen that significant improvements in detection performance can be achieved by increasing the number of subcarriers mapped in order to generate a signature. By using a mapped subcarrier set size of 5 instead of 3, a 25% increase in the average detection ratio y_{sig}/y_0 can be achieved for SNR = 5 dB. This improvement comes however at the cost of an increase in overhead from 1.56% to 2.6% for a system with 192 data subcarriers. Additionally, it was seen that, although reliable signal detection is possible using cyclostationary signatures at SNR > 5 dB, performance deteriorates considerably for SNR < 0 dB. This suggests that, while cyclostationary signatures may not be suitable for facilitating very low power signal detection using short observation times, they hold much potential in the context of DySPAN rendezvous and coordination.

Secondly, it was found that signature detection performance can be improved considerably by increasing the signal observation time adopted. For a signature generated using a set of 3 mapped subcarriers, an increase in the detection rate from 70% to 90% can be obtained for an associated reduction in false alarm rate from 20% to ≈ 5%

by increasing the observation time from $6T$ to $10T$. Ideal detector performance with 100% detection rate and 0% false alarm rate was achieved over 2000 simulations for an observation time of just $16T$. For a signature generated using a set of 5 mapped subcarriers, this was achieved for an observation time of $12T$ and for 7 mapped subcarriers, the same performance was achieved using an observation time equivalent to 10 OFDM symbols, $10T$. An IEEE 802.16 WiMax system using a 3.5 MHz bandwidth and 1/8 cyclic prefix requires a minimum frame size of 34 symbols [10]. Thus a 3-carrier cyclostationary signature may be successfully detected using an observation time of less than half a single IEEE 802.16 frame.

Finally, by comparing the performance of a cyclostationary signature detector with that of a simple inherent feature detector, it was seen that significant reductions in the observation times required for reliable signal detection may be achieved. It is noted that in addition to overcoming the requirement for long observation times associated with the use of inherent signal cyclostationarity, cyclostationary signatures afford a level of flexibility and manipulation which is not possible using inherent features.

6.3 Signal Detection in Frequency-Selective Fading Channels

6.3.1 Overview

As discussed in the previous chapter, a limitation of cyclostationary signatures generated using single OFDM subcarrier set mapping is the sensitivity exhibited to frequency-selective fading. A deep fade occurring at the frequency of a mapped set may distort the signature and deteriorate detection performance. Robustness is provided in typical OFDM-based systems through the use of a cyclic prefix, however this approach requires close frequency and time synchronization with the signal of interest. In the context of signal detection, this is not possible and so an alternative approach is required.

The effects of frequency selective fading may be overcome by increasing the frequency diversity of the cyclostationary signature. This may be achieved through use of multiple mapped subcarrier sets in order to generate features at a number of discrete spectral frequencies. Through use of a constant mapping separation, p, each feature occurs at a common single cyclic frequency, α. In performing detection, additional complexity is not required as each feature may be individually detected using the single feature detector (see Eqn. 6.2). Alternatively, the optimum detector may be approximated by:

$$y_\alpha = \max_{0 \le k \le N-1} \sum_{m=0}^{M-1} H[m]\widehat{C}_x^\alpha[k-m] \tag{6.6}$$

where the ideal spectral correlation function for multiple-feature signatures is approximated by $H[m]$, a periodic pulse train. It should be noted that unique multiple-feature signatures may still be generated through choice of set spacing p to generate a signature at discrete cyclic frequency α_{sig}. Thus multiple-feature signatures may also be used to achieve network identification.

A range of simulations are used to examine detection performance using multiple-feature cyclostationary signatures in frequency-selective fading channels.

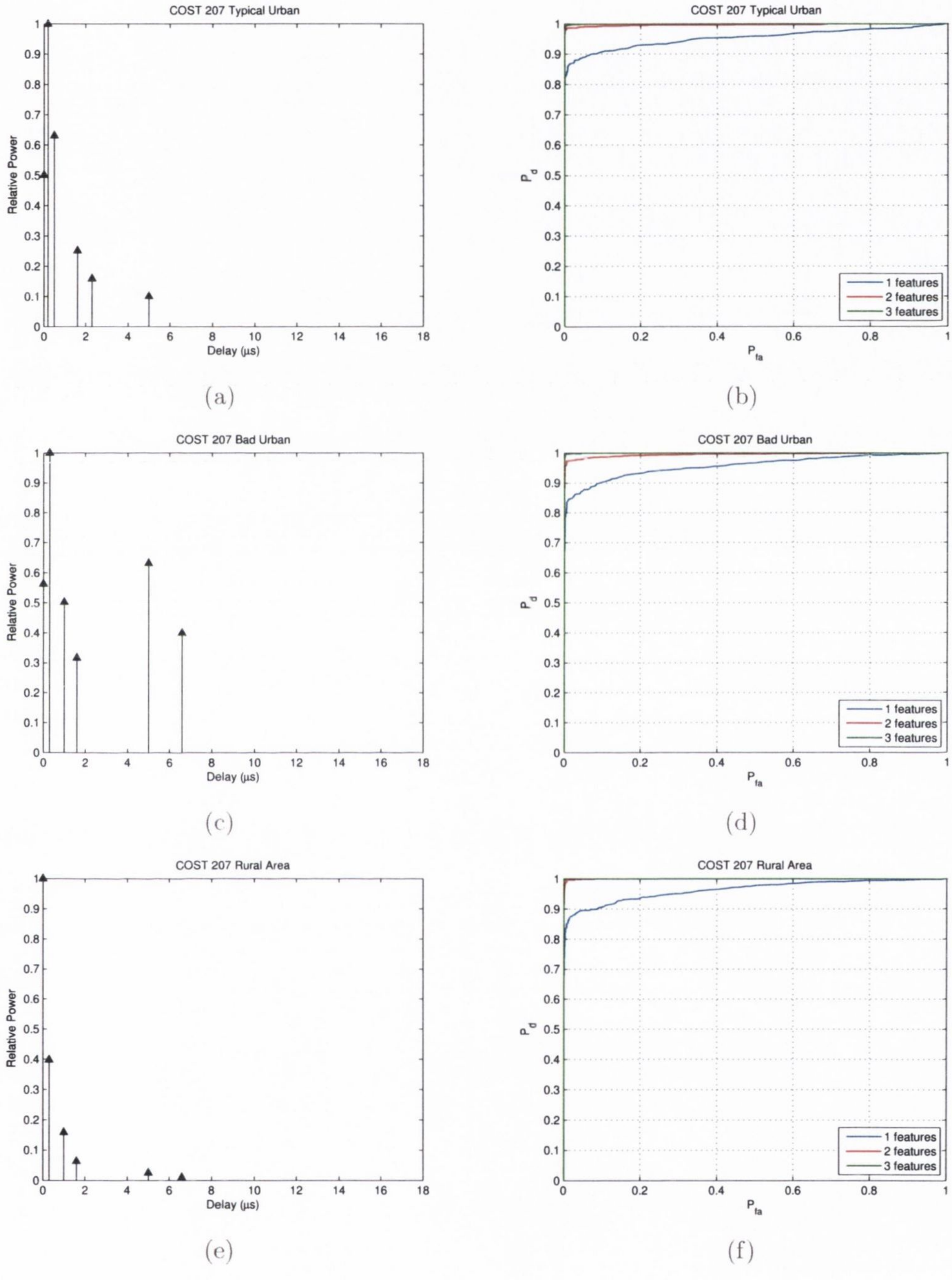
6.3.2 Multiple-feature Signature Detection Performance

256-subcarrier OFDM signals are considered as before, with subcarriers distributed as follows: 192 data, 55 guard, 8 pilot and 1 DC. Data is randomly generated and QPSK modulated with a 16 sample cyclic prefix prepended to each OFDM symbol. Cyclostationary features are embedded at cyclic frequency $\alpha = 16/T_s$ using mapped sets of 3 subcarriers. A 4 MHz signal is simulated with a number of frequency-selective multipath channels modelled using the COST 207 [111] channel profiles as well as an exponentially decayed channel model. Signatures are generated using between 1 and 3 unique features and ROC performance is examined for each using Monte Carlo simulations. Probabilities of detection (P_d) and false alarm (P_{fa}) are recorded over 2000 simulations. Gaussian white noise is added for $SNR \approx 5$ dB and a single feature detector with signal observation time of $\Delta t = 30T$ is used. The delay profiles for each channel model and the ROC performance for each signature type are presented in Fig. 6.10 and 6.11.

Results show the reduction in ROC performance for single feature signatures under frequency-selective fading. For a false alarm rate of 0 as determined over 2000 simulation runs, a single feature signature can achieve an average detection rate of approximately 75%. Using a signature comprising 2 unique features, the detection rate increases to $\approx 92\%$ when averaged across the channel models, increasing to $\approx 98\%$ for a 3-feature signature.

6.3.3 Discussion

Although improved performance is achieved using multiple-feature signatures, these improvements come with the cost of increased overhead. Multiple-feature signatures are



(a) (b) (c) (d) (e) (f)

Fig. 6.10: Delay spread profiles and ROC performance for multiple-feature signatures.

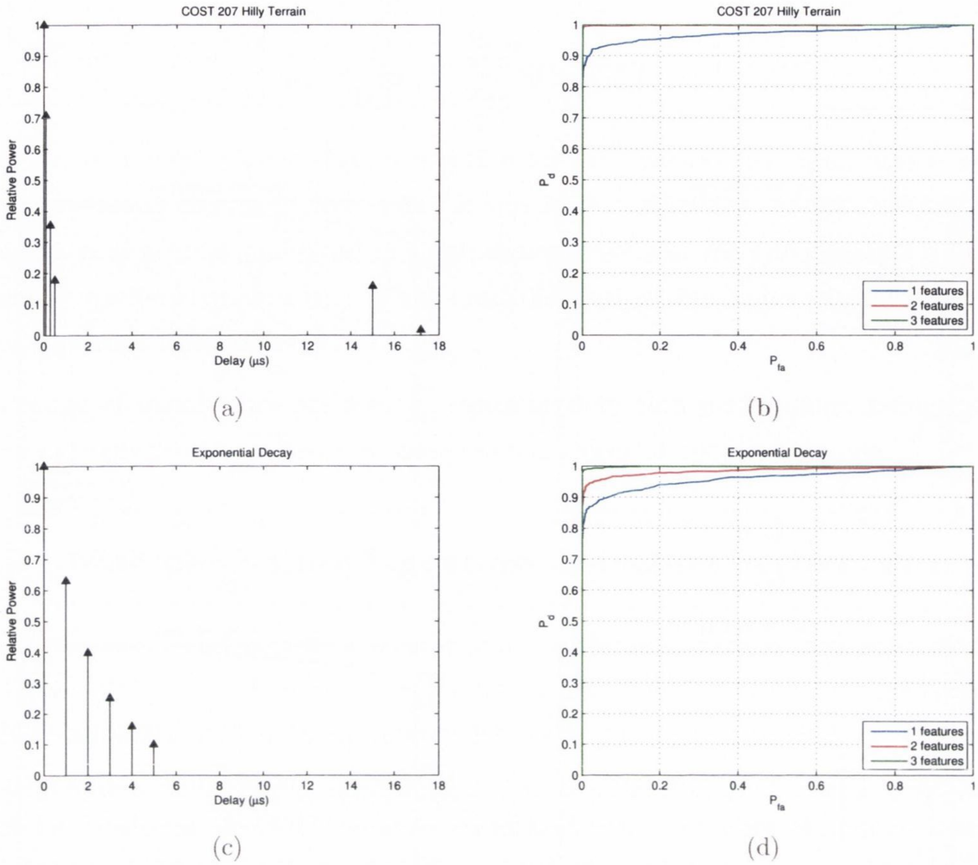


Fig. 6.11: Delay spread profiles and ROC performance for multiple-feature signatures.

generated through the use of multiple mapped sets of OFDM subcarriers, resulting in fewer subcarriers which may used to carry independent data. The trade-off is illustrated in Table 6.2, where the overhead associated with the single-feature and multiple-feature signature types used in simulations are compared. The system overhead here is given for the case of 256-subcarrier OFDM, where 55 guard subcarriers and 8 pilot subcarriers are used. In the context of cognitive radio operation, it may be possible to choose the number of embedded features dynamically on the basis of prevailing channel conditions. In this way, system overhead may be minimized and overall throughput maximized.

Number of Features	Redundant Carriers	Overhead
1	3	1.56 %
2	6	3.125 %
3	9	4.688 %

Tab. 6.2: Multiple-Feature Signature Overhead

Examining the performance of a signature detector under conditions of frequency-selective fading illustrates the importance of power normalization in estimating spectral correlation. Power normalization is achieved through use of the AF (Eqn. 6.1). Although use of the AF increases the complexity of the signature detector, the performance gains are considerable. This is illustrated by Fig. 6.12 which shows ROC performance for signature detection using the time-smoothed cyclic cross periodogram (TS-CCP) (Eqn. 5.9) alone.

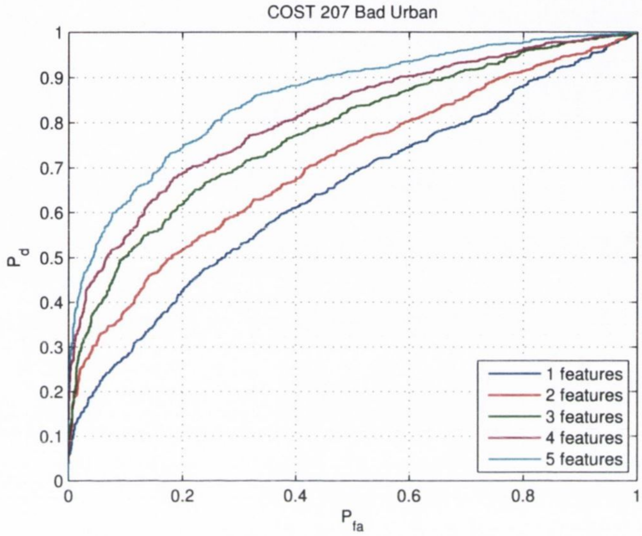


Fig. 6.12: ROC performance for signature detector without power normalization in COST 207 Bad Urban channel.

6.4 Network Identification

6.4.1 Overview

The use of cyclostationary signatures as unique network identifiers was discussed in the previous chapter. Using OFDM subcarrier-mapping, cyclostationary features may be generated at one of a number of discrete cyclic frequencies. Thus, by embedding a signature with a particular cyclic frequency in a waveform, a transmitting device allows that waveform to be uniquely identified by receiving devices. In the context of DySPAN rendezvous and coordination, all nodes within a single network may embed the same unique signature within any transmitted signals. Nodes wishing to join the network may then detect peer nodes and establish a communications link by detecting this unique signature. As the signature is present in all signals transmitted by nodes within the network, identification can be performed using any intercepted signal within that network.

In using cyclostationary signatures to perform network identification, a key system limitation is the number of unique signatures which can be used by that system. In the context of DySPAN rendezvous and coordination, a straightforward method for differentiating between signatures is on the basis of the cyclic frequency, α, at which the signature occurs. As we have seen, signatures may be embedded using OFDM subcarrier mapping at cyclic frequencies

$$\alpha_{sig} = \frac{p}{T_s} \tag{6.7}$$

where p is the frequency separation between mapped sets and T_s is the OFDM source symbol duration. Using this approach, the maximum number of unique single-feature signatures which may be generated by the OFDM-based system is $N - 2M + 1$ where N is the total number of subcarriers used in the system and M is the number of subcarriers in the mapped set. For multiple-feature signatures, the number of unique signatures drops to $\frac{N}{R} - 2M + 1$ where R is the number of independent features comprising the signature. In the case of a typical system using single-feature signatures with 256 subcarriers and mapped sets of 3 subcarriers, this approach yields 251 unique signatures which may be used.

As well as being able to generate a large number of unique signatures, however, it is necessary to successfully detect and differentiate between each of these signatures. In performing detection and network identification, a key parameter is the cyclic frequency resolution of the signature detector design adopted. In Chapter 5, a highly efficient signature detector was presented(Fig. 5.8). This detector relies upon fast Fourier transform (FFT) rotation in the frequency domain in order to perform the α-shift required to detect a signature and in doing so achieves a low level of computational complexity. A limitation of this approach however, is the low cyclic frequency resolution of such a detector. Recall from Chapter 5 that the duration of an OFDM symbol is $T = T_g + T_s$ where T_s is the source symbol duration and T_g is the duration of the appended cyclic prefix. In a system where $T_g \neq 0$, the frequency resolution of the detector is $\frac{1}{T}$. Under these circumstances, signatures can only be detected where

$$\frac{p}{T_s} = \frac{q}{T} \qquad p, q < N - 2M + 1 \tag{6.8}$$

Taking an example system with $N = 256$, $M = 3$ and $T_g = \frac{T_s}{16}$, signatures may be detected using the frequency-domain shifting detector at

$$\alpha = \frac{16p}{T_s} \qquad 1 \leq p \leq 15 \tag{6.9}$$

and the maximum number of unique signatures which can be used is 15.

Depending upon the application, 15 unique signatures may be sufficient. If however, a greater number of signatures is required, a signature detector with a smaller cyclic frequency resolution must be designed. Fig. 6.13 illustrates such a detector.

The efficiency of the frequency-domain shifting detector arises due to the use of a circular rotation in the frequency domain to achieve the required α shift. However, the use of this approach limits the cyclic frequency of the detector to $q.\Delta f$ where the frequency resolution, $\Delta f = 1/T$. In order to perform detection at an arbitrary cyclic frequency, it must be possible to perform an arbitrary α shift. As illustrated in Fig. 6.13, this can be achieved in the time domain through multiplication with a complex exponential series.

Following frequency shifting, two FFT stages are required to transform both the shifted and non-shifted signal samples. These samples are correlated and time-averaged to calculate the SCF, $S_x^\alpha(f)$. Calculation of the AF, $C_x^\alpha(f)$ is performed through normalization with a suitable power series as shown. Although the use of time-domain frequency shifting increases the computational complexity of the detector, it effectively facilitates the detection of cyclostationary signatures at all cyclic frequencies.

6.4.2 Network Identification Performance

Monte-Carlo simulations are carried out to examine the performance of signatures used for network identification under frequency-selective channel conditions. The time-shifting detector illustrated in Fig. 6.13 is used to provide the necessary cyclic frequency resolution and four unique signatures are considered with cyclic frequencies outlined in Table 6.3.

Signature	Cyclic Frequency
α_1	$29/T_s$
α_2	$30/T_s$
α_3	$31/T_s$
α_4	$32/T_s$

Tab. 6.3: Signature Cyclic Frequencies

The minimum signature separation of $1/T_s$ is adopted in order to assess network identification performance in the case where the maximum number of signatures are in use.

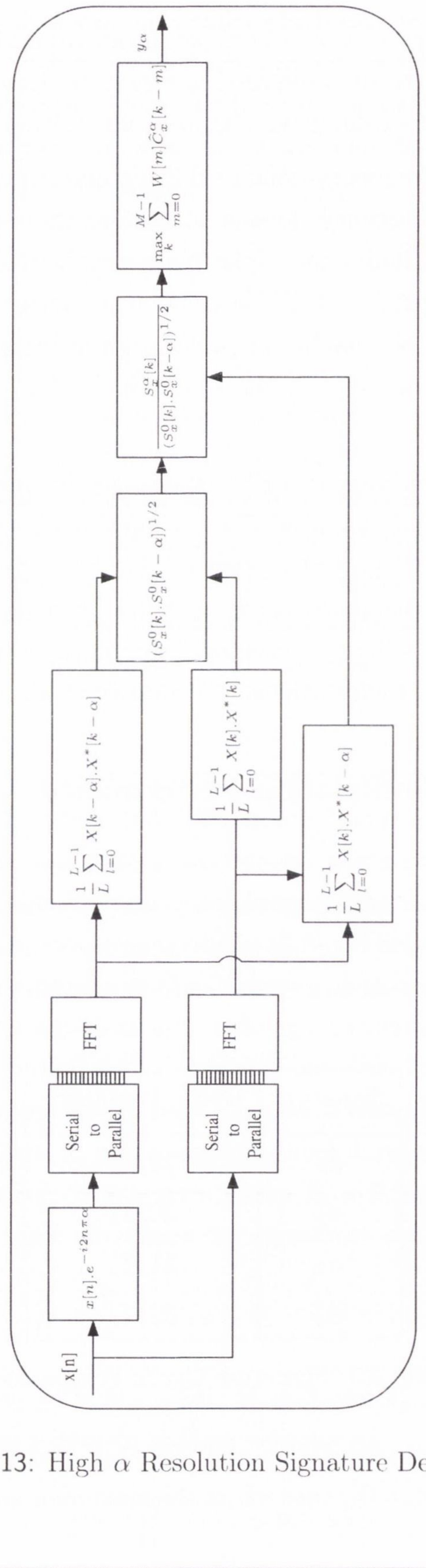


Fig. 6.13: High α Resolution Signature Detector

An exponential decay frequency-selective channel model (see Fig. 6.11(c)) is simulated and multiple-feature signatures containing 3 independent features are generated as before. QPSK modulated data symbols are simulated using 256-subcarrier OFDM signals with cyclic prefix length 16 as before. Gaussian white noise is added for $-20\,\text{dB} \leq SNR \leq 20\,\text{dB}$. For each iteration, a signal is generated with embedded signature α_j randomly chosen for $j \in [1, 2, 3, 4]$. Detection is performed for each cyclic frequency using the time-domain shifting detector and identification is performed using decision statistic:

$$z = \arg\max_j y_{\alpha_j} \tag{6.10}$$

A probability of identification, P_j is defined as:

$$P_j = p(z = j | x_j) \tag{6.11}$$

where x_j is an OFDM signal containing a cyclostationary signature with cyclic frequency α_j. Results are presented in Fig. 6.14 for observation times between $5T$ and $30T$.

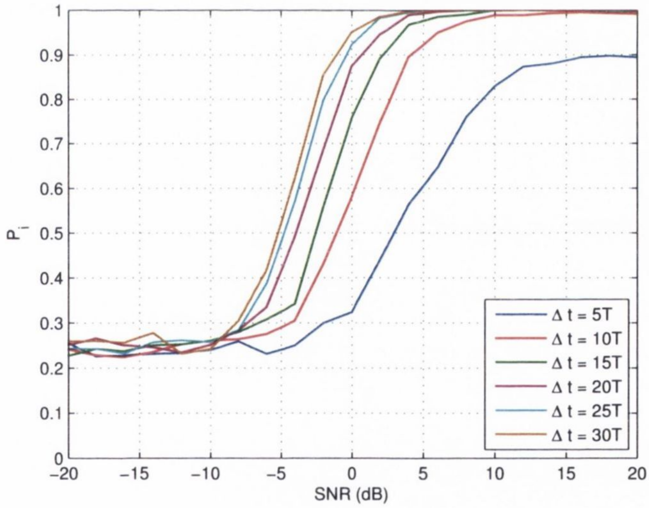


Fig. 6.14: Performance of Network Identifier using Cyclostationary Signatures.

It can be seen that performance of the identifier improves as the signal observation time is increased. Using an observation time of just $5T$, signatures can be differentiated with a 90% probability at $SNR \geq 15\,\text{dB}$. However, by increasing the observation time to $30T$, a signature identification rate of 100% can be achieved for $SNR \geq 5\,\text{dB}$. This rate falls to approximately 95% at $SNR \approx 0\,\text{dB}$ with performance falling more rapidly for lower levels of SNR.

6.4.3 Discussion

Results show that cyclostationary signatures may be successfully used to perform network identification under frequency-selective fading conditions. By adopting signatures with the minimum cyclic frequency separation, it was shown that a relatively large number of unique signatures can be successfully utilized within a single OFDM-based waveform. Cyclostationary signatures may be used for network identification where each device within a particular network uses a common identifying signature. In this way, devices from differing networks with similar OFDM-based waveforms can perform rendezvous and coordination with their peers using the signatures embedded in transmitted signals. The existence of large numbers of unique signatures facilitates simultaneous network identification within many co-located networks, provided that no two networks adopt the same signature. In order to ensure that each network adopts a unique signature, an assignment mechanism is required. In the case where networks require approval or certification in order to operate within a given band, signatures could be assigned in a centralized manner by the approving authority. In the absence of such an authority, a distributed assignment mechanism may be possible based upon observations made of other networks active within the same spectrum band.

In addition to examining the use of cyclostationary signatures for network identification, it was illustrated that the complexity of the chosen signature detector design may be chosen on the basis of the number of unique signatures required by the application. In the case where a small number of unique signatures suffice, the low-complexity FFT shifting detector design may be adopted. However, if large numbers of signatures are needed, the more complex time-domain frequency shifting design may be used.

The cyclic frequency of an embedded feature may be used to provide an identifying signature in the context where the transmit frequency of the SOI is unknown. In this way, features occurring at any spectral frequency within the received bandwidth may be used to identify that SOI. However, in the case where the transmit frequency of the signal is known in advance, it may be possible to generate more complex signatures by using both the cyclic and spectral frequencies of the embedded feature to identify that signal. In this way, it may be possible to create greater numbers of unique signatures or to perform more reliable network identification.

6.5 Frequency Acquisition

6.5.1 Overview

A key use of cyclostationary signatures in the context of DySPAN rendezvous and coordination is frequency acquisition. Following the detection of a signature within an SOI and network identification, timing and frequency synchronization must take place in order for a communications link to be established.

Using a signature detector based on the use of a cyclic cross periodogram (CCP), detection is performed in the frequency domain. This allows the spectral frequencies of detected cyclostationary features to be directly determined from the output of the detector. If the relationship between the detected feature and the carrier frequency of the SOI is known, the spectral frequency of that feature can be used to estimate the carrier frequency of the signal.

In the case where the operating bandwidth of the receiver is greater than that of the SOI, the use of a CCP-based detector facilitates the detection of signals containing embedded signatures with any carrier frequency within that receive bandwidth. Using the detected features to estimate the carrier frequency of the signal allows the bandwidth and carrier frequency of that receiver to be adjusted in order to achieve synchronization and establish a communications link.

Carrier frequency estimation using an embedded single-feature signature may be performed directly. However, in the case of a multiple-feature signature such as that illustrated in Fig. 6.15, additional processing is required in order to identify the location of all features present.

6.5.2 Acquisition Performance

Monte-Carlo simulations are used to examine frequency acquisition performance using embedded cyclostationary signatures. A 5MHz spectrum band is simulated using a 1280-bin inverse fast Fourier transform (IFFT). Of these, 256 contiguous bins are chosen to simulate a signal transmitted using 20% of the available bandwidth. As before, subcarriers are allocated as follows: 192 data, 8 pilot, 55 guard, 1 DC carrier. The index of the DC carrier bin, n_o is randomly chosen as $128 \leq n_0 \leq 1152$ and a further fractional frequency offset f_{frac} is added as

$$y[k] = x[k]e^{2\pi f_{frac} ki} \qquad (6.12)$$

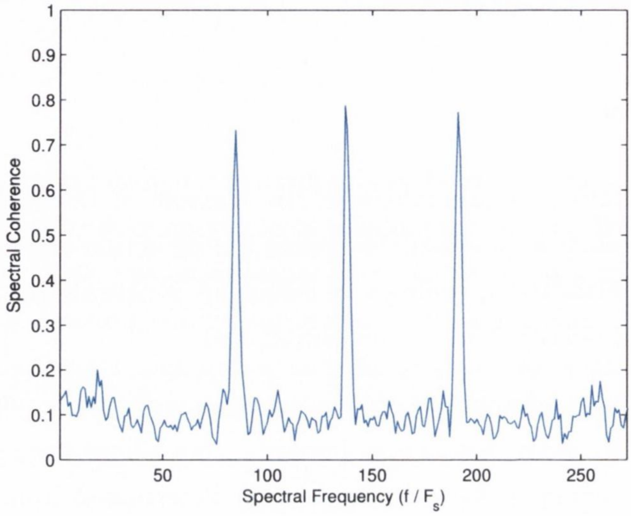


Fig. 6.15: Spectral Frequency of an OFDM signal containing an embedded multiple-feature signature.

A multiple-feature cyclostationary signature is generated with cyclic frequency $\alpha = 16/256F_s$, using three sets of 3 mapped subcarriers (as illustrated in Fig. 6.15). A frequency selective channel is simulated using the exponential decay channel model as before. Gaussian white noise is added for $-20\,\text{dB} \leq SNR \leq 20\,\text{dB}$ and signature detection is performed over the full simulated bandwidth as before using the frequency-domain shifting detector (5.13). An observation time of $\Delta t = 30T$ is considered, and carrier frequency estimation is performed using the detected signatures. Carrier frequency estimates are used to establish a probability of acquisition defined as

$$P_a = p(f_0 - \Delta f \leq f_{est} \leq f_0 + \Delta f) \tag{6.13}$$

where Δf is the subcarrier spacing and f_0 is the true carrier frequency. Results are presented in Fig. 6.16.

Results indicate that embedded cyclostationary signatures may be successfully used to perform carrier frequency estimation to within a single subcarrier spacing of the true value. This is shown to be true under frequency-selective channel conditions using a multiple-feature signature with three independent features. For SNR of greater than 6 dB the probability of acquisition, P_a is seen to be greater than 95%. Below this level, it can be seen that acquisition performance deteriorates with a P_a of approximately 85% at 0 dB. At high levels of SNR, it can be seen that the probability of acquisition remains constant at approximately 98%. This loss of 2% performance can be explained by the use of a time-variant multipath channel and incorrect estimation of the central

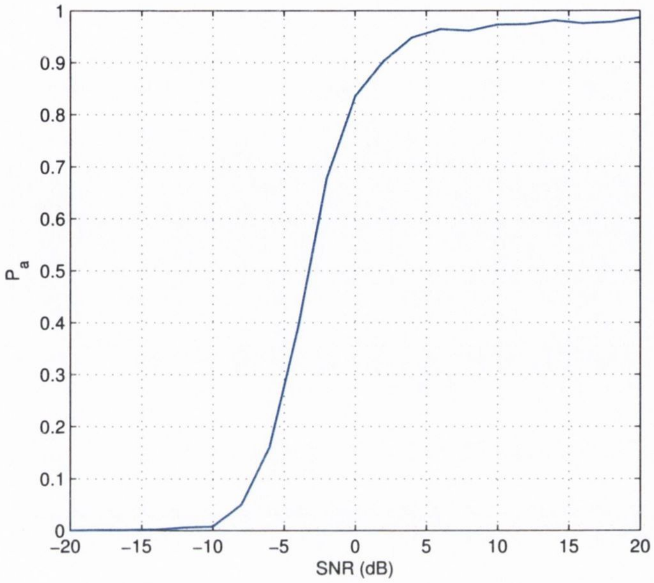


Fig. 6.16: Frequency acquisition performance using embedded cyclostationary signatures.

feature. At times of severe fading, acquisition may not be possible even at high levels of SNR.

6.5.3 Discussion

As discussed in Chapter 5, a wide range of frequency acquisition schemes for OFDM-based signals exist. These existing approaches are not suited to the unique challenge of frequency acquisition for DySPAN rendezvous and coordination where the signal of interest may lie in a wide frequency band relative to the bandwidth of the signal itself. It has been shown however, that under these conditions embedded cyclostationary signatures may be effectively used to achieve carrier frequency estimation to within one subcarrier spacing of the true value.

Following carrier frequency estimation using a detected cyclostationary signature, a fine frequency tracking approach may be leveraged to achieve the highly accurate frequency synchronization required by OFDM-based systems. One such frequency tracking approach is that proposed by Schmidl and Cox [105] and discussed in the previous chapter. The fractional frequency offset estimation approach proposed by Schmidl and Cox provides robust frequency synchronization with an acquisition range of +/- 1 OFDM subcarrier spacing. This is achieved using a frame preamble symbol consisting of two repeated symbol halves. By adopting a time-delayed autocorrelation, frame detection, symbol timing and fractional frequency offset estimation is performed.

By combining the use of embedded cyclostationary signatures with a frequency tracking approach such as Schmidl and Cox, a complete solution for achieving signal detection, frequency acquisition and synchronization in DySPAN networks can be implemented.

6.6 Summary

In Chapter 5, cyclostationary signatures were identified as a potentially useful tool in overcoming a number of key challenges associated with rendezvous and coordination in DySPAN networks. In this chapter, signatures have been assessed using simulation results in terms of their performance under a number of scenarios associated with these challenges.

Initial assessments focussed on the parameters used to generate and detect cyclostationary signatures. An important trade-off exists in the generation of cyclostationary signatures between the overhead involved and the detection performance which can be achieved. The overhead associated with generating signatures arises due to the use of mapped OFDM subcarriers. Although subcarriers within the mapping source set carry data, subcarriers in the mapping destination set must carry that same data and so are effectively lost. As the set of mapped subcarriers increases, so too does the overhead involved. Using simulations, it was found that detection performance can be greatly improved through the use of greater mapped set sizes. An initial improvement was identified as an increased detection ratio y_{sig}/y_0 where y_{sig} is the detection statistic in the presence of a signature and y_0 is the detection statistic for a signal without an embedded signature. This ratio quantifies the ease with which a signal containing an embedded signature can be discriminated from one without. Simulation results indicated that the optimum mapped subcarrier set size lies between 3 and 7 for an associated overhead of between 1.56 and 3.65 %. This assessment of subcarrier set sizes was further examined in the context of the signal observation time required for reliable signature detection. ROC analyses in the presence of Gaussian white noise were used to determine comparable required observation times. Using a set of 3 mapped subcarriers, it was found that an observation time of 16 symbol durations was required for a detection rate of 99% and an associated false alarm rate of 1%. Using a set of 5 mapped subcarriers, it was found that this observation time decreased to just 10 symbol durations for comparable performance. A further reduction to 8 symbol durations was achieved using a set of 7 subcarriers. These findings were further examined using signature detection histograms associated with the ROC analyses carried out.

In Chapter 5, the limitations associated with the use of inherent signal cyclostationarity were identified as key motivation for the use of intentionally embedded cyclostationary signatures to achieve DySPAN rendezvous and coordination. Simulations were used to illustrate the benefits of using embedded signatures over the use of inherent signal features. A signal detector was implemented using the cyclostationary features inherent to OFDM signals due to the use of a cyclic prefix. Comparisons showed that detection performance using inherent features and an observation time of 60 symbol durations could be achieved using an embedded 3-subcarrier signature and an observation time of just 8 symbol durations. Furthermore, it was noted that these performance improvements were achieved in addition to the adaptability and flexibility afforded by the use of embedded signatures.

While initial performance assessments of cyclostationary signatures provided promising results, further tests were required to assess their use under more challenging, real world conditions. In order to simulate these conditions, further ROC analyses were carried out using a range of frequency-selective multipath channel models. In the previous chapter it was seen that frequency selective fading can negatively impact signature detection when a deep fade occurs at the frequency of a mapped subcarrier set. By embedding signatures comprising more than one independent cyclostationary feature, it is possible to achieve greater frequency diversity and greater robustness under conditions of frequency-selective fading. Simulation results showed that a signature of 3 independent features, each generated using a set of 3 mapped subcarriers, may be used to provide excellent detection performance under a wide range of multipath channel models. In addition to illustrating the performance advantages of multiple-feature signatures, simulations were used to outline the importance of power normalization in signature detection. Simulations carried out using a detector without power normalization showed that even the use of 5 independent features could not compensate for the deterioration in performance.

Having assessed the use of cyclostationary signatures in the context of signal detection, it was necessary to examine their use in the second application proposed - that of network identification. As discussed in the previous chapter, OFDM subcarrier mapping facilitates the generation of signatures at specific cyclic frequencies. By embedding signatures with a specific cyclic frequency in a signal, a transmitter allows that signal to be uniquely identified. In the case where all members of a network utilize the same signature, that signature may be used to achieve network identification. Simulation results were used to show that a signature identification rate of 100% can be achieved using a minimum signature separation for signals with an SNR of above 5 dB. This was possible under conditions of freqeuency-selective fading using a signature of 3 independent features, each generated using mapped sets of 3 subcarriers. An interesting trade-off was identified between the complexity of the signature detector adopted and the number of unique signatures which may be identified. This trade-off arises due to the α resolution of the detector implemented and presents a key design decision in the realization of a wireless system using cyclostationary signatures for network identification.

A valuable application of cyclostationary signatures identified in Chapter 5 is that of frequency acquisition. The implementation of a signature detector based upon the use of a CCP permits detected cyclostationary features to be accurately located in spectral frequency. Using this approach, it is possible to determine the carrier frequency of a detected SOI using an embedded signature. Simulations were used to illustrate that carrier frequency estimation can be successfully performed to an accuracy of a single subcarrier spacing using an embedded signature under conditions of frequency-selective fading. In addition, it was shown that frequency acquisition can be achieved using a sampled bandwidth greater than that of the SOI. This result is key in the context of DySPAN rendezvous as it indicates that wide-band receivers may be leveraged to perform high speed scanning of wide frequency bands for signature-containing signals.

An important result of the frequency acquisition analysis carried out was the frequency estimation accuracy which can be achieved using embedded signatures. Fine frequency tracking algorithms are typically adopted in OFDM based systems to avoid the effects of ACI. One such algorithm is the Schmidl and Cox approach which provides a frequency acquisition range of +/- one subcarrier spacing. As carrier frequency estimation may be reliably performed to within this range using an embedded cyclostationary signature, the Schmidl and Cox algorithm provides a highly suitable frequency tracking algorithm which may be adopted in systems employing signatures for DySPAN rendezvous and coordination.

In this chapter it has been illustrated that cyclostationary signatures may be successfully employed to achieve signal detection, network coordination and frequency acquisition and that they are indeed a promising tool for overcoming the challenges of rendezvous and coordination in DySPAN systems. Valuable insights have been gained into the key processes involved in the generation and detection of signatures and a number of critical design decisions to be considered in adopting the use of signatures in an OFDM based system have been identified. Simulations have provided a key means of assessing the performance of signatures under a range of conditions. However, simulations only serve to model real-world conditions and so provide an incomplete assessment. In order to fully examine the suitability of cyclostationary signatures when applied in real-world networks, it is necessary to design and implement real-world systems which can be tested and monitored. The following chapter addresses this requirement and discusses the implementation of an OFDM based wireless system using embedded cyclostationary signatures upon a highly flexible platform for software radio experimentation. Experiments carried out using this system are discussed in Chapter 8 and presented results are examined in order to fully assess cyclostationary signatures as a potential solution to the challenge of DySPAN rendezvous and coordination.

7. IMPLEMENTATION OF A PROTOTYPE TRANSCEIVER

7.1 Introduction

In Chapter 6, cyclostationary signatures were shown to be a powerful potential tool in overcoming the challenge of Dynamic Spectrum Access Network (DySPAN) rendezvous and coordination. Simulation results can tell us much about the performance which can be achieved using embedded signatures however, in order to fully examine their use in Orthogonal Frequency Division Multiplexing (OFDM)-based systems, a real-world experimental prototype is required.

In this chapter I present a transceiver prototype, designed and implemented to perform real-world testing of an OFDM-based system using embedded cyclostationary signatures for detection, network identification and frequency acquisition. Section 7.2 firstly presents the platform used for our prototype, examining the radio frequency (RF)-front end and baseband processor in turn and discussing their inherent advantages and disadvantages. Section 7.3 outlines Implementing Radio In Software (IRIS), a highly reconfigurable software radio architecture adopted for our transceiver implementation. Following this initial discussion of the development platform, Section 7.4 presents the transceiver as implemented upon the platform. The transmitter and receiver designs are discussed in turn and key design decisions are outlined. Variations upon the designs adopted are also examined in the context of alternative applications. Finally, Section 7.5 concludes the chapter.

7.2 Experimental Platform

7.2.1 Overview

In order to perform real-world experiments using embedded cyclostationary signatures, a prototype transceiver must be designed and implemented. A wide range of platforms exist for the development of prototype wireless transceivers, each with their own advantages and drawbacks. By examining the design requirements of our system, we can choose a platform which is most suited to our needs.

In an OFDM-based transceiver system, the generation, detection and analysis of embedded cyclostationary signatures may be performed using baseband signals. For this reason, I will look separately at the platform requirements in terms of the RF-front end and the baseband processor to be adopted.

The *RF-front end* serves to up-convert and transmit signals generated in the baseband processor and to down-convert and digitize received signals prior to processing. Key factors in the choice of a suitable front end include transmit and receive frequencies, bandwidths and power levels. DySPAN systems are capable, by definition, of adjusting the carrier frequencies and bandwidths used in order to efficiently utilize available resources and to adapt to environmental conditions. Therefore, in addressing the challenge of rendezvous and coordination for DySPAN systems, the ability to dynamically adjust transmit and receive carrier frequencies and bandwidths is essential. Further flexibility in the transmit and receive gains of the front end are desirable in order to manipulate signal powers and obtain required signal-to-noise ratio (SNR) levels. In addition to flexibility in front end operating parameters, it is a requirement that RF equipment may be easily integrated with the baseband processing platform to be adopted. The ability to "plug and play" the front end permits design and implementation efforts to be focused upon the baseband transceiver system.

The *baseband processor* is responsible for the generation of waveforms to be transmitted and the analysis of waveforms received, downconverted and digitized by the RF front end. While the possible processing platforms range from application-specific integrated circuits (ASICs) through field programmable gate arrays (FPGAs) to digital signal processors (DSPs) and general purpose processors (GPPs), a key factor in choosing one suitable for adoption as the baseband processor for an OFDM-based transceiver is the speed and flexibility with which transceiver designs can be prototyped and tested. In considering the need for rapid prototype development, subjective issues such as experience and the learning curve associated with a given platform must be taken into account as well as objective factors such as the development tools which may be available for that platform. In terms of performance, the processing power of the platform will dictate the bandwidth of the signals which may be successfully generated and analysed in real time. While the ability to store and process an signal of interest (SOI) offline may ease processing requirements, it may also be desirable to perform experiments using live signals. Once again an important issue in choosing a suitable platform is the ease with which that platform may be integrated with the RF front end chosen. When rapid prototype development is a priority, interconnectivity issues must be avoided where possible.

With these requirements in mind, the platform chosen to implement our prototype transceiver is a highly reconfigurable software radio engine known as IRIS running on a GPP and using an RF-front end specifically designed for use with GPP-based software radios, the Univeral Software Radio Peripheral (USRP). In the next sections I will look at the main motivation for choosing this particular platform.

7.2.2 The Universal Software Radio Peripheral (USRP)

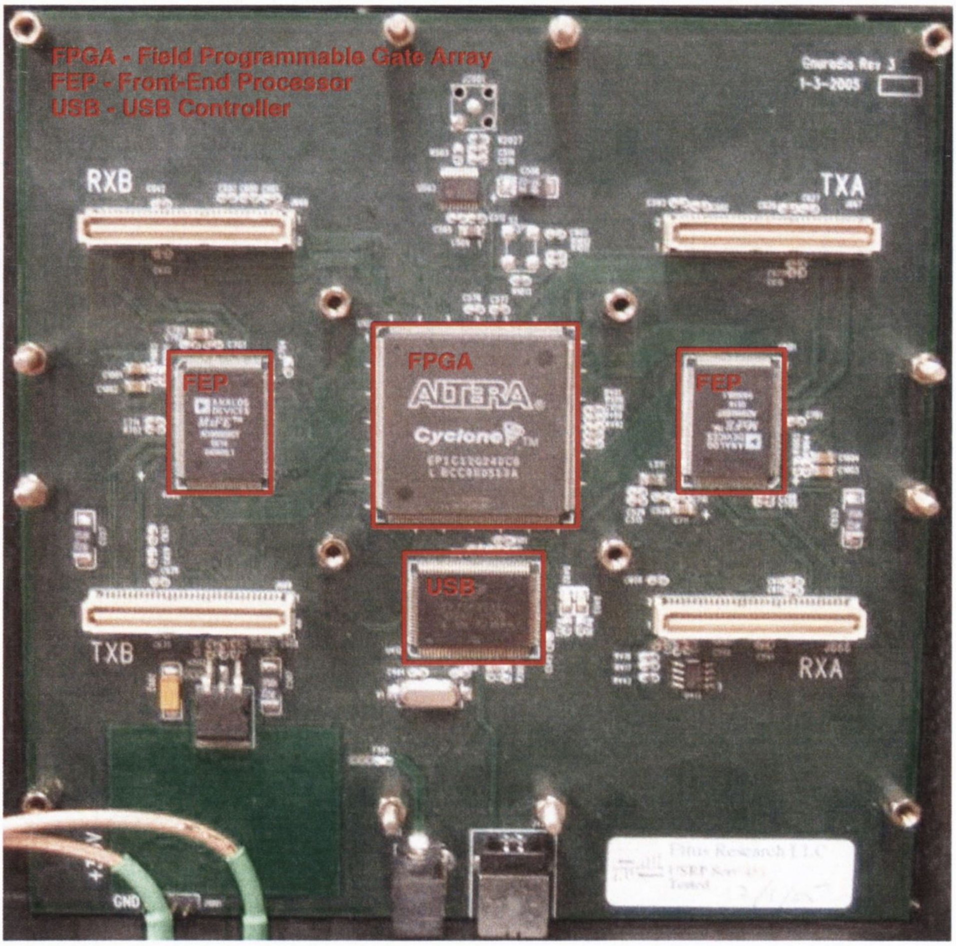


Fig. 7.1: The Universal Software Radio Peripheral (USRP) motherboard

The USRP [112] is an RF-front end designed specifically for use with GPP-based software radio systems. The modular architecture used comprises a motherboard with a high-speed USB 2.0 interface and a variety of daughterboards designed for transmission and reception using frequency bands up to 2.9 GHz.

The motherboard itself features four 64 MS/s 12-bit analog to digital converters (ADCs) and four 128 MS/s 14-bit digital to analog converters (DACs), permitting use of 4 input and output channels (or 2 input and output in-phase - quadrature (I-Q) pairs). The board also includes an FPGA implementing four digital downconverters (DDCs) with programmable decimation rates and two digital upconverters (DUCs) with programmable interpolation rates. The use of an FPGA permits high sample-rate processing to be performed on the board, allowing low sample-rate processing to be performed on the host computer. This allows baseband signal data to be transferred over the USB 2.0 link, greatly reducing the data rate required. However, this interface is still the main bottleneck for the system, restricting effective usable bandwidth to less than 8 MHz using 16-bit I-Q samples. Fig. 7.1 shows the USRP motherboard with FPGA, front-end processors (FEPs) and USB controller highlighted. Each FEP contains two DACs and two ADCs.

The key strength of the USRP lies in the flexibility provided in carrier frequencies, sampled bandwidths and signal powers. Each operating parameter is controlled using register values, read and written over the USB 2.0 interface. The usable range of parameter values is dependent upon the transceiver daughterboard in use. For example, using the RFX2400 daughterboard, a frequency range of 2.3 to 2.9 GHz is supported with a maximum transmit power of 50 mW (17 dBm) and an adaptive gain control (AGC) range of 70 dB. Furthermore, the relatively low cost of the USRP makes it a highly attractive RF-front end option for rapid prototype implementation.

An additional motivation for use of the USRP is the open source nature of the platform. All drivers and firmware as well as FPGA and daughterboard designs are available without the need for any purchased licenses. This allows a complete understanding of the platform operation to be gained and facilitates any adaptation which may be required for a given application.

While the USRP is often used in tandem with the GNU Radio [113] project software engine, the flexibility of the system permits the use of any software radio environment, running upon a wide range of possible GPP-based platforms. For the implementation of an OFDM-based transceiver using embedded cyclostationary signatures, a highly reconfigurable software radio engine developed at University of Dublin, Trinity College and known as IRIS [114] was adopted. IRIS is presented in Section 7.3 below.

7.2.3 The General Purpose Processor (GPP)

The adoption of the USRP as the RF-front end permits the use of a GPP-based software radio engine to perform baseband processing within our transceiver prototype. In order to rapidly prototype the cyclostationary signature-based system, the ability to use a GPP-based platform provided a number of valuable advantages over other possibilities. This section outlines these advantages and provides a brief discussion of the use of GPP-based software radio systems.

In Section 7.2.1 the principal requirements of a baseband processor for system prototyping were identified as the speed and flexibility with which systems can be implemented as well as the processing power available and the ease with which the baseband processing platform may be integrated with the chosen RF-front end. In terms of development speed and flexibility, GPP-based systems provide significant advantages over alternative platforms due to the availability of high-level programming languages and the wide range of tools available for software development. Using an integrated development environment (IDE) complete with code debug and profiling capabilities, key algorithms can be rapidly implemented, tested and optimized prior to deployment for experimentation. The use of high-level programming languages also serves to greatly reduce the learning curve typically required for radio transceiver implementation. The flexibility afforded by a GPP-based platform allows for a level of adaptability and reconfiguration which cannot be easily achieved using alternatives. As all baseband processing may be performed in software, processing algorithms can be adapted on-the-fly as required. In Section 7.4 it will be seen how this adaptability is leveraged to implement a general OFDM transceiver using embedded signatures which can be dynamically adapted to the current application.

Using the USRP, straightforward integration of the RF-front end with the GPP-based processor can be achieved. As a USB 2.0 interface is used, any GPP platform supporting this standard can read and write baseband signals from and to the front end and control its operating parameters as required. USB 2.0 is supported by most of the personal computers (PCs) available today, meaning that a software install is all that's needed to realize a highly reconfigurable software radio transceiver using a PC and the USRP.

While substantial processing power is available in modern PCs, one limitation of GPP-based platforms when used for baseband processing is the requirement for real-time operation. The time taken to process a set number of data samples can vary over a number of tests on a GPP due to the overhead of thread schedulers, memory access controller functions and other processes which may be executing on the same platform. This variation in processing time does not typically occur on FPGA or DSP-based platforms for example as upon these platforms, resources are dedicated to the algorithm being executed. Therefore, in order to achieve real-time operation upon a GPP-based platforms, care must be taken to ensure sufficient spare processing time is available for overhead operations. For some applications, data buffering may be used to avoid timing issues. Indeed, the availability of non-volatile memory on the order of hundreds of gigabytes on modern PCs means that an entire signal transmission history may be stored and processed offline. However, for time-critical applications such as Time Division Multiple Access (TDMA) channel access and query-response protocols using time-outs, the use of data buffering may not be possible. A second limitation of typical GPP-based platforms is the power required. Power consumption is typically much higher than comparable FPGA or DSP-based implementations and for this reason GPP-based platforms are not typically suitable for power-critical applications such as mobile handheld transceiver applications. In the context of rapidly prototyping a transceiver using embedded cyclostationary signatures however, power consumption is not a critical factor.

A final advantage of the use of a GPP-based baseband processing platform is the increasing range of such platforms available. Many modern PCs feature multi-core processor architectures which permit software radio developers to leverage parallelism in radio applications and increase the power of baseband processor implementations. Furthermore, the introduction of advanced processor architectures designed for high speed vector processing greatly increases the scope for high data-rate baseband processors running algorithms implemented using high-level programming languages. One such architecture is the Cell Broadband Engine Architecture [115] jointly developed by IBM, Toshiba and Sony Computer Entertainment. The Cell processor features a single Power Architecture based power processing element (PPE) and multiple synergistic processing elements (SPEs), linked together by an internal high speed bus. The multithreaded PPE may run a conventional operating system and serves to control the SPEs which are optimized for vector processing. Using a platform such as the Cell processor, major gains in data throughput can be achieved.

7.3 Implementing Radio In Software (IRIS)

7.3.1 Overview

IRIS is a highly reconfigurable software radio architecture designed by Mackenzie [114] to take full advantage of the flexibility afforded by a GPP-based platform. IRIS was designed with the objective of creating a component-based architecture for software radio with a very high level of reconfigurability at all levels of the radio. In this section I give a brief outline of the IRIS architecture, for a more comprehensive treatment, the reader is referred to [114].

The use of a component-based architecture permits the high levels of complexity associated with radio transceiver designs to be effectively managed using encapsulation and abstraction. The radio is divided into a number of subsystems, each of which is encapsulated in a radio component with a set of generic interfaces for setting operating parameters, controlling the component lifecycle, passing signal data to be processed and querying component capabilities. These interfaces provide an abstraction of the component implementation and allow a radio designer to use the component functionality without requiring knowledge of the implementation details. To create a software radio instance, the designer may employ existing components as well as creating new, custom components.

In order to assemble a set of components into a working software radio instance, a mechanism is required to define those components as well as the inter-relationships which exist between them. Within IRIS, this is achieved using a configuration document written in eXtensible Markup Language (XML). This document unambiguously outlines the components which comprise the radio, initial operating parameters to be used within each and the overall radio structure, dictating signal data paths.

The following sections discuss some of the details of the IRIS architecture. Section 7.3.2 outlines the key elements of the architecture and the manner in which they interact to manage a component-based software radio instance. Section 7.3.3 addresses the basic building block of IRIS, the radio component. Features of the architecture which support reconfiguration at all levels of the radio are examined in Section 7.3.4.

7.3.2 Architecture

The key elements comprising the IRIS software radio architecture are illustrated in Fig. 7.2 and consist of:

- The Radio Configuration
- The IRIS application programming interface (API)
- The XML Configuration Parser
- The Radio Engine
- The Component Manager
- The Control Logic Manager

I will now address each of these elements in turn and examine their specific roles in the management of a software radio instance.

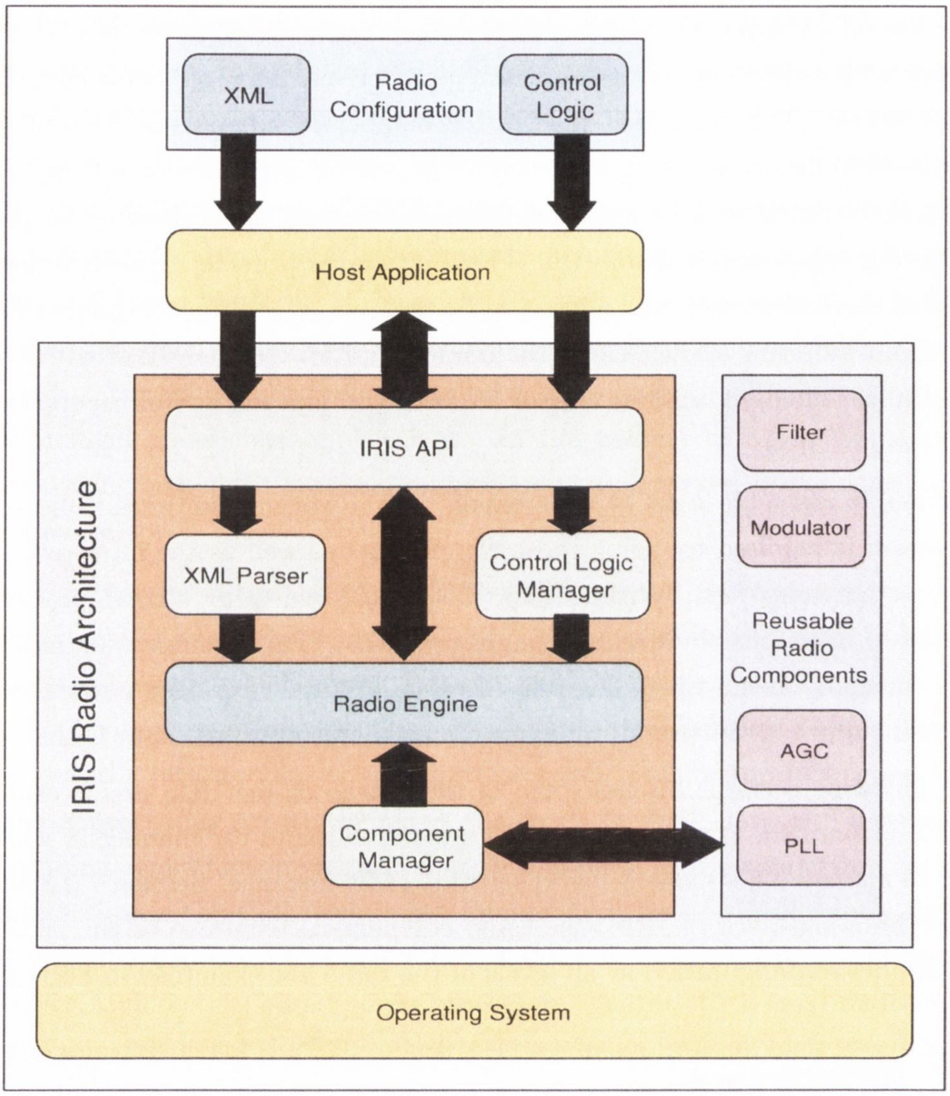


Fig. 7.2: The IRIS software radio architecture

Radio Configuration

The Radio Configuration specifies the overall structure of the radio, the components which make up a particular software radio instance and their initial operating parameters as well as the interactions which may occur between the individual components. This configuration consists of an XML document and a radio-specific set of instructions known as *Control Logic*. The Control Logic serves as a type of "glue" which binds the individual components together. An important aspect of any component-based design is the careful management of dependencies which may arise between particular components. A software component is, by definition, *a unit of independent deployment* [116]. Any inter-component dependencies will severely compromise the reusability of those components within the framework. By handling radio-specific dependencies using generic component interfaces, Control Logic permits interaction between components without compromising reusability.

IRIS API

Provided with a radio configuration document and control logic specific to that radio, a host application may create a software radio instance and instruct it to commence operation. The architectural element which permits a host application to access this functionality is the IRIS API. The API exposes all functionality required by an application to generate multiple software radio instances, pass data to and from them and control their lifecycle from creation and start-up to close-down and destruction.

XML Configuration Parser

The IRIS API allows a host application to create a software radio instance using a configuration document and radio-specific control logic. Within the IRIS architecture, the first task in creating a radio instance is to parse the configuration document to generate a data structure describing the structure of the radio. The Configuration Parser provides this functionality, supplying a data structure which can be used by the Radio Engine to instantiate the required components and structure them correctly to form the desired radio configuration.

Radio Engine

The Radio Engine is the core of the IRIS architecture with responsibility for creation and instantiation of radio components, structuring of components according to the radio configuration, management of signal data flow within the radio and control of the radio lifecycle. In managing the operation of the radio instance, the Radio Engine employs each of the other elements within the architecture to perform tasks as required.

Component Manager

In order to instantiate the individual components required for a particular radio configuration, the Radio Engine makes use of the Component Manager. Components are made available from one or more repositories and the Component Manager is responsible for locating a required component, loading it and making it available for integration within the particular radio instance. When the radio is shut down, the Radio Engine uses the Component Manager to unload and safely destroy all component instances.

Control Logic Manager

Using a configuration document provided by the host application, the IRIS radio engine can determine the radio components required, their initial states and the manner in which they are structured to form the radio. However, as well as the configuration document, the host application may provide control logic, a set of instructions for handling inter-component interactions and preserving component independence. In order to integrate this control logic with the components which comprise the radio, the radio engine makes use of the control logic manager. Control Logic may be written using one of a number of languages and it is the role of the control logic manager to load and present it in a generic way for use by the radio engine. Through the Control Logic Manager, the radio engine attaches the Control Logic to the individual components and permits it to handle interactions as they occur.

7.3.3 The IRIS Radio Component

The *Radio Component* forms the basic building block of the IRIS architecture. Used to contain a generic signal processing algorithm or to encapsulate a particular radio subsystem (e.g. a hardware driver), the radio component provides an abstraction from particular implementation details and permits the system designer to employ the component using a number of generic interfaces. Radio components are written in the C++ programming language and compiled into libraries which may be dynamically loaded by the system as required.

As radio components may be used to encapsulate a wide range of functions, three specific types are specified within the architecture:

- DSP Components
- IO Components
- Standalone Components

DSP components wrap a specific signal processing algorithm within a generic component. Examples include low-pass filters, timing recovery algorithms and frequency modulation (FM) modulators. While DSP components typically support both signal data inputs and outputs, *input/output (IO)* components are designed to encapsulate data sources or sinks and so support either signal data outputs or inputs. *Standalone* components do not generally form part of the signal processing chain but support functionality such as timers and external hardware control.

The key to a component-based framework is the use of a generic wrapper which allows components to be treated uniformly, regardless of the differing types of functionality which they provide. Within the IRIS framework, this wrapper consists of eight specific interfaces through which the operation of individual components can be controlled. These interfaces are illustrated in Fig. 7.3.

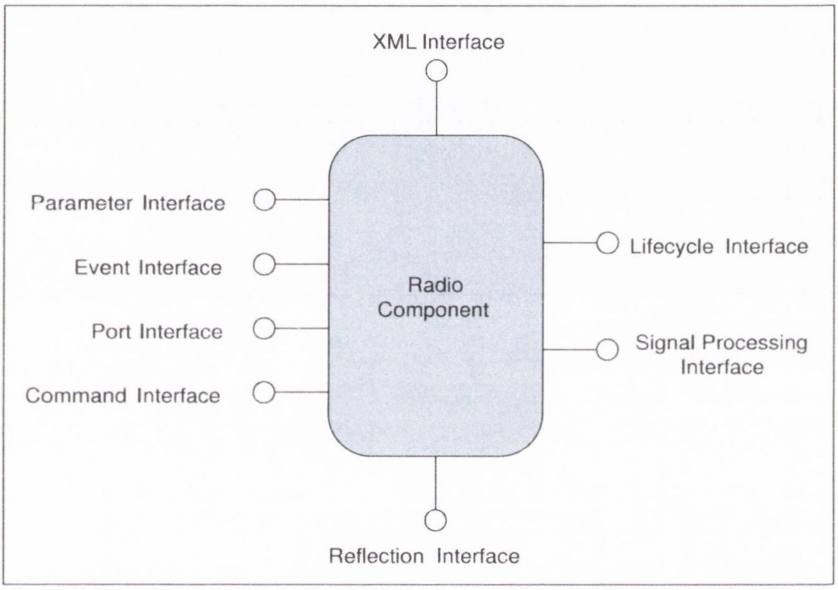


Fig. 7.3: The IRIS radio component interfaces

In order to facilitate the flow of signal data along a chain of processing components, the *Signal Processing* interface is used to expose all signal data inputs and outputs supported by a component. By exposing these inputs and outputs, the component can permit external agents to access them when required. In this way, the radio engine passes data for processing to each component in the chain. Thus data flows through the radio instance from source to sink.

The *Lifecycle* interface is used to control initialization of a component prior to inclusion in a signal processing chain and clean up of the same component prior to destruction when it is no longer needed. Using the lifecycle interface, a designer can perform component-specific functions such as memory allocation and deallocation.

A key element in supporting reconfiguration within the IRIS architecture is the *Parameter* interface exposed by each radio component. The parameters exposed by a component are used to alter the fundamental operation of that component and may be queried and dynamically reconfigured through the parameter interface.

While the parameter interface supports reconfiguration of a radio component by an external client, the *Event* interface permits components to signal important observations to external clients and trigger any required reconfiguration of the radio. By signalling a particular event, a component can alert the radio engine to an observation and provide it with the opportunity to perform any reconfiguration necessary. For example, a radio comprising a signal detection component may need to reconfigure in response to a detected signal. An *event* permits the detection component to internally trigger that reconfiguration when a signal is detected. Control logic is the IRIS element responsible for handling component events and performing any required changes to the system. As the response to an event is dependent upon the particular radio configuration, control logic is typically radio-specific and is provided as an input to the IRIS architecture upon the creation of a radio instance.

The *Port* interface permits external clients to asynchronously pass data to a component. While digital signal data is passed through the signal processing interface, the port interface provides an input for non-signal data.

The operating parameters of a component can be directly reconfigured by external clients using the parameter interface however, purely function-based operations are also supported by the *Command* interface. Such operations include resetting a synchronizer or turning on pilot subcarriers in an OFDM modulator.

In order to query information about a particular component, external clients can employ the *Reflection* interface. Through this interface, information regarding the component such as exposed parameters and supported events can be obtained as well as general information such as author and version.

Rather than querying particular details about a given component, clients can use the *XML* interface to obtain a full XML description. This description includes all information available through the reflection interface as well as component configuration options and capabilities. Using the XML description, automatic component use without user intervention is made possible.

As components must support a large number of detailed interfaces, large amounts of code are required. In order to reduce the programming effort involved in implementing new components for the IRIS framework, a scripting language was created to automate much of the process. This scripting language is written within the C++ header file of the component and is used to describe attributes including parameters, events, ports and commands to be supported by the component. In order to avoid compilation issues, all scripting tags are embedded in C++ comments. Prior to compilation, a Java parser is used to read the embedded tags and automatically generate much of the code required by the IRIS architecture. Furthermore, object inheritance is used to provide functionality common to all components of a given type. In this way, the programming effort required to implement a new component can be reduced to the implementation of a small number of functions.

7.3.4 Reconfiguration

One of the main motivations for the IRIS software radio architecture is the flexibility afforded by a GPP based platform and the ability to support a level of adaptability and reconfiguration which cannot easily be achieved using alternative platforms. In designing IRIS, three specific levels of reconfigurability were supported:

- Parametric level
- Structural level
- Application level

In this section I will discuss each of these levels of reconfiguration and examine some of the features of the IRIS architecture which support them.

Parametric reconfiguration involves the adjustment of operating parameters within individual components of a radio instance. Examples of this level of reconfiguration would include changing the tap values within a filter component or increasing the detection threshold in an energy detector component. Within the IRIS architecture, the parameter interface permits components to expose specific parameters for reconfiguration. While parameters are used to specify the initial state of a given component, they may also be labelled *dynamic*, indicating that they may be dynamically reconfigured at run time to alter the operation of that component.

Structural reconfiguration is used to change the order of radio components within a radio instance. This type of reconfiguration is used for example to replace a binary phase shift keying (BPSK) modulator component with a quadrature phase shift keying (QPSK) modulator or to add a low-pass filter to a signal processing chain. The functionality required to insert, remove and replace component instances within a running radio instance is exposed through the IRIS API. Within a radio configuration document, each component instance is allocated a uniquely identifying character string. This character string allows an external client to specify that particular component instance for removal or replacement. In the case where a new component instance must be created for insertion in a running radio, the Component Manager is employed to load, initialize and supply the required component. In order to perform structural reconfiguration of a running radio instance, the Radio Engine supports suspension of the signal data flow to ensure data and radio structural integrity.

Application reconfiguration is used to completely change the overall functionality of the software radio. This approach can be used to switch an FM receiver to a BPSK or OFDM transmitter for example and typically involves the termination of a running radio instance prior to creation of a new instance. The key IRIS element supporting application reconfiguration is the XML configuration document used to specify the structure and initial state of the components comprising the radio instance. By generating a new configuration document, the designer can deploy a completely new radio instance using the available components as required.

The IRIS architecture supports reconfiguration in response to both internal and external triggers. An internal trigger occurs within the radio itself, for example within a signal detection component, while an external trigger occurs outside the radio such as a user command.

Internal reconfiguration triggers are supported within the IRIS architecture by the component events described in the previous section. A component may trigger an event in response to an observation and this event will prompt the radio to reconfigure itself as required. External reconfiguration triggers are supported through the use of XML configuration documents. While the configuration document is used primarily to implement application-level reconfiguration, it can also be used to perform structural and parametric reconfiguration by an external radio client. In order to trigger reconfiguration in this way within a running radio instance, an external client can use the IRIS API to pass a new configuration document to the engine. Upon receipt of the new configuration, the Radio Engine employs the Configuration Parser to perform a comparison with the configuration of the currently running radio. Where the new configuration may be applied using a small number of structural and parametric reconfigurations, a vector of such reconfiguration steps is generated. By executing these specific steps, the radio can be reconfigured without the need for a full engine shut down and restart.

Fig. 7.4: The experimental platform

7.3.5 Summary

The combination of the IRIS software radio architecture with a powerful GPP-based platform and USRP RF-front end provides an extremely flexible experimentation platform for rapidly prototyping our OFDM-based transceiver. In particular the component-based architecture of IRIS can be leveraged to provide a number of key advantages. The first advantage lies in the availability of existing radio components which can be employed within our transceiver prototype. The current IRIS radio component repository contains over 100 DSP, IO and standalone components. Of these, potentially useful components include phase shift keyed (PSK) and OFDM modulators and demodulators, data whitening and file IO components as well as components encapsulating drivers for the USRP front end hardware. In addition to employing existing components as they stand, a number of components may be modified slightly for use within the transceiver design.

A second key advantage of the IRIS component framework is the ability to implement individual components in isolation from the full transceiver signal processing chains. Using a simplified configuration comprising file IO components, new and existing components can be developed and tested with locally stored test data. As components are deemed stable, they can be incorporated in increasingly complex configurations until the full transceiver signal processing chain is realized using live data streamed to and from the USRP hardware.

In addition to these advantages, the dynamic reconfiguration capabilities of IRIS can be effectively leveraged to simplify the process of developing and debugging new radio components. By exposing and reconfiguring key operating parameters of a new component, comprehensive tests may be carried out in which the full operating range of that component is tested.

The experimental platform comprising the USRP RF-front end and IRIS running on an Intel dual-core GPP is illustrated in Fig. 7.4. The implementation of an OFDM-based transceiver using cyclostationary signatures within the IRIS architecture is described in the following sections.

7.4 Transceiver Implementation

7.4.1 Overview

In the previous sections key factors in the choice of an implementation platform were discussed and an overview of that platform was provided. In this section I examine the implementation of a full OFDM-based transceiver upon that platform, using embedded cyclostationary signatures to achieve the tasks of signal detection, network identification and frequency rendezvous. Through the implementation of a real-world prototype, cyclostationary signatures can be demonstrated to be a highly effective tool in overcoming the challenge of rendezvous and coordination for DySPAN systems.

While the implementation of an OFDM transceiver in itself presents a number of specific challenges, the adoption of a highly versatile GPP-based software radio platform made it possible to overcome these challenges and successfully incorporate the use of cyclostationary signatures without the need for significant further development. At the core of the development process was the path taken from simulation-based algorithm prototypes to real platform-based implementations.

The development path adopted for the experimental transceiver is outlined in Table 7.1. In the first phase, all algorithms were initially developed and tested using the MATLAB simulation environment. The second phase of development involved the use of an Anritsu MG3700A vector signal generator. Test signals were generated using the MATLAB environment and stored on file in I-Q format. These signals were transferred to the signal generator and transmitted over the air at suitable data rates and carrier frequencies. The signals transmitted in this way were received using the USRP

RF-front ends and stored. These stored signals were then used to further examine the performance of signature detection and OFDM receiver algorithms in the MATLAB environment. In the third phase, signature detection and OFDM receive radio components were implemented for the IRIS architecture. These components were tested using signals transmitted by the signal generator. Finally, having completed and tested a working receiver implementation, components were created for the transmit chain and overall system performance was examined using live signals transmitted and received using USRP front-ends.

Phase	Signal Generation	Signal Transmission	Signal Reception
1	MATLAB	MATLAB channel model	MATLAB
2	MATLAB	Sig. Gen. → USRP	MATLAB
3	MATLAB	Sig. Gen. → USRP	IRIS
4	IRIS	USRP → USRP	IRIS

Tab. 7.1: Development path adopted for the experimental transceiver.

The IRIS software radio architecture supports the simultaneous execution of many signal processing chains upon a single platform and so can be used to support a full transceiver system. For simplicity however, it was decided to initially develop the transmit and receive signal chains independently before combining both in a transceiver configuration. In the following sections I address the implementation of these signal chains and the IRIS radio components which comprise them. Key design decisions are discussed and a number of possible alternative design choices are outlined.

7.4.2 Transmitter

In designing an OFDM-based transmitter incorporating the use of embedded cyclostationary signatures, a number of important goals were specified. In addition to the development of a robust yet flexible transmitter, it is important to support the generation of a wide range of cyclostationary signature types. In order to provide a flexible trade-off between signature robustness and overhead, it is necessary to support the use of different mapped subcarrier set sizes. Furthermore, the generation of multiple features must be supported in addition to single-feature signatures. The ability to generate signatures at a number of different cyclic frequencies is also key in order to facilitate network identification. Finally, flexibility in the data rate and carrier frequency of transmitted signals is central to the concept of DySPAN experimentation.

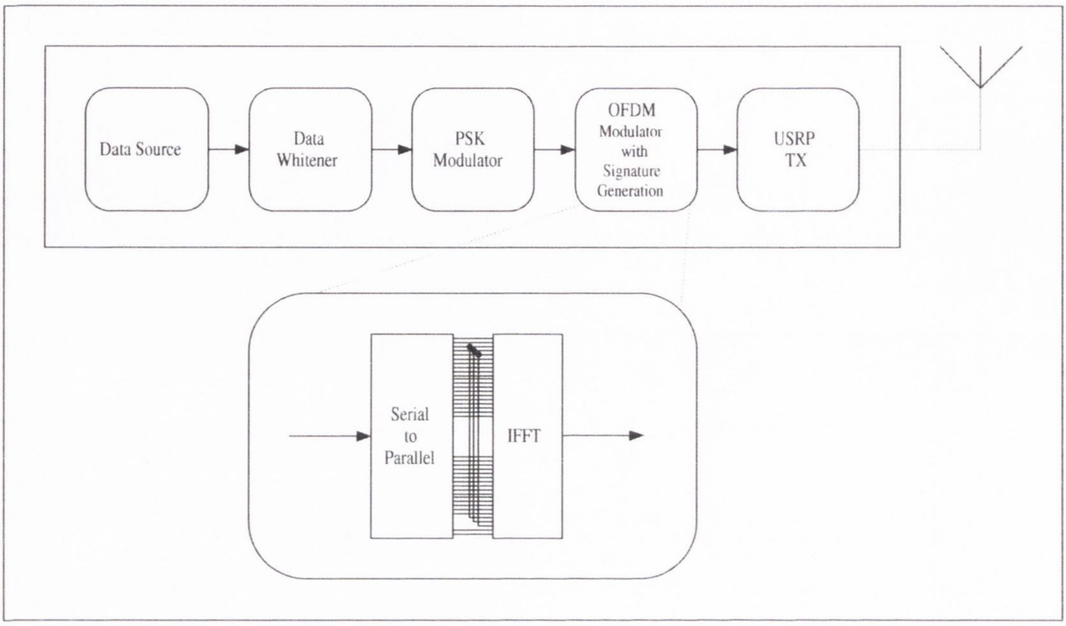


Fig. 7.5: The transmitter structure

The transmitter design adopted in order to fulfil these design goals is illustrated in Fig. 7.5. Five components are specified in all:

- Data source
- Data whitener
- PSK modulator
- OFDM modulator supporting signature generation
- USRP transmit driver

The *Data source* is used to provide a stream of data to be transmitted. Depending upon the application, this data may originate from one of a wide range of sources. Using existing IRIS radio components, data may be sourced from a file in local storage or an interface such as an ethernet, infra-red (IR) or serial connection as well as an application running on the local host. The first operation upon this data takes place in the *data whitener* component and consists of whitening with a pseudo-noise (PN) data sequence. The process of whitening prior to OFDM modulation serves to reduce the peak-to-average power ratio (PAPR) in the transmitted OFDM signal, reducing clipping distortion which may occur. Following the whitener, the signal is modulated using a PSK modulator. Using parametric reconfiguration, the modulation complexity used at any given time may be chosen from the library supported by the modulator. The modulated signal is then converted to a parallel stream and mapped onto subcarriers within the OFDM modulator. Subcarrier set mapping within this component is used to embed the required cyclostationary signature. Finally the signal is passed to the USRP front end for transmission by the USRP transmit driver.

A number of the components required for our transmit signal chain were available in the IRIS radio component repository and could be reused with minor modifications. New development efforts focused upon the OFDM modulator component as it is here that signatures must be embedded in the waveform for transmission. A suitable modulator was implemented and the generation of embedded cyclostationary signatures through subcarrier set mapping was supported. In order to support flexible mapped subcarrier set sizes and generation of multiple-feature signatures, a number of reconfigurable parameters were exposed. As mentioned earlier, by exposing parameters, a component permits an external client to access these parameters and alter them when required. The exposed parameters are outlined in Table 7.2. The *mapped_set_size*,

Parameter	Adjusted feature
mapped_set_size	Number of mapped subcarriers per set
num_features	Number of independent signature features
cyclic_frequency	Cyclic frequency of embedded signature
ifft_size	Number of subcarriers in the tx signal
num_pilots	Number of pilot subcarriers generated
cyclic_prefix	Cyclic prefix length
preamble	Specify the OFDM frame preamble to be used
symbols_per_frame	Number of symbols per tx frame

Tab. 7.2: Reconfigurable parameters exposed by the OFDM modulator component.

num_features and *cyclic_frequency* parameters permit an external client to completely specify the signature type to be embedded in the transmitted waveform. For multiple-feature signatures, embedded features are uniformly distributed in spectral frequency to provide maximum frequency diversity. The additional parameters listed are not directly associated with the generation of signatures but rather serve to support the generation of highly flexible OFDM waveforms both in terms of the individual symbols and the overall OFDM frame.

The design goals of data-rate and carrier frequency flexibility are achieved through the use of reconfigurable parameters exposed by the USRP transmit driver. Table 7.3 outlines the most important of these parameters. By dynamically adjusting any of

Parameter	Adjusted feature
centre_frequency	Tx signal carrier frequency
interpolation	Interpolation factor (tx signal data rate)
gain	Tx signal power

Tab. 7.3: Reconfigurable parameters exposed by the USRP transmit component.

these three parameters at run-time, the properties of the transmitted signal are directly impacted.

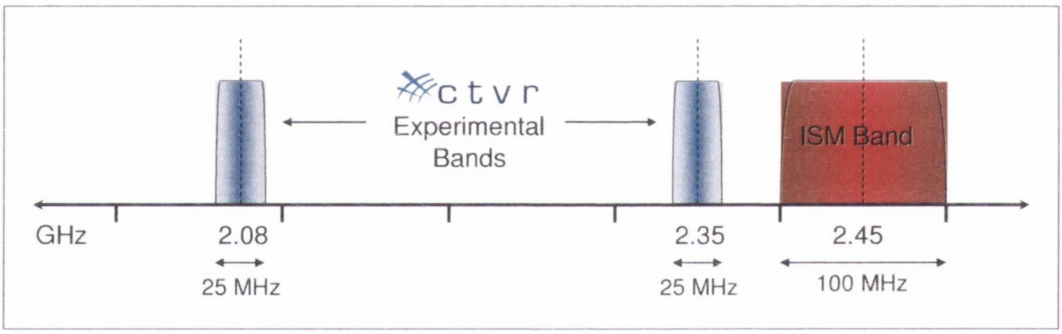


Fig. 7.6: The CTVR licensed bands

In order to perform real-world experiments using our prototype transmitter, a suitable frequency band had to be chosen in which to operate. The flexibility of the USRP front end means that carrier frequencies between 400 MHz and 2.9 GHz can be chosen, given a suitable daughterboard. One possibility is to use the Industrial, Scientific and Medical (ISM) bands at 433.92 MHz or 2.45 GHz, however experiments performed at these frequencies can be unreliable due to the presence of interfering devices at these frequencies. Fortunately, Centre for Telecommunications Value-Chain Research (CTVR) holds a license issued by ComReg, the Irish communications regulator, permitting low-powered wireless network experimentation in two frequency bands, located at 2.08 and 2.35 GHz. These bands are illustrated in Fig. 7.6 with the ISM bands shown for comparison. Using these allocated bands, experiments can be carried out without the risk of unexpected interference and reliable results can be obtained.

7.4.3 Receiver

In designing an OFDM receiver supporting cyclostationary signature detection analysis, a number of key goals were identified. Firstly, the receiver must be capable of scanning a defined frequency band in order to detect signals containing embedded signatures at any carrier frequency within that band. Secondly, a receiver architecture was required which facilitates dynamic switching between this initial scanning mode and a second communication mode. In the scanning mode, the receiver must scan across a frequency band. Upon detection of a signature, rendezvous must be achieved with the SOI and the receiver must enter the communication mode in order to receive and demodulate the transmitted data. Events which trigger switches between both modes must also be supported.

Further design goals addressed the cyclostationary signature detector directly. In order to support detection, network identification and rendezvous, the detector must also be capable of analysing a detected signature, using it to uniquely identify the transmitter and perform estimation of the SOI carrier frequency. Furthermore, the detector must support reliable detection of a wide range of signature types. Specifically, detection of multiple-feature as well as single-feature signatures must be supported as well as reliable detection of signatures generated using different mapped subcarrier set sizes.

The receiver architecture adopted in order to achieve these design goals is illustrated in Fig. 7.7. The architecture features a branched signal data path, one branch feeding the cyclostationary signature detector and the other feeding the OFDM demodulation chain. A switch allows the signal data to be directed towards one of the two paths depending on the current mode of operation. In the scanning mode, data is directed toward the detector to facilitate scanning of a particular frequency band. In the communication mode, data is directed to the OFDM demodulator, PSK demodulator and data dewhitener before reaching the data sink. As with the data source component in the transmitter architecture, the data sink may take a number of forms including an ethernet, IR or serial connection, local file storage or an application on the host system. A key element of the receiver architecture is the *control logic*. In order to support flexible frequency band scanning and receiver mode switching, a number of specific interactions between components are required. The control logic handles each of these interactions while ensuring that inter-component dependencies do not arise. More detail on the operation of the control logic is provided later in this section.

An important design decision was made concerning the granularity of components in the receiver architecture. The functions of signature detection and analysis could have

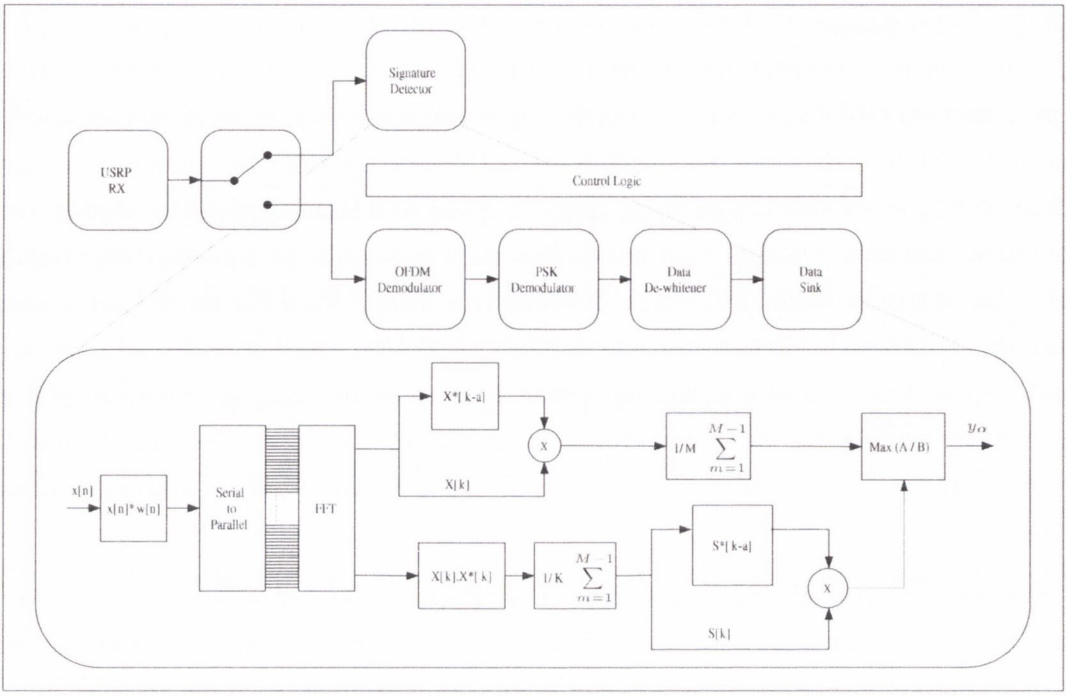


Fig. 7.7: The transmitter structure

been combined with that of the OFDM demodulator in one component. However, by separating those functions into two components, the ability to reuse both in alternative applications is maintained.

As with the transmitter, a number of pre-existing IRIS radio components were available in the repository for modification and use in the design. However, design and development of a suitable cyclostationary signature detector, OFDM demodulator and control logic were required. These components are examined in turn in the following sections.

Cyclostationary Signature Detector

The cyclostationary signature detector component was developed using the time-smoothed cyclic cross periodogram (TS-CCP)-based architecture described in Section 5.5. As illustrated in Fig. 5.8, this design uses fast Fourier transform (FFT)-shifting to realize a highly efficient detector. In order to support the flexibility required by our design goals, a number of events used to trigger radio reconfiguration and reconfigurable parameters were incorporated in the design. These are outlined in Table 7.4.

The implemented signature detector searches a spectral frequency band for signatures embedded at a single cyclic frequency specified by the parameter *cyclic_frequency*.

Parameter	Adjusted feature
cyclic_frequency	Cyclic frequency of signature to be detected
fft_size	Size of fft used for detection
threshold	Detection threshold
start_frequency	Start of frequency band
stop_frequency	End of frequency band
frequency_step	Frequency step used for scanning
obs_time	Observation time used for detection
Event	**Use**
sig_detected	Signify a detected signature
next_freq	Specify a change in rx frequency

Tab. 7.4: Reconfigurable parameters and events exposed by the cyclostationary signature detector.

In this way network identification is supported as only those signatures at the cyclic frequency of interest are detected, all others are disregarded. The *fft_size* parameter serves two purposes; it determines the spectral frequency resolution to be used by the detector but it also dictates the size of the averaging window used. As discussed in Chapter 4, the averaging window size must be carefully chosen in order to avoid phase randomization and the resulting loss of cyclostationarity. Another key parameter is the *threshold* which dictates the detection trade-off between false alarms and missed detections. As power normalization is performed using the autocoherence function (AF) (see Eq. 5.11), threshold levels are set in the range [0,1]. This threshold is set by the radio designer according to the requirements of the current application. Frequency band scanning is driven by the signature detector and dictated by the *start_frequency*, *stop_frequency* and *frequency_step* parameters.

Two events are supported by the detector in order to trigger reconfiguration of the radio when required. The *next_freq* event is signalled by the component to indicate that no signature has been detected within the currently sampled bandwidth and that the receiver centre frequency should be adjusted to analyse a new spectral frequency band. The process of frequency band scanning is illustrated in Fig. 7.9 and discussed below. The observation time used by the detector is determined by the *obs_time* parameter. Secondly, the *sig_detected* event is used to indicate the detection of a signal containing an embedded cyclostationary signature.

Although the FFT-shifting detector was sufficient for much of the experimentation carried out using the transceiver prototype, a number of design variations were developed for specific applications. The first variation in the detector design was the development of the time-domain shifting detector introduced in Chapter 6 and illustrated in Fig. 6.13. As discussed, the time-domain shifting detector facilitates signature detection at arbitrary values of the cyclic frequency and accordingly, permits the use of a greater number of unique signatures.

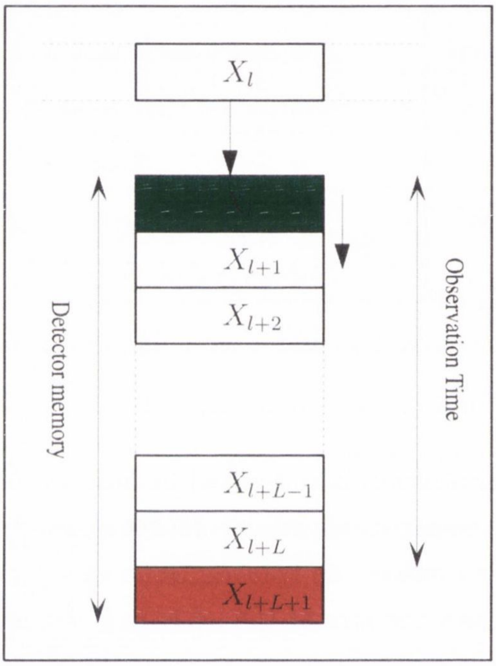


Fig. 7.8: Signal storage for iterative detector

The second variation on the basic detector design was developed in order to support monitoring for signature-containing signals over a long time period. Spectrum band scanning involves the use of a dwell time equal to the observation time required for reliable detection. The *dwell time* is the length of time during which the receiver centre frequency is held constant. Following this time period, the receiver centre frequency is adjusted in order to sample and analyse a new portion of the spectrum band. However, the use of a short dwell time requires an SOI to be present continuously in time in the portion of spectrum analysed. In many systems, such as TDMA networks, communications may be bursty and there will be periods in which no signal is present. Under these circumstances, a longer dwell time is required in order to guarantee capture of an SOI. In order to perform spectrum *monitoring*, the dwell time is increased while the observation time is held constant. In this way, a portion of the spectrum band can be continuously monitored for the appearance of an SOI. The dwell time of a detector can be increased while maintaining a constant observation time through the use of an iterative detector design:

$$C_l = C_{l+1} + X_l - X_{l+L+1} \tag{7.1}$$

where C_l is the current AF estimate, X_l is the current FFT window and X_{l+L+1} is the most recent FFT window which does not fall within the detector observation time. Thus, in order to implement an iterative detector, $L+1$ FFT windows must be stored in memory, as illustrated in Fig. 7.8. GPP-based platforms in particular facilitate this type of design due to the availability of abundant memory.

OFDM Demodulator

In order to achieve time and frequency synchronization with a received signal, and to extract transmitted data symbols from the individual subcarriers, an existing OFDM demodulator component was adapted for use with signature-containing signals. These adaptations dealt primarily with the presence of mapped subcarrier sets in the received signal.

Parameter	Adjusted feature
mapped_set_size	Number of mapped subcarriers per signature set
num_features	Number of independent signature features
cyclic_frequency	Cyclic frequency of embedded signature
ifft_size	Number of subcarriers in the rx signal
num_pilots	Number of pilot subcarriers in rx signal
cyclic_prefix	Cyclic prefix length in rx signal
preamble	Frame preamble used in rx signal
symbols_per_frame	Number of symbols per rx frame
threshold	Frame detection threshold
Event	**Use**
signal_lost	Signify a loss of rx signal

Tab. 7.5: Reconfigurable parameters and events exposed by the OFDM demodulator.

The reconfigurable parameters and events supported by the OFDM demodulator component are outlined in Table 7.5. It can be seen that many of the parameters exposed in the OFDM modulator component are mirrored in the demodulator. In this way, the demodulator can be configured to receive any signal generated by the modulator component. The only parameter for which this is not the case is the *threshold* parameter which is used to define the trade off in frame detection between false alarms and missed detections. Using the *mapped_set_size*, *num_features* and *cyclic_frequency* parameters, the demodulator can determine the subcarriers which were mapped in order to generate the embedded signature. Using this knowledge, data symbols can be extracted correctly from the OFDM subcarriers and passed along the receiver signal processing chain. It should be noted that, as some data symbols are transmitted redundantly in order to generate a signature, these symbols are effectively transmitted with repetition coding. Accordingly, these symbols are more robust to transmission errors and may be used to carry high-priority data.

A single event is supported by the demodulator component. This is the *signal_lost* event which serves to trigger a change in receiver mode from communication to frequency scanning for the SOI. The control logic which handles this event is discussed in the next section.

Control Logic

An important part of the receiver architecture is the application-specific *control logic* which handles all inter-component reactions. By handling events which may be triggered by specific components, the control logic manages any system reconfigurations which are necessary. Specifically, the receiver architecture control logic supports two critical processes; the frequency scanning process used to detect signature-containing signals and the mode-switching process between scanning and communication or vice-versa.

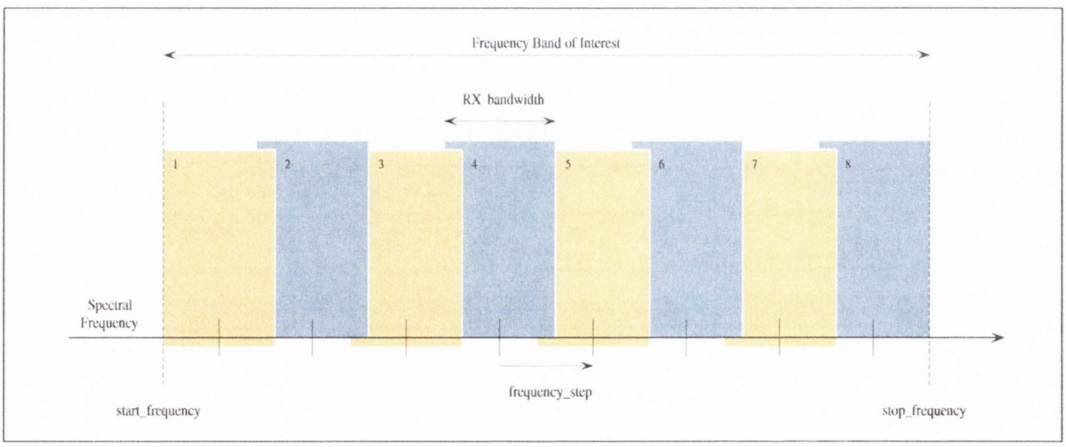


Fig. 7.9: Frequency band scanning

The *frequency scanning* process is driven by the signature detector component. When a portion of the spectrum has been scanned without a detection, the detector triggers the *next_frequency* event. In response to this event, the control logic sets the *centre_frequency* parameter on the USRP through the receive driver component. Once the receive frequency has been adjusted, the detector can start to analyse the sampled bandwidth for the presence of a signature-containing signature. Fig. 7.9 illustrates the process of scanning a frequency band of interest. Typically, the receiver bandwidth is less than that of the frequency band to be analysed. Therefore, in order to analyse the band, the centre frequency of the receiver is incremented in steps through the band. At each step, the sampled bandwidth is analysed for the presence of a signature-containing signal. The case where an SOI is present at a step boundary is handled through the use of a small spectrum overlap as shown.

It should be noted that, in scanning a frequency band for an SOI, the bandwidth of the receiver determines the number of frequency steps required. A key advantage of the use of cyclostationary signatures for DySPAN rendezvous and coordination is the ability to detect a signature-containing signal within a large sampled bandwidth. Thus, by maximizing the receiver bandwidth, the time required to scan a given frequency band can be minimized. As an increase in receiver bandwidth implies an associated increase in computation required for detection, the maximum bandwidth may be limited by the peak processing power available. A further limitation on this approach is the danger of saturating the RF-front end by choosing a receive bandwidth encompassing a number of high-powered signals.

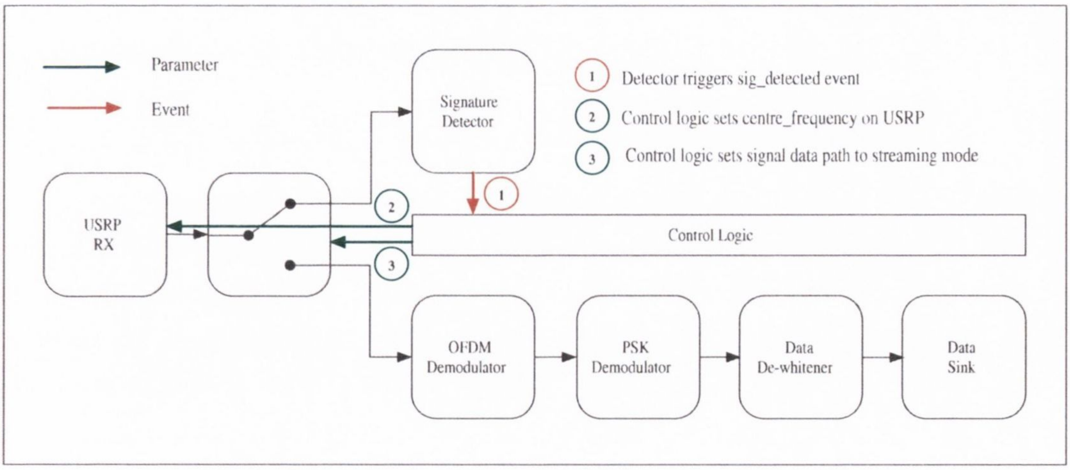


Fig. 7.10: Receiver mode switch from scanning to streaming

The *mode-switching* process is the second key function supported by the receiver control logic. The switching process from scanning to communication mode is illustrated in Fig. 7.10. As shown, the process is triggered upon the detection of a signature-containing signal within the signature detector. The *sig_ detected* event contains the estimated carrier frequency of the detected signal and this is passed to the control logic and used to set the centre frequency of the USRP. Once the receive frequency is adapted, the signal data path is switched to the OFDM demodulation signal processing chain.

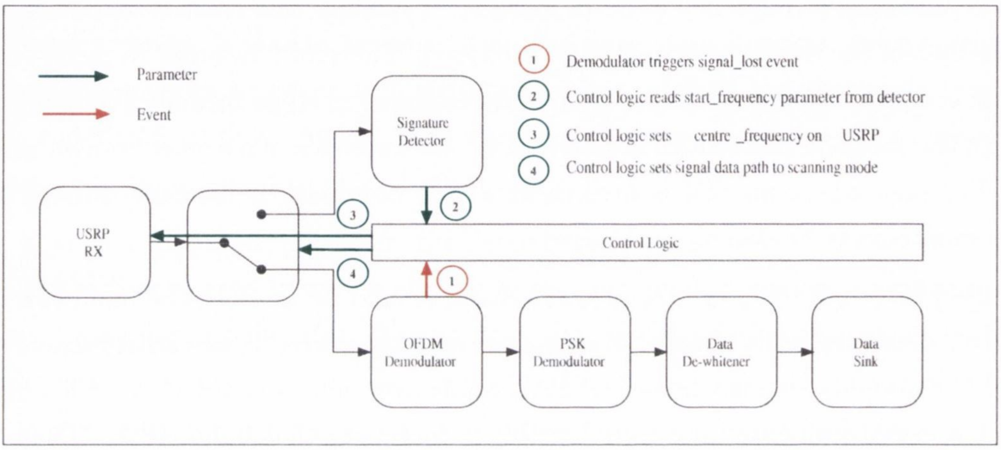


Fig. 7.11: Receiver mode switch from streaming to scanning

The reverse process switches the receiver mode from communication to scanning as illustrated in Fig. 7.11. This switch is triggered by the OFDM demodulator component upon loss of the received signal. A signal is determined to be lost after a defined timeout. The *signal_ lost* event is handled by the control logic which proceeds to read the *start_ frequency* parameter of the signature detector component. The USRP centre frequency is set to this value through the receive driver component. Once the frequency is set, the signal data path is switched to the detector component and the frequency scanning process begins once again.

While the IRIS radio components developed for our OFDM-based receiver architecture provide all the key functionality required, it can be seen that the control logic plays an essential role as the "glue" which holds these components together. By effectively managing inter-component interactions, the control logic provides the application-level functionality needed to realise our design goals.

7.4.4 Summary

The IRIS software radio architecture played a key role in the implementation of our prototype transceiver. A considerable degree of complexity is involved in the design and development of such a system. However, the use of a component-based, reconfigurable architecture allowed that complexity to be effectively managed using encapsulation and abstraction. At the application level, the separation of the transmit and receive signal processing chains simplified their development prior to incorporation in a full transceiver system. Within the processing chains themselves, the separation of key functions into components allowed each to be developed and tested in isolation before being placed together in the chain. In this way, the process of isolating and correcting errors and oversights was greatly simplified.

As well as greatly simplifying the design and development process, the use of a highly reconfigurable architecture permitted design variations and alternatives to be easily developed and included in the transceiver prototype for comparison. Using both structural and parametric reconfiguration, the transceiver prototype can be easily adapted as applications require. For example, the replacement of the main signature detector component with the iterative detector permits spectrum band monitoring to be performed.

7.5 Summary

Chapter 6 provided a number of key insights into the use of cyclostationary signatures for DySPAN rendezvous and coordination using simulation results. However, in order to truly test the potential of cyclostationary signatures, experiments must be conducted using real over-the-air transmissions. This chapter has presented the prototype OFDM transceiver designed and implemented in order to perform such experiments. The experimental platform adopted for our transceiver has been outlined and the design and development of each key transceiver element has been examined.

In the next chapter, experiments carried out using our transceiver prototype are outlined. Experimental results are presented and key insights gained in the use of OFDM-based cyclostationary signatures are discussed.

8. EXPERIMENTAL ANALYSIS

8.1 Introduction

In Chapter 7, I examined the design and implementation of an Orthogonal Frequency Division Multiplexing (OFDM)-based transceiver for cyclostationary signature experimentation. In this chapter, I outline experiments carried out to assess the use of cyclostationary signatures for Dynamic Spectrum Access Network (DySPAN) rendezvous and coordination using real-world systems. Comparisons are drawn between experimental and simulation results and key insights into the use of signatures in OFDM-based systems are presented.

The principal aim in carrying out experiments is to assess the performance of real-world systems using embedded cyclostationary signatures for rendezvous and coordination. Computer simulations provide a useful technique for assessing system performance by modelling real-world conditions. However, these models cannot take into account all the factors of a real-world system and so can only provide an approximation of the system performance. For example, although noise may be modelled as white and uncorrelated in simulations, real-world noise is rarely perfectly white or uncorrelated. Experimental results obtained using a suitable transceiver platform provide a more complete view of the system and serve to verify those results obtained through simulation. In addition, experiments allow us to test the capabilities of our implemented transceiver system.

Our experiments focused upon three applications of cyclostationary signatures:

- Signal Detection
- Network Identification
- Frequency Acquisition

Together, these applications comprise the key requirements for rendezvous in DySPAN systems and can be successfully used in achieving DySPAN coordination. The applications were examined using simulation results in Chapter 6. By carrying out similar experiments using our transceiver system, results obtained through simulation can be verified and greater insights can be obtained into the use of cyclostationary signatures.

Fig. 8.1: Vector signal generator and signal analyser used for experimentation.

Test and analysis equipment played a key role in carrying out experiments using cyclostationary signatures. In particular, the Anritsu MG3700A vector signal generator and MS2781A Signature spectrum analyser shown in Fig. 8.1 were employed to generate and analyse signature-containing OFDM signals.

The MG3700A signal generator allows arbitrary waveforms to be generated and transmitted over the air. Carrier frequencies between 250 kHz and 6 GHz are supported and sample rates of between 20 kHz and 160 MHz can be used. Transmit power levels between -120 dBm and 10 dBm are supported with an accuracy of +/- 0.5 dB for carrier frequencies between 250 kHz and 3 GHz.

OFDM signals containing embedded cyclostationary signatures were generated using the transmitter outlined in the previous chapter and stored on disk. These signals were then transferred to the signal generator and used to test our receiver implementation. While it would have been possible to transmit these signals directly using the Univeral Software Radio Peripheral (USRP), the use of the signal generator allowed for much greater accuracy in transmit frequency and power level to be achieved. The USRP is a highly effective radio frequency (RF)-front end for software radio experimentation. However, the accuracy of the USRP in carrier frequency and power level is far less than that of calibrated test equipment such as the MG3700A. Using the signal generator, more reliable experimental results were obtained. In addition, the MG3700A can be controlled remotely over an ethernet connection, permitting automated experiments to be carried out using predefined transmit frequencies and power levels.

The MS2781A Signature spectrum analyser supports frequency ranges between 100 Hz and 8 GHz with resolution bandwidths between 0.1 Hz and 8 MHz. Although the analyser was not used to receive signals of interest, it was used extensively to verify the carrier frequencies, power levels and bandwidths of transmitted signals.

In examining the use of embedded signatures for signal detection, experiments focused upon the parameters used for signal generation and detection. Specifically, the effect of mapped subcarrier set sizes was examined. Recall that a cyclostationary signature is generated by transmitting data redundantly upon a set of mapped OFDM subcarriers. This creates a spectral correlation pattern in the transmitted signal which can be detected using cyclostationary analysis. While the use of a greater mapped set size increases the overhead incurred through the use of signatures, it can also improve the detection performance achieved at the receiver. This was illustrated using simulations in Chapter 6, Fig. 6.1. In Section 8.2.2, I present experimental results for detector performance and compare these results with those obtained using simulations.

As well as examining the effect of mapped set sizes, experiments were carried out to assess the effect of signal observation times upon detector performance. As discussed in Chapter 6 and illustrated in Fig. 6.2, spectral correlation estimates improve with greater signal observation times. However, greater signal observation times mean longer times required for reliable DySPAN rendezvous. This trade-off is examined using experimental results in Section 8.2.3. Results show that reliable detection of embedded signatures can be achieved using an observation time of less than 20 symbol durations.

Section 8.3 focuses upon the use of cyclostationary signatures for network identification. Cyclostationary signatures generated using OFDM subcarrier mapping are easily manipulated in both spectral and cyclic frequency. In this way, signatures with unique properties can be generated and used for identification in OFDM-based systems. This approach was examined using simulation results in Chapter 6. In Fig. 6.14 the performance of a network identifier using unique embedded signatures is presented. Experiments carried out using our transceiver implementation verify these results and again examine the effect of signal observation times on identifier performance.

The use of cyclostationary signatures to achieve frequency acquisition is addressed using experimental results in Section 8.4. Cyclostationary signal analysis does not require synchronization with the signal of interest (SOI) and so provides a highly flexible tool for the analysis of signals whose bandwidth or carrier frequency are unknown. For OFDM-based systems, the presence of an embedded cyclostationary signature in an SOI allows that signal to be detected and carrier frequency estimation to be performed. A key advantage of this approach is the ability to employ a wide-band receiver in order to detect and estimate the carrier frequency of signals transmitted at any frequency within a band of interest. Experimental results show that carrier frequency estimation can be reliably performed to within a single subcarrier spacing using a receive bandwidth four times that of the SOI bandwidth.

Simulation results presented in Chapter 6 showed cyclostationary signatures to be a potentially powerful tool for overcoming the challenge of DySPAN rendezvous and coordination. By implementing a real-world transceiver and carrying out experiments using over-the-air signals, I illustrate the practical application of embedded signatures and demonstrate the flexibility with which they may be used in advanced wireless systems.

8.2 Signal Detection

8.2.1 Experimental Setup

In order to examine the performance of our cyclostationary signature detector using over-the-air signals, the MG3700A vector signal generator was used together with the USRP RF-front end and the Implementing Radio In Software (IRIS) transceiver implementation. Suitable signals were generated using the IRIS transmitter and stored to file in in-phase - quadrature (I-Q) format. These were then loaded onto the signal generator and transmitted within the upper Centre for Telecommunications Value-Chain Research (CTVR) licensed band, discussed in Section 7.4.2, at 2.35 GHz. OFDM signals were generated with 256 subcarriers, of which 55 were reserved as guard carriers and 1 was designated the zero-frequency, direct current (DC) carrier. A 1/16 cyclic prefix was added to each symbol generated. Subcarriers were modulated using randomly generated quadrature phase shift keying (QPSK) data symbols and subcarrier set mapping was used to embed single-feature signatures with a cyclic frequency arbitrarily chosen as $\alpha = 32/T_s$. Subcarrier set sizes between 1 and 9 were employed to facilitate performance comparisons. Signals without embedded signatures were also generated.

Generated signals were transmitted with a sample rate of 1 MHz using the signal generator with centre frequency 2.35 GHz. These transmitted signals were captured at a distance of 3 metres using an RFX2400 USRP daughterboard set to sample a bandwidth of 1 MHz centred at 2.35 GHz. The downconverted samples were then transferred to the IRIS software radio engine via USB and processed by the receiver. Transmit power levels were set between -8 and -36 dBm to give an estimated receive signal-to-noise ratio (SNR) of between 12 and -6 dB.

SNR estimation at the receiver was achieved using captured signals comprising noise only and both noise and a known OFDM signal. The power spectral density (PSD) was calculated for each and averaged over 1000 windows of 1024 samples. Mean powers were estimated over bandwidths of both the noise only (P_n) and the noise and signal samples (P_{s+n}). These mean powers were then used to calculate the estimated SNR as:

$$SNR_{est} = 10log_{10}(\frac{P_{s+n}}{P_n} - 1) \tag{8.1}$$

Signature detection was performed using the frequency domain-shifting single-cycle detector:

$$y_\alpha = \max_k \sum_{m=0}^{M-1} W[m]\widehat{C}_x^\alpha[k-m] \tag{8.2}$$

where $W[k]$ is a rectangular window of width $M.\Delta f$ (M is the number of mapped subcarriers used to generate the embedded signature, Δf is the OFDM subcarrrier spacing). The spectral coherence estimate, $\widehat{C}_x^\alpha[k]$ is defined as:

$$C_x^\alpha[k] = \frac{S_x^\alpha[k]}{(S_x^0[k+\alpha/2]S_x^0[k-\alpha/2])^{1/2}} \tag{8.3}$$

where $S_x^\alpha(f)$ is the time-smoothed cyclic cross periodogram (TS-CCP), presented in Chapter 4.

8.2.2 Mapped Subcarrier Set Sizes

In Chapter 6 it was seen that, by choosing the number of mapped subcarriers used to generate a signature, a basic trade-off is made between system overhead and detection performance. Overhead is incurred as subcarriers used to carry mapped data symbols may not carry independent data. However, signatures created using greater numbers of mapped subcarriers contain more power and so may be more reliably detected.

The improvement in detection performance which can be achieved using greater numbers of mapped subcarriers was examined using simulation results in Section 6.2. By carrying out experiments using a real-world platform, we can verify these results and gain an insight into detector performance using over-the-air signals.

Suitable OFDM signals with and without embedded signatures were generated in software and stored in I-Q format on the MG3700A vector signal generator. These were then transmitted at power levels between -8 and -36 dBm. Within the receiver, SNR estimation was performed and the TS-CCP signature detector was used to calculate the detection statistic, y_α for a signal observation time equivalent to 30 OFDM symbol durations, $\Delta t = 30T$. 1000 runs were used to calculate average detection statistics for signals both with and without signatures. For each value of the estimated SNR, a detection ratio y_{sig}/y_0 was calculated. Here y_{sig} is the average detection statistic for signals containing embedded signatures and y_0 is the average statistic for signals without signatures. This ratio represents a measure of the confidence with which detection decisions can be made and provides an initial means of comparing detection performance for different signature types and associated detectors. More detailed comparisons are drawn using receiver operating characteristic (ROC) performance in the next section.

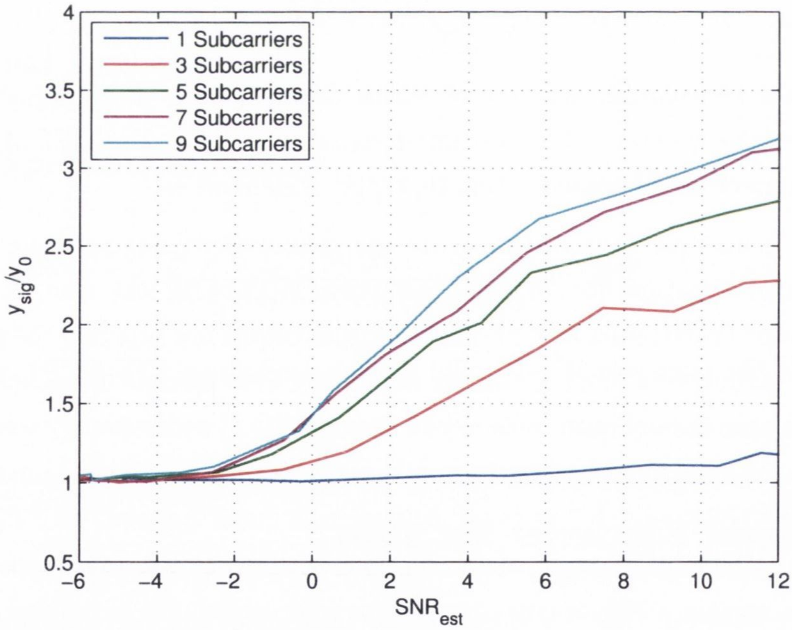


Fig. 8.2: Signature detection ratio performance with increasing mapped subcarrier set sizes over a range of SNR values.

Experimental results are illustrated in Fig. 8.2 for estimated SNR between -6 and 12 dB. Equivalent results obtained using simulations are illustrated in Fig. 6.1 in Section 6.2 and a direct comparison for a subset of results is illustrated in Fig. 8.3. Here, experimental results are illustrated using continuous lines and simulation results are illustrated using dashed lines. Comparing these results, it can be seen that a similar improvement in detection performance is observed with increasing subcarrier set size. While a detection ratio of ≈ 1.5 can be achieved using a set of 3 subcarriers for an estimated SNR of 3 dB, this ratio increases to ≈ 2 when a subcarrier set size of 7 is employed. In terms of absolute ratio values however, experimental results exhibit a decrease in performance over those obtained through simulation. For example, at 5 dB SNR, a 3-subcarrier signature is detected with ratio $y_{sig}/y_0 \approx 2$ using simulations. This value falls to ≈ 1.75 for experimental results. An explanation for this fall in performance is the use of white Gaussian noise in simulations. Under experimental conditions, the wireless channel noise is unlikely to be perfectly white and uncorrelated, resulting in the reduced performance observed. Although detector performance falls slightly under experimental conditions, cyclostationary signatures may be used to achieve excellent detection results for signals received with SNR of greater than 0 dB. This is demonstrated in greater detail in the next section.

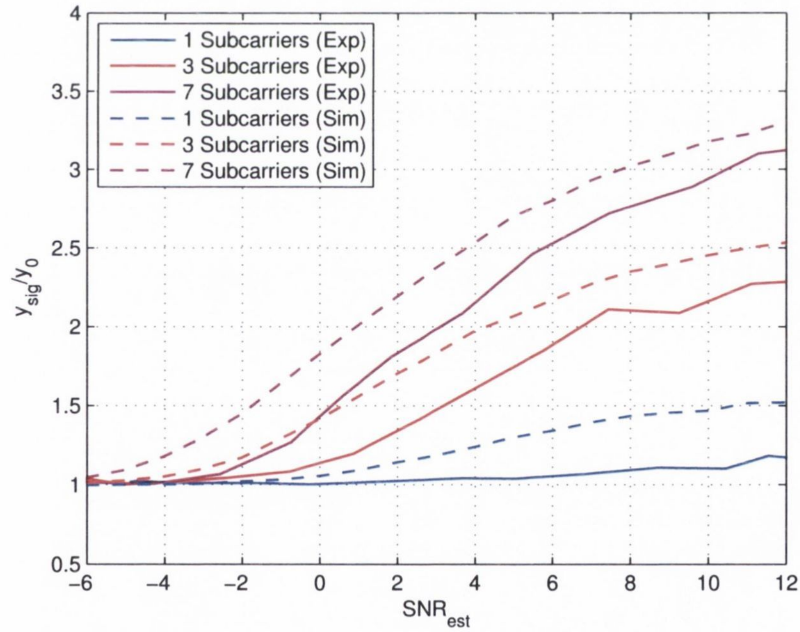


Fig. 8.3: Comparison of simulation and experimental results for signature detection.

8.2.3 Observation Times

In generating a cyclostationary signature, mapped subcarrier set sizes are the key parameter in determining the detection performance which can be achieved. However, in detecting an embedded signature, the observation time employed in the detector is the key factor. This was shown using simulation results in Section 6.2.2 of Chapter 6.

As discussed in Chapter 4, observation time is a key factor in determining the reliability of spectrum correlation function (SCF) estimates used for cyclostationary signal analysis. In the context of DySPAN rendezvous and coordination, required observation time is a critical performance metric as it dictates the speed with which rendezvous can be achieved. A recognized limitation of cyclostationary signal analysis is the typically long observation time required for reliable feature estimation. One of the principal advantages of cyclostationary signatures generated using OFDM subcarrier set mapping is the reduction in observation time required for reliable detection. As discussed in Chapter 5, this is achieved due to the relatively large spectral frequency resolution, Δf, which is required to resolve features embedded using mapped subcarriers. In carrying out experiments using our transceiver implementation and over-the-air signals, observed simulation results can be verified and the roles of observation time and mapped subcarrier set sizes can be further examined in determining signature detection performance.

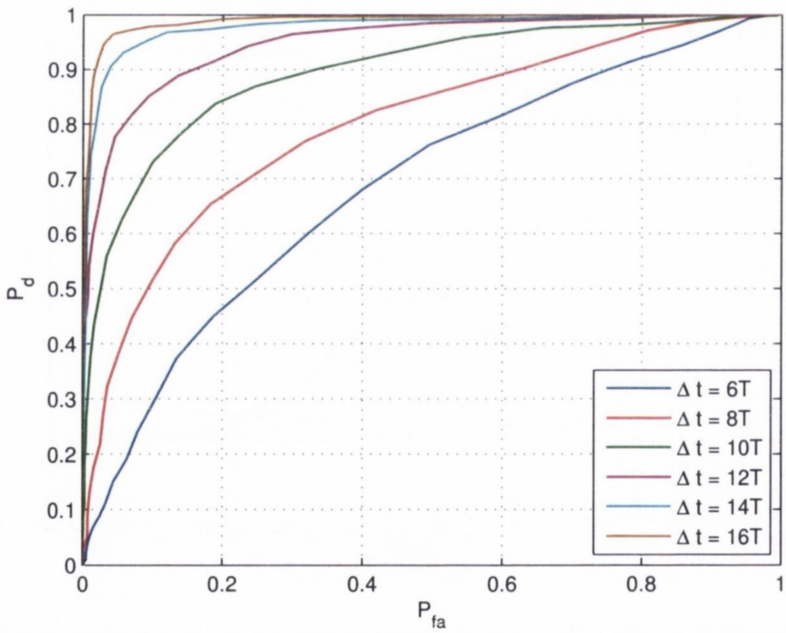


Fig. 8.4: ROC performance with increasing observation time for $M = 3$.

Experiments were carried out using OFDM signals as before. Suitable signals were generated and transmitted using the MG3700A signal generator. Single feature signatures were embedded in a number of signals using mapped subcarrier set sizes of

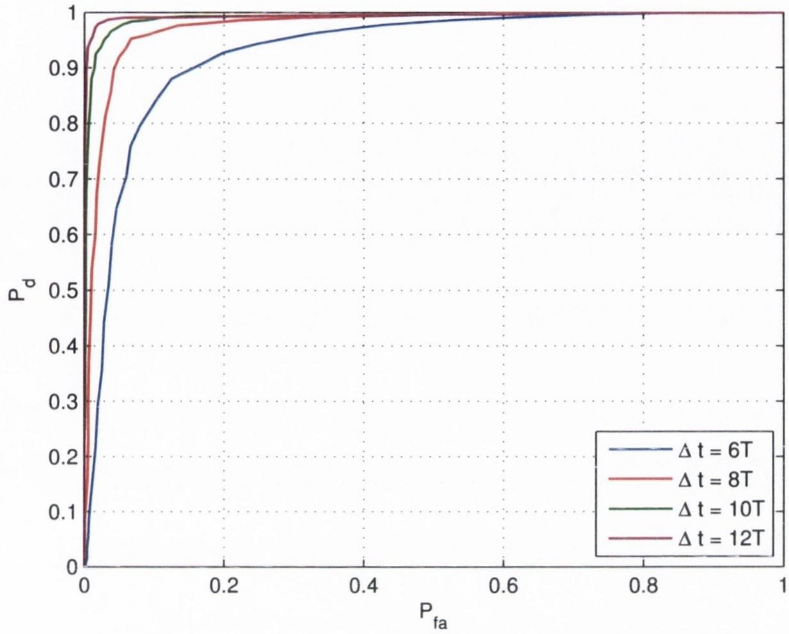


Fig. 8.5: ROC performance with increasing observation time for $M = 5$.

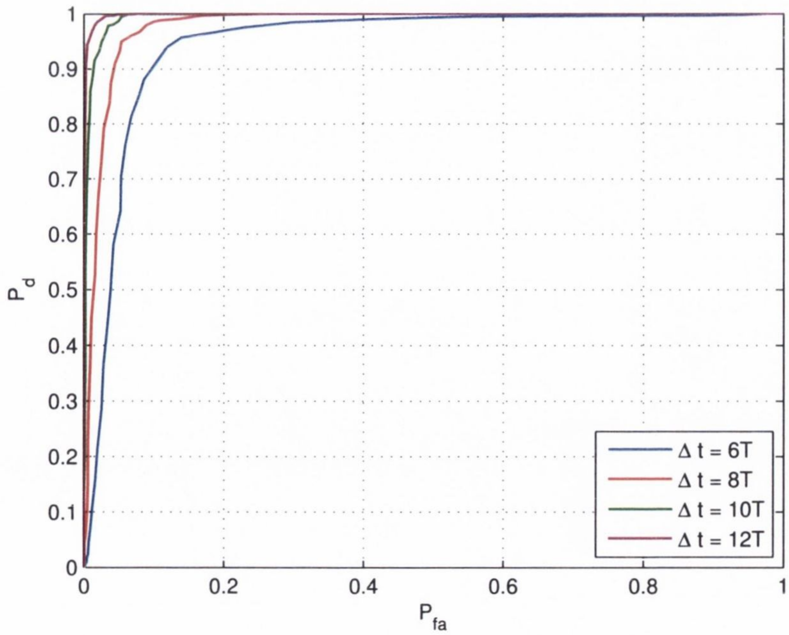


Fig. 8.6: ROC performance with increasing observation time for $M = 7$.

3, 5 and 7. A transmit power of -16 dBm was used to give an estimated receive SNR of $\approx$ 5 dB. At the receiver, signals were analysed using the frequency-shifting single cycle detector presented in Chapter 5. Detection statistics were recorded over a range of observation times for signals with and without signatures and used to generate the ROC graphs illustrated in Fig. 8.4, Fig. 8.5 and Fig. 8.6.

Results show that significant improvements in detection performance can be achieved using increased observation times. Using a 3-subcarrier signature, a detection rate of 90% with an associated false alarm rate of 15% can be achieved using an observation time equivalent to 12 OFDM symbol durations. By increasing the observation time to 16 symbol durations, the achieved detection rate increases to $\approx$ 98% with an associated false alarm rate of $\approx$ 2%. Figs. 8.5 and 8.6 show that comparable performance can be achieved using reduced observation times for signatures generated with greater subcarrier set sizes.

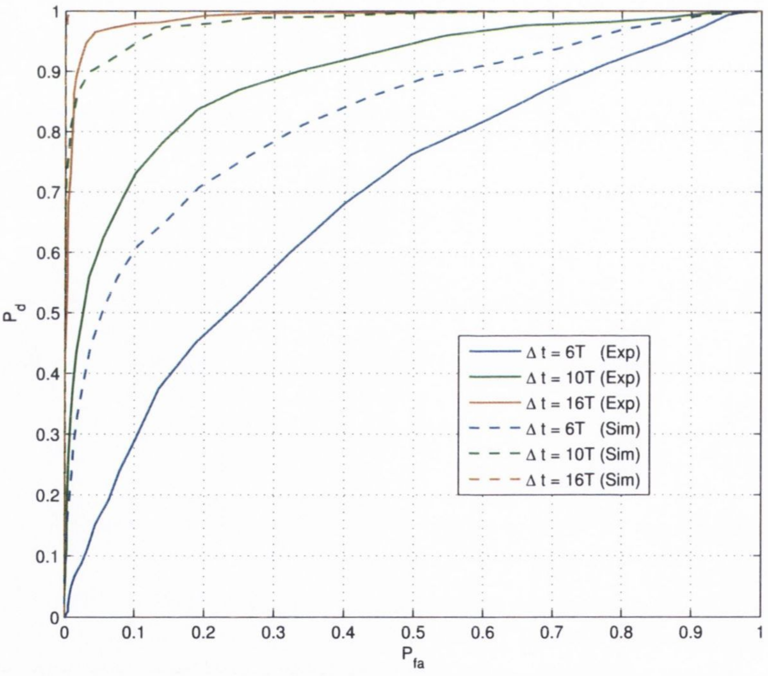


Fig. 8.7: Comparison of simulated and experimental ROC performance with increasing observation time for $M = 3$.

Fig 8.7 directly compares experimental results for $M = 3$ with those obtained using simulations in Section 6.2.3. Comparisons show a fall in detector performance for real-world experiments. Similarly to the fall in performance observed in the previous section, this can be explained by the use of white Gaussian noise in simulations. As real-world channels rarely exhibit perfectly white, uncorrelated noise, this can reduce the reliability of our SCF estimates.

Figs. 8.8, 8.9 and 8.10 present the detection statistics underlying the ROC results and allow us to examine our detector performance in greater detail. Once again, in these histograms, an overlap between values of y_{sig} and y_0 indicates that perfect detection results cannot be obtained. Therefore, the greater the distance between the values of y_{sig} and y_0, the better the detection performance which can be achieved.

Comparing results with those presented in Section 6.2.3, it can be seen that detection statistics for signals without embedded signatures closely match those obtained using simulations. However, statistics show a fall in the mean recorded for signature-containing signals due to the presence of real-world channel noise. As with our simulations, increased observation times can be seen to reduce the mean and variance of recorded detection statistics for signals without embedded signatures, y_0. These figures also illustrate that an increase in the mapped subcarrier set size causes a reduction in the mean values of y_0 observed, resulting in significant improvements in detector performance.

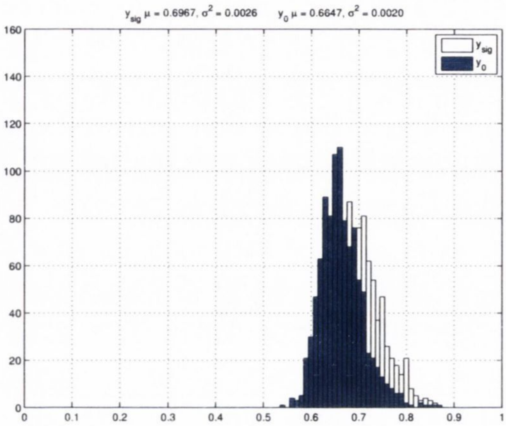
8.3 Network Identification

8.3.1 Experimental Setup

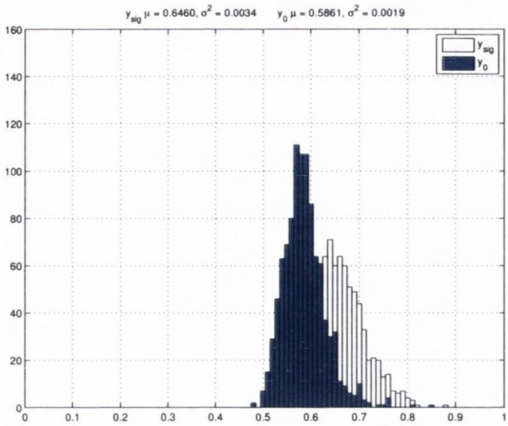
Network identification forms an important element of the rendezvous process for DySPAN systems. A device performing rendezvous must identify compatible networks before choosing one which it wishes to join. In the case of reconfigurable radio devices which may operate within a number of differing network types, the ability to perform network identification is especially important.

Cyclostationary signatures facilitate network identification for DySPAN systems by permitting individual networks to choose a unique identifier to be embedded in all signals transmitted by members of that network. Upon detection of a signature-containing signal, a device may use the properties of that signature to uniquely identify the network in question. One property of a cyclostationary signature which may be manipulated in order to provide this unique identifier is the cyclic frequency. As discussed in Section 5.3, the cyclic frequency of a signature is determined by the mapped subcarrier set spacing. By choosing specific sets of subcarriers to map, the cyclic frequency of the embedded signature can be manipulated.

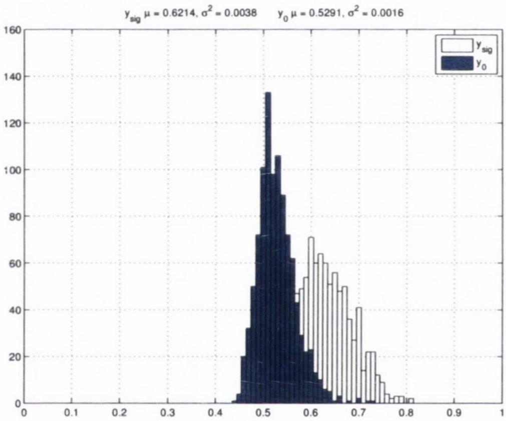
The performance of cyclostationary signatures when used for network identifica-



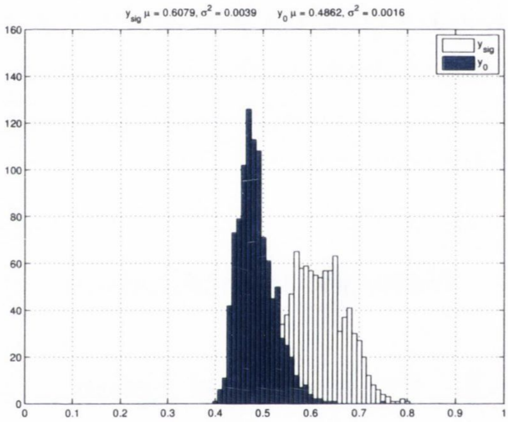
(a) $\Delta t = 6T$



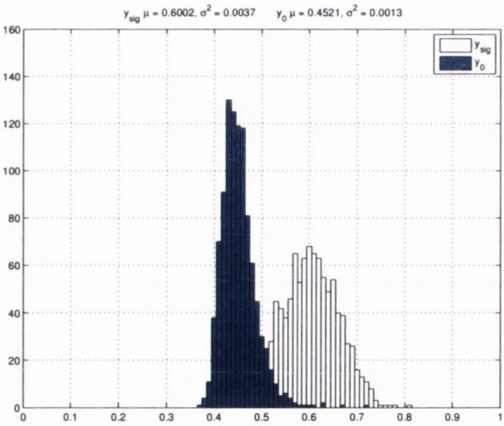
(b) $\Delta t = 8T$



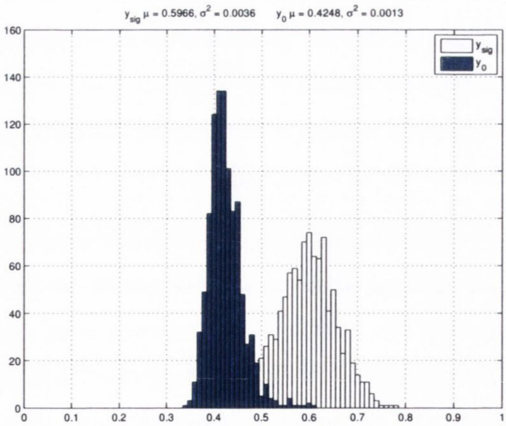
(c) $\Delta t = 10T$



(d) $\Delta t = 12T$

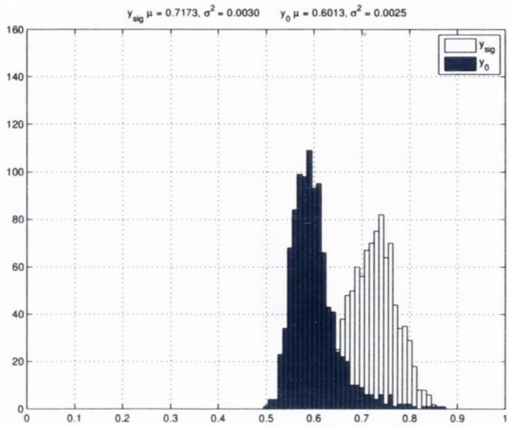


(e) $\Delta t = 14T$

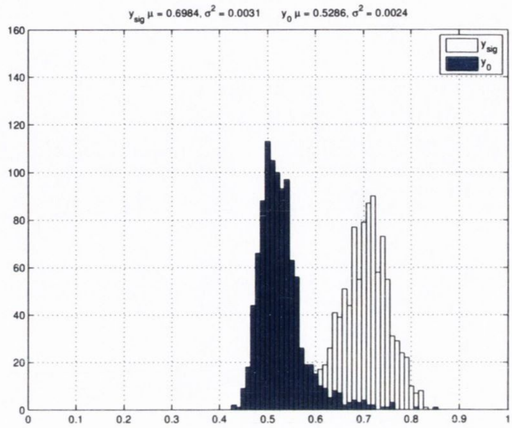


(f) $\Delta t = 16T$

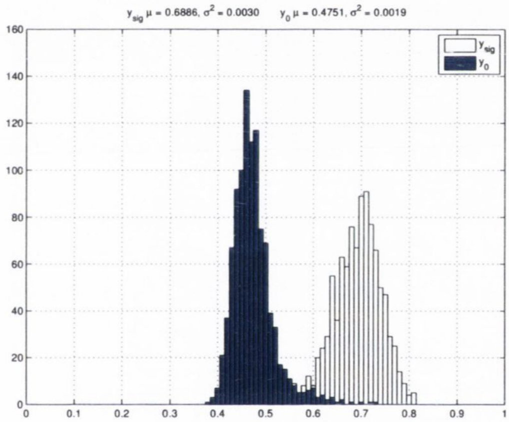
Fig. 8.8: Histograms of y_{sig} and y_0 underlying ROC analyses for $M = 3$.



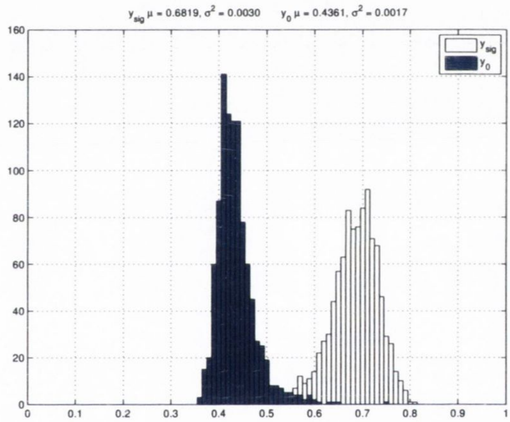
(a) $\Delta t = 6T$



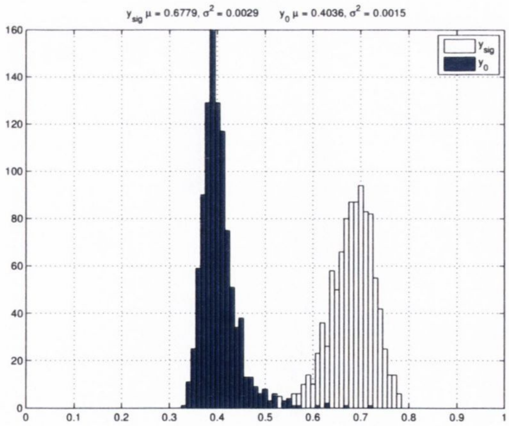
(b) $\Delta t = 8T$



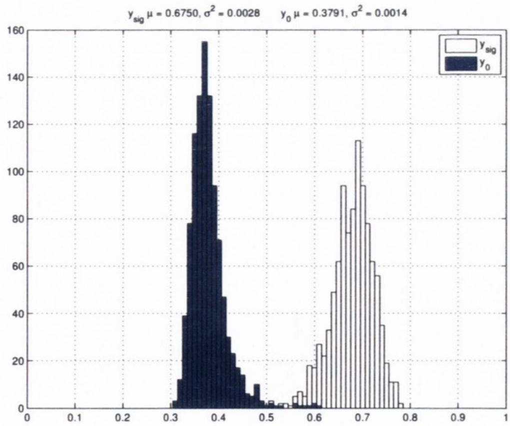
(c) $\Delta t = 10T$



(d) $\Delta t = 12T$

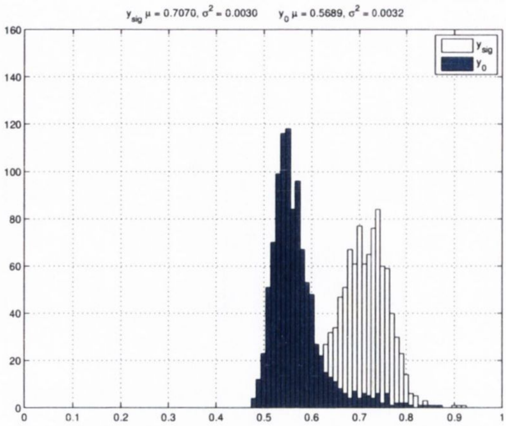


(e) $\Delta t = 14T$

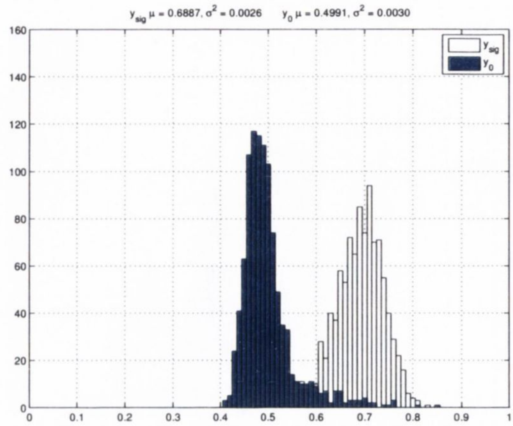


(f) $\Delta t = 16T$

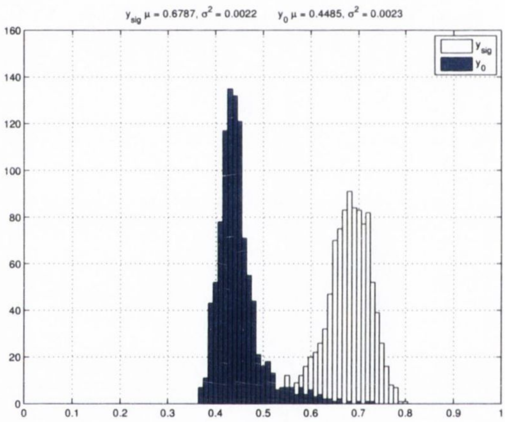
Fig. 8.9: Histograms of y_{sig} and y_0 underlying ROC analyses for $M = 5$.



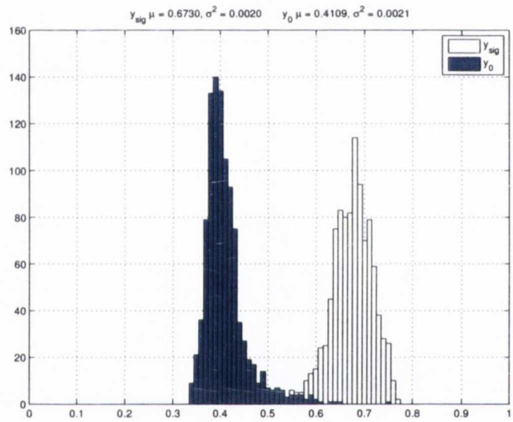
(a) $\Delta t = 6T$



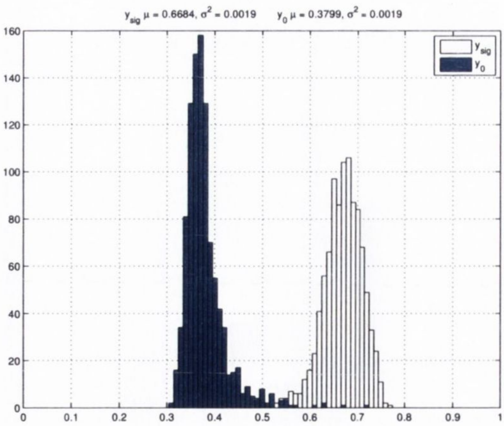
(b) $\Delta t = 8T$



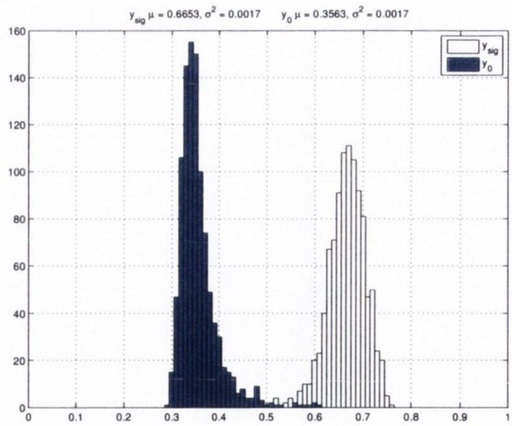
(c) $\Delta t = 10T$



(d) $\Delta t = 12T$



(e) $\Delta t = 14T$



(f) $\Delta t = 16T$

Fig. 8.10: Histograms of y_{sig} and y_0 underlying ROC analyses for $M = 7$.

tion was initially examined using simulations. The results of these simulations are outlined in Section 6.4. In order to further examine the use of signatures in this way, experiments were carried out using our experimental transceiver. Suitable signals were generated using our transmitter implementation and transmitted using the MG3700A signal generator in order to provide highly accurate control over transmit frequencies and power levels. Subcarrier set mapping was used to embed multiple-feature signatures in the transmitted signals. For each signature, three sets of three subcarriers were used to embed three independent cyclostationary features. Similarly to the approach adopted for our simulations, signatures were chosen with the minimum cyclic frequency separation. The cyclic frequencies of the embedded signatures are outlined in Table 8.1.

Signature	Cyclic Frequency
α_1	$29/T_s$
α_2	$30/T_s$
α_3	$31/T_s$
α_4	$32/T_s$

Tab. 8.1: Signature cyclic frequencies

Signals were transmitted with power levels between -8 and -36 dBm for a received SNR of between 10 and -5 dB. As in simulations, the time-domain shifting detector was adopted and signature detection was carried out at each cyclic frequency for observation times ranging from 5 to 30 OFDM symbol durations. Network identification performance is assessed by comparing detection results at each of the four cyclic frequencies with the known signature cyclic frequency. 250 tests were performed for each signature, power level and observation time. The statistic z was calculated as:

$$z = \arg\max_j y_{\alpha_j} \tag{8.4}$$

where y_{α_j} is the output of the detector at each cyclic frequency α_j. The probability of identification, P_j was calculated using z as:

$$P_j = p(z = j|x_j) \tag{8.5}$$

where x_j is an OFDM signal containing a cyclostationary signature with cyclic frequency α_j.

8.3.2 Network Identification Performance

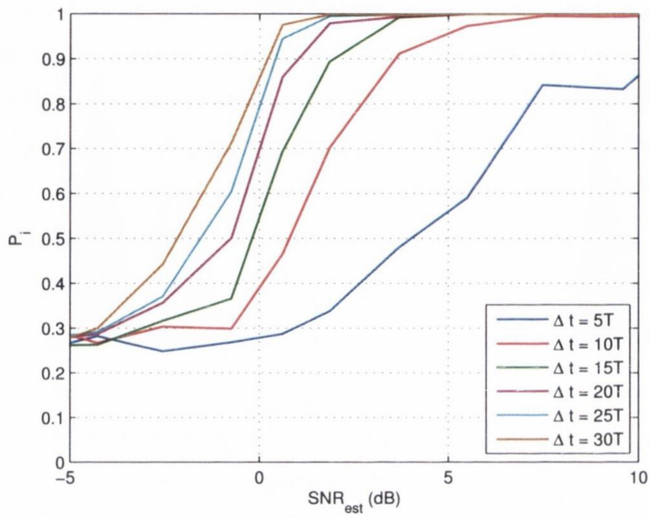


Fig. 8.11: Performance of network identifier using cyclostationary signatures.

Experimental results obtained using our transceiver implementation are illustrated in Fig. 8.11. Performance can be seen to improve significantly with increasing observation time, as before. While a P_i of 100% can be achieved at 5 dB SNR using an observation time of just 15 symbol durations, this performance falls with decreasing SNR and greater observation times are required to achieve equivalent performance. At SNR levels below 0 dB, identification performance falls rapidly.

Comparing our experimental results to those obtained using simulations in Fig. 8.12, it can be seen that real-world performance closely matches that observed in Section 6.4. One difference which can be seen is the more rapid deterioration in performance at low levels of SNR exhibited by our experimental results. This discrepancy can be explained as before by the use of white Gaussian noise in our simulations. As real-world noise is rarely perfectly white and uncorrelated, it can reduce the accuracy of spectral correlation estimates at low levels of SNR. A second difference between the simulated and experimental results are the higher levels of performance achieved in experiments at the higher SNR levels. This is explained by the use of an exponentially decayed multipath model in simulations. Experimental channel conditions in an indoor environment are unlikely to involve such a long delay spread and so in this case improved results are observed under experimental conditions.

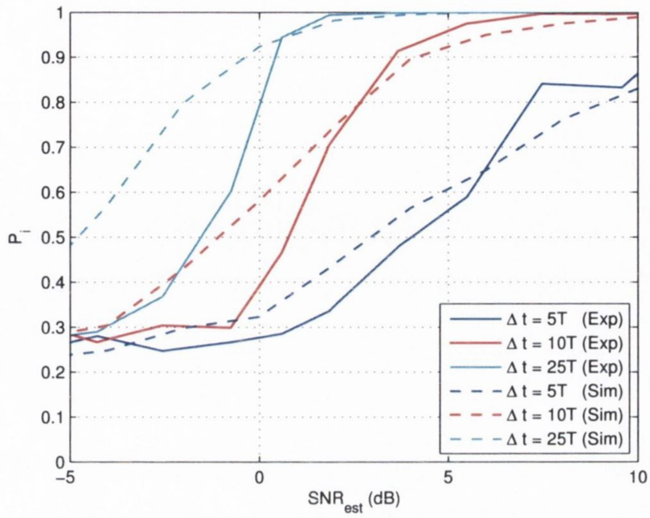


Fig. 8.12: Comparison of simulated and experimental performance of network identifier.

8.4 Frequency Acquisition

8.4.1 Experimental Setup

The final experiment carried out using our transceiver implementation focused upon the use of embedded cyclostationary signatures to perform carrier frequency estimation. As discussed in Chapter 5, the spectral frequency of cyclostationary features embedded using OFDM subcarrier set mapping is accurately known. Upon detection of a signature-containing signal, these features can be used to accurately estimate the carrier frequency of the signal. In the case of DySPAN systems, this is a fundamental requirement for rendezvous and network coordination. A particular advantage of the use of cyclostationary signatures in this way is the ability to perform carrier frequency estimation for a signal whose bandwidth is significantly smaller than the bandwidth sampled in the receiver.

In order to examine the real-world performance of cyclostationary signatures used for carrier frequency estimation, suitable signals were generated using our transmitter implementation and transmitted using the MG3700A vector signal generator. The use of a signal generator permitted the power levels and carrier frequencies of transmitted signals to be accurately known. 256-subcarrier OFDM signals were generated using QPSK modulated random data. Multiple-feature signatures were embedded as before using three mapped sets of three subcarriers. Using the MG3700A, these signals were transmitted with a 1 MHz bandwidth, giving a subcarrier spacing of 3906.25 Hz.

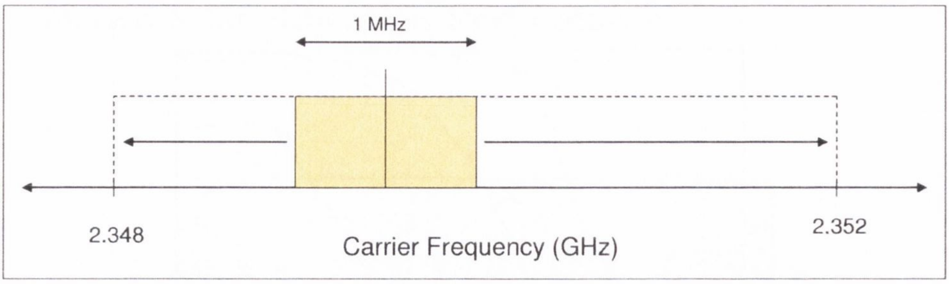


Fig. 8.13: Carrier frequencies of transmitted experimental signals.

Signals were transmitted using the CTVR licensed bands with carrier frequencies randomly chosen between 2.3485 and 2.3515 GHz for each test. In this way, our 1 MHz signal was transmitted at a known carrier frequency within a 4 MHz channel. Fig. 8.13 illustrates the frequency band used. Power levels of between -8 and -22 dBm were used for estimated receiver SNR levels of between approximately 12 and 0 dB. At each power level, 100 tests were carried out using different transmit frequencies. For each test, a single tone was transmitted by the signal generator to facilitate carrier frequency calibration of the USRP RF front-end. As the relative frequency offset between the USRP and MG3700A varies slightly from test to test, the use of a tone with a known frequency allowed us to calculate this offset and so improve the accuracy of our estimation results. This tone was followed by the SOI. At the receiver, the USRP was set to sample the full 4 MHz bandwidth centred at 2.35 GHz. Signature detection and carrier frequency estimation was performed for each test by the frequency-domain shifting detector implementation. An observation time of 30 symbol durations was used.

Programming scripts were used to automate the testing process. Fig. 8.14 illustrates the sequence used for each test. Remote control of the signal generator was facilitated using an ethernet interface while the IRIS software radio engine was dynamically reconfigured using eXtensible Markup Language (XML) configuration scripts, pushed to IRIS over ethernet. The sequence for each test comprised four steps. Firstly, the central controller initiated transmission of a single tone at 2.35 GHz. This tone was used to calibrate the USRP for each test. Secondly, the controller initiated a timed signal capture on the software radio engine. The first part of this capture consists of the single fixed tone. Once the tone was captured, the controller triggered the MG3700A to switch the transmitted waveform from the single tone to the OFDM signal containing the embedded signature. At the same time, the carrier frequency of that signal was adjusted to a randomly chosen frequency between 2.2485 and 2.3515 GHz. Once that signal had been captured using IRIS, the controller switched off transmission on

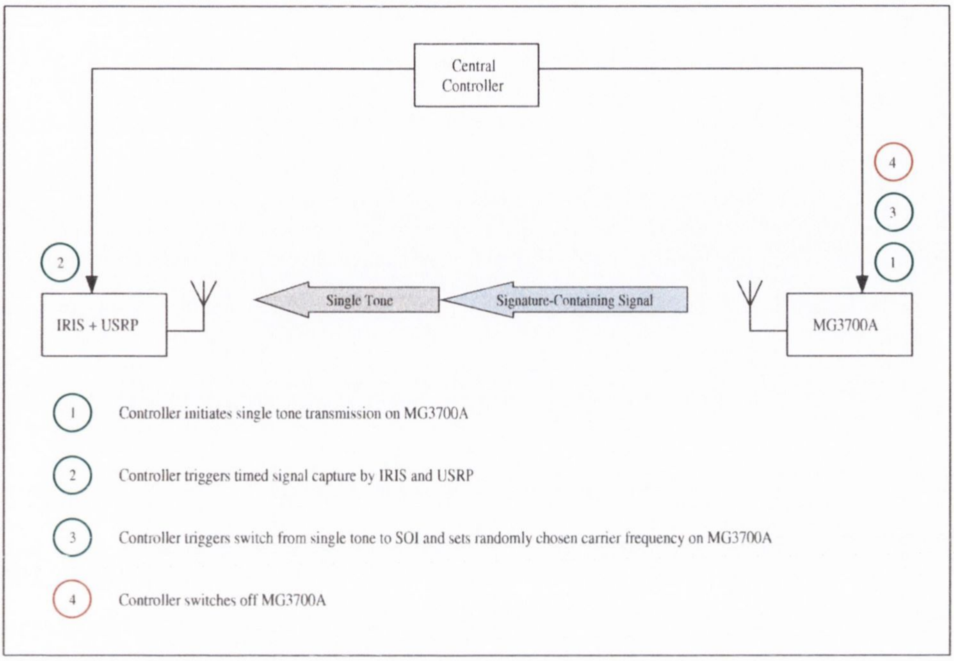


Fig. 8.14: Automated signal capturing sequence used for each frequency acquisition test.

the signal generator to complete the test. In this way, each signal capture comprised two parts, the first containing the single tone and the second containing the SOI at a carrier frequency randomly chosen by the controller.

This signal capture sequence was performed repeatedly, in a loop, to provide sufficient captured data to perform our analysis. Following the signal capture process, the signal data for each test was processed offline using our transceiver implementation to perform carrier frequency estimation and provide results. These results are presented in the next section.

8.4.2 Performance

Actual transmit frequencies were recorded together with carrier frequency estimates for each test and were used to generate the results illustrated in Figs. 8.15 to 8.17. The results in red illustrate the distribution of actual transmit frequencies between 2.348 and 2.352 GHz. The distribution of our carrier frequency estimates are illustrated in blue. The estimates are shown in a distribution within a single subcarrier spacing of the true value (+/- Δf). It should be noted that all estimates exceeding a single subcarrier spacing from the true value are represented in the outer bars of the histogram. It can be seen that, although the carrier frequencies used in the tests are widely distributed, estimation of those frequencies using the embedded signatures is highly accurate to within a single subcarrier spacing.

Results show that cyclostationary signatures may be very reliably used to estimate signal carrier frequencies for signals received with SNR of 3 dB or greater. Carrier frequency estimates determined for signals with SNR of above 7 dB were shown to be accurate within +/- Δf in 100% of tests. At an estimated receiver SNR of 6.1947 dB, estimates were accurate in 98% of tests and at 3.5636 dB, 95% of tests were shown to be accurate.

A probability of acquisition, P_a is defined as

$$P_a = p(f_0 - \Delta f \leq f_{est} \leq f_0 + \Delta f) \tag{8.6}$$

where Δf is the subcarrier spacing and f_0 is the true carrier frequency. Using our experimental results, a detector threshold was chosen such that the probability of detection, P_d was 95%. With this threshold, the probability of acquisition calculated for each value of the estimated receiver SNR is illustrated in Fig. 8.18. Simulation results from Section 6.5.2 are also provided for comparison.

Comparing both sets of results, it can be seen that the performance observed for simulations has been verified by our experiments. As in our simulation results, performance is relatively constant above 5 dB SNR. Simulation results indicated an average P_a of 98% at these levels. The use of a multipath fading channel explains the loss of 2% performance. For our experiments, an average P_a of almost 100% is observed. Below 5 dB SNR, performance can be seen to deteriorate. At 3 dB, a P_a of approximately 95% is observed for our experimental transceiver. This closely matches simulation results. Below 3 dB, performance is seen to deteriorate more rapidly for experimental results than in simulations. As before, this discrepancy can be explained by the use of white Gaussian noise in our simulations.

8.5 Summary

The key aims in performing cyclostationary signature experiments using a real-world transceiver implementation included the verification of performance results obtained using computer simulations and the testing of the implemented transceiver.

Within the three key application areas of signal detection, network identification and carrier frequency estimation, experimental results obtained and presented in this chapter have fully verified the performance observed using simulations. Indeed, it has been seen that experimental results closely match those obtained using simulations

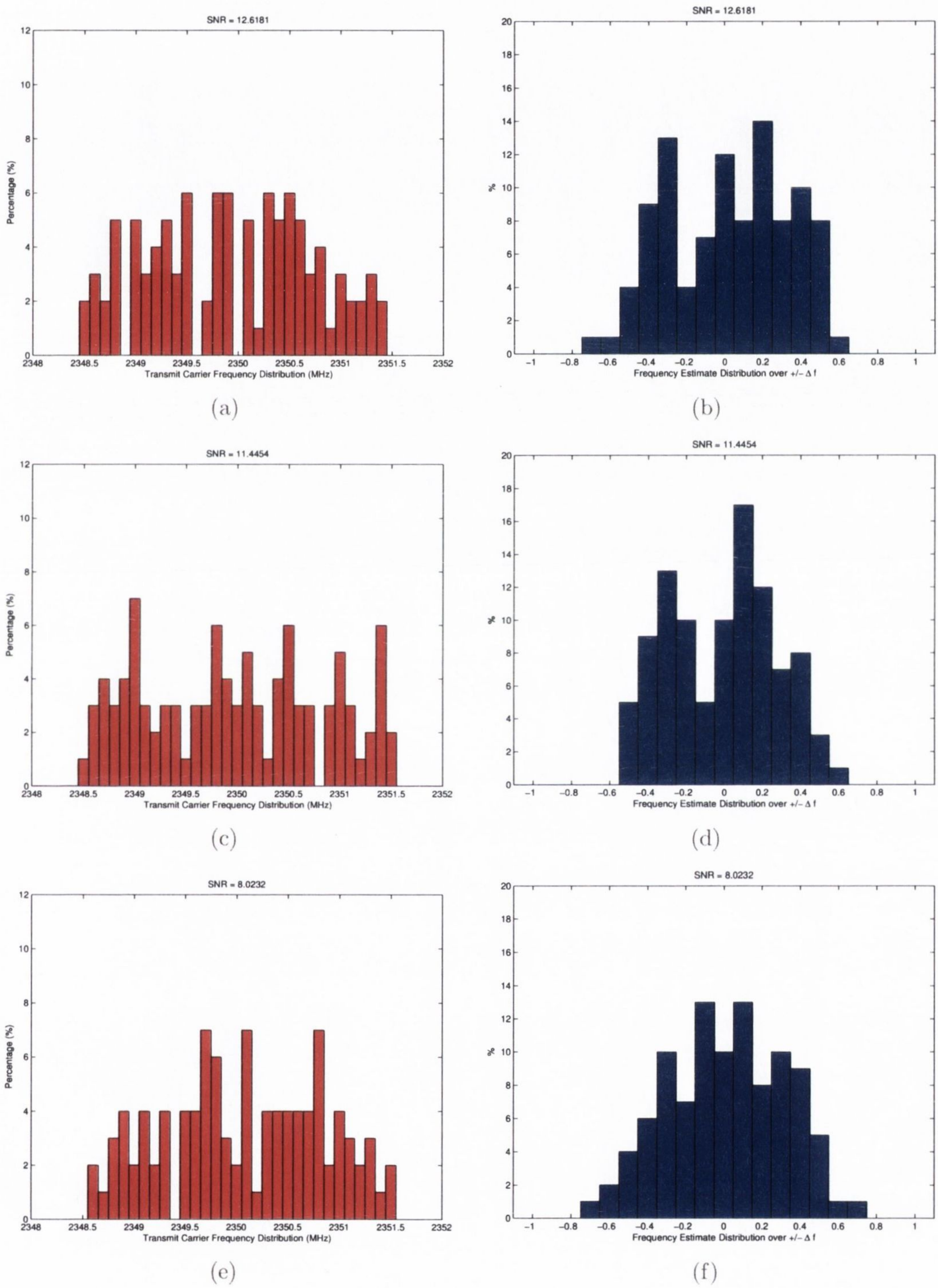


Fig. 8.15: Frequency acquisition performance I

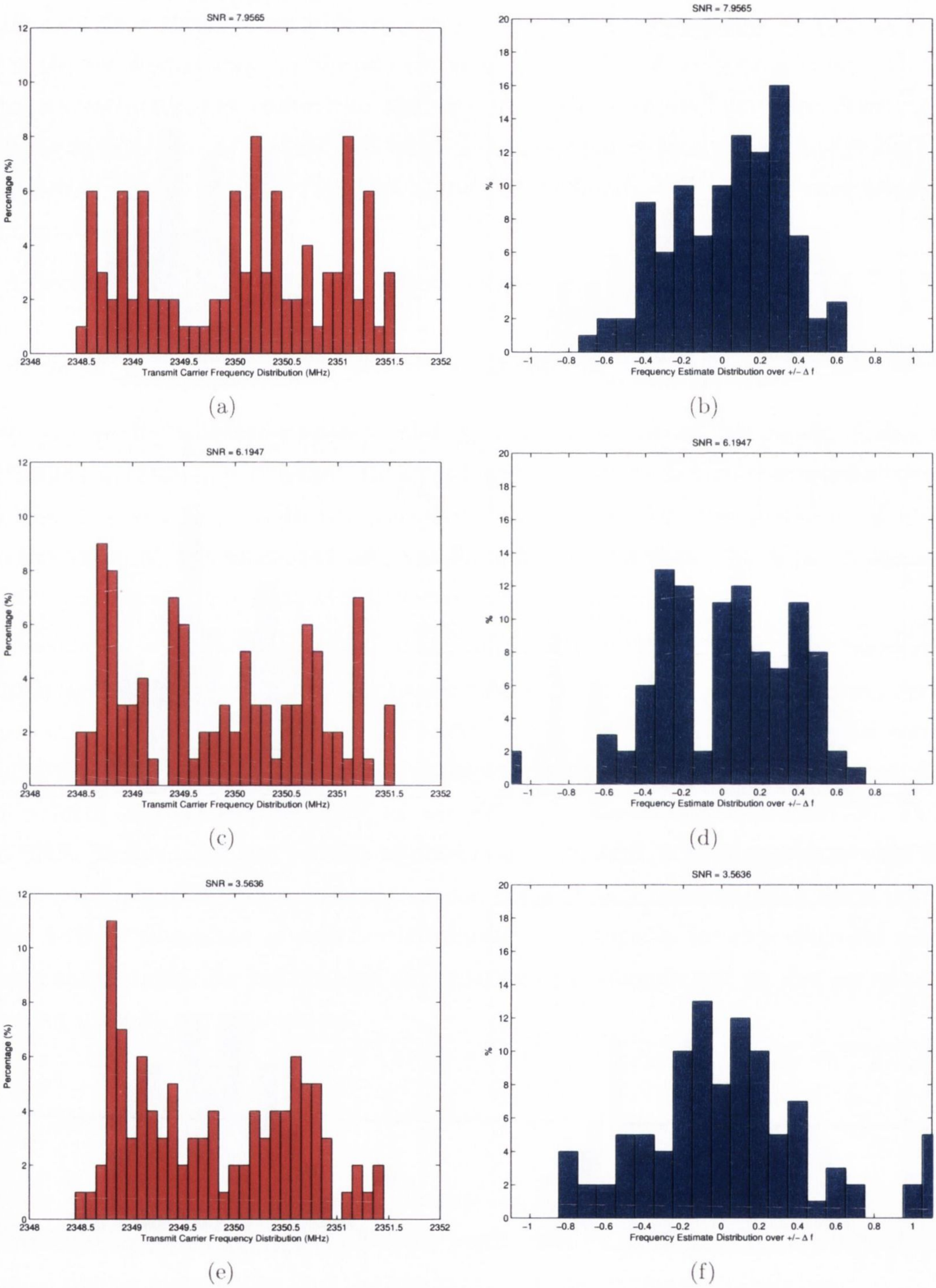


Fig. 8.16: Frequency acquisition performance II

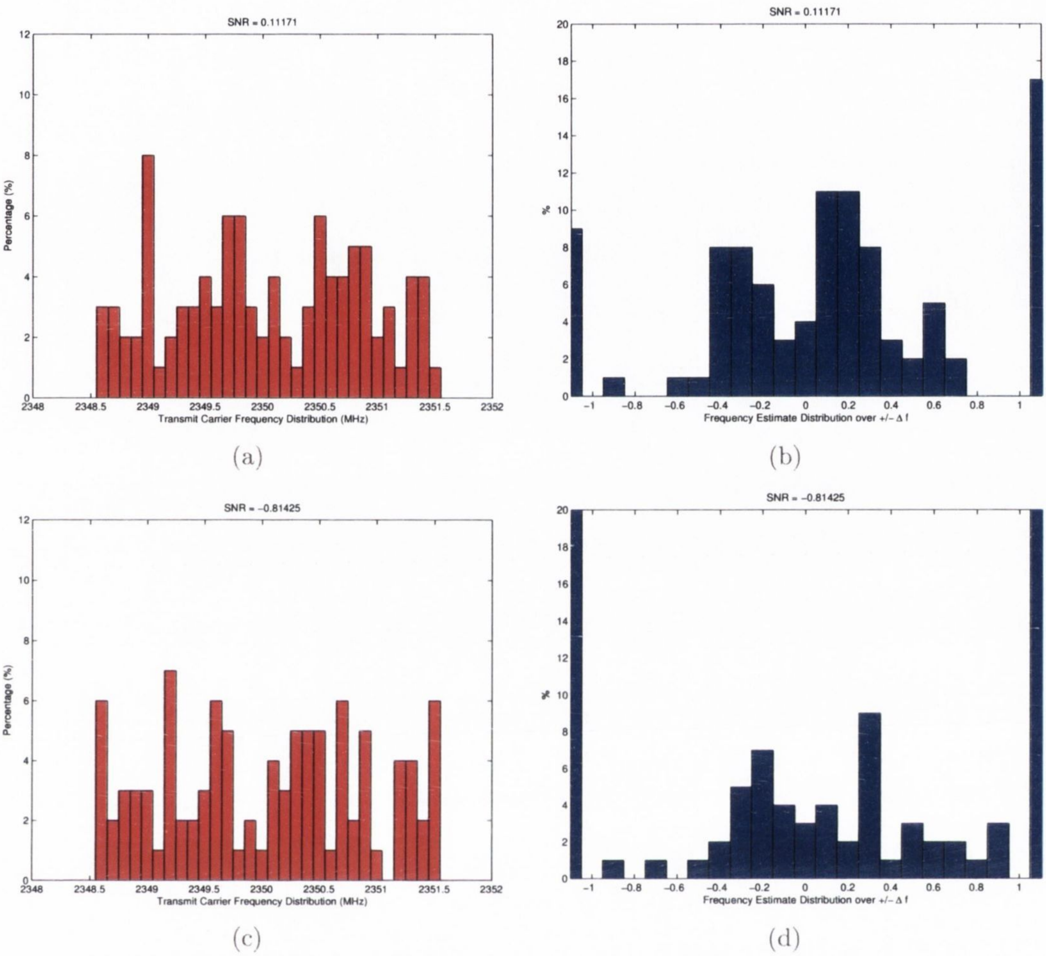


Fig. 8.17: Frequency acquisition performance III

in each instance. The key difference observed in each case is a small reduction in performance at low levels of receiver SNR due to the presence of real-world noise. As noted before, the presence of noise which is not completely white and uncorrelated causes a reduction in the accuracy of our spectral correlation estimates when compared with simulations. Having verified performance results in this way, I have proven the utility of cyclostationary signatures in overcoming the challenge of DySPAN rendezvous and coordination.

In the area of signal detection, it was shown that a single-feature signature generated using 3 mapped subcarriers may be used to achieve a detection rate of $\approx 98\%$ for an associated false alarm rate of $\approx 2\%$ using an observation time equivalent to just 16 OFDM symbol durations. This is less than half the minimum frame duration for an 802.16 WiMAX system employing a 3.5 MHz bandwidth and a $1/8$ cyclic prefix. Thus, in order to detect and use an embedded cyclostationary signature in such a system,

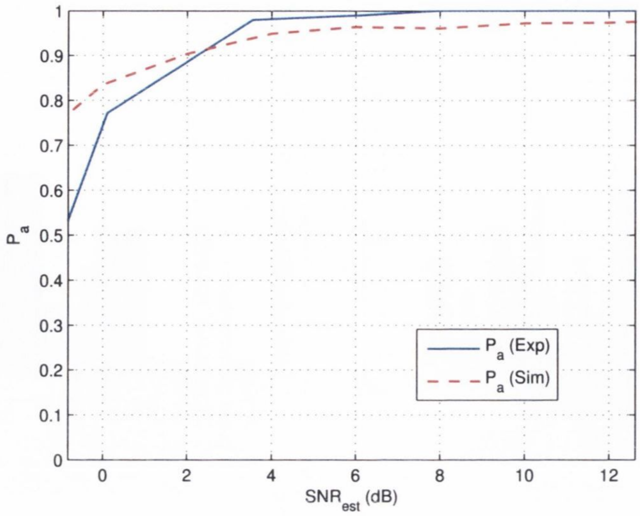


Fig. 8.18: Frequency acquisition performance using embedded cyclostationary signatures.

less than half a single frame must be captured and analyzed. Furthermore, it was shown that this required observation time may be decreased using a greater number of mapped subcarriers.

Cyclostationary signatures were also shown to provide a highly effective technique for achieving network identification. Using the minimum signature separation, it was shown that 4 unique signatures can be successfully identified at SNR levels above 3 dB with an observation time of just 20 symbol durations. Results showed that an identification rate of 100% was achieved over 250 tests for all SNR levels above 3 dB.

In the area of frequency acquisition, a critical requirement for DySPAN rendezvous, results showed that cyclostationary signatures may be used to reliably estimate the carrier frequency of a detected signal to within a single subcarrier spacing. At SNR levels above 3 dB, tests showed an accuracy rate of 95% or greater. A number of frequency synchronization approaches exist for OFDM-based systems where the acquisition range extends to a single subcarrier spacing [105]. Thus, by incorporating the use of cyclostationary signatures within a transceiver using such approaches, signal detection, identification and full synchronization can be achieved for DySPAN systems. Importantly, this was shown to be true in the case where the bandwidth sampled by the receiver is much greater than the bandwidth of the SOI itself. These findings show that cyclostationary signatures may be accurately used to achieve rapid network rendezvous where a wide-band signature detector is employed.

In carrying out experiments using the software-radio based transceiver, the key advantages of such a flexible implementation became apparent. Specifically, the ability to dynamically reconfigure the system during the course of operation greatly facilitated the automation of tests. The use of a component-based design made it possible to incorporate signal processing components which were tailored to the requirements of a specific task. One example of this is a signature detector component designed to permit the estimation of detection statistics at a range of observation times. While impractical for deployment in a real-world system, this component was very useful in the collection of test data.

9. CONCLUSIONS

9.1 Introduction

This dissertation has shown that intentionally embedded cyclic features or *cyclostationary signatures* are a highly effective tool for overcoming the challenge of rendezvous and coordination in emerging multi-carrier Dynamic Spectrum Access Networks (DySPANs). Through the use of computer simulations, transceiver prototype implementation and over-the-air experimentation, it has been shown that cyclostationary signatures provide excellent performance for signal detection, network identification and frequency acquisition. Furthermore, it has been shown that these signatures require low signalling overhead, low transmit and receive architecture complexity and short signal observation times yet form a robust and highly flexible tool for achieving a range of critical tasks in DySPANs.

This chapter draws conclusions from the dissertation and highlights a number of key developments which have taken place since the research began.

9.2 Summary of Contributions

This dissertation has shown that embedded cyclostationary signatures provide a highly flexible yet robust technique for overcoming the challenge of rendezvous and coordination in emerging multi-carrier Dynamic Spectrum Access Networks (DySPANs). The following section examines each of the contributions presented by the dissertation to substantiate this claim.

Emerging DySPAN Systems and the Challenge of Rendezvous and Coordination

The dissertation provides an overview of emerging DySPAN systems and the main driving forces behind them. In Chapter 2 specifically, the need for dynamic spectrum access was outlined in the context of the increasing value of radio-frequency spectrum and the usage inefficiencies which have arisen as a result of legacy spectrum management policies. The chapter examined the history of spectrum management and illustrated the key problems to which this history has given rise. A comprehensive overview was provided of the spectrum policy reform debate spanning the initial arguments of Herzel and Coase in the 1950s to the present day. In addition to examining these DySPAN drivers, the dissertation examined the synergistic combination of spectrum policy reform and technological advance which is creating opportunities for the development and deployment of these systems.

The complex issue of network rendezvous and coordination in these emerging DySPAN systems was also addressed. Although the potential benefits of dynamic spectrum access technology are significant, so too are the technical challenges. One well recognized issue is that of low-power signal detection for white-space identification. However, an equally significant challenge is that of rendezvous and coordination. While considerable research effort is currently being devoted to the low-power detection issue, there is far less emphasis on rendezvous and coordination.

In Chapter 3, solutions for network rendezvous in existing and emerging networks were examined and compared. The dissertation showed that these existing solutions rely heavily on prior knowledge of operating frequencies and channelization schemes. As DySPAN systems must operate without this prior knowledge, they cannot take advantage of the existing solutions and new mechanisms must be developed. Taking this approach, the dissertation illustrated the key requirements for a DySPAN rendezvous and coordination solution and showed the considerable challenge involved.

Cyclostationary Signatures: Enabling DySPAN Systems

The most significant contribution of this dissertation is the proposal of a solution to the challenge of rendezvous and coordination in multi-carrier DySPAN systems. The proposed solution involves the generation of intentionally embedded cyclostationary signatures in transmitted data-carrying waveforms. These signatures form a type of watermark which may be easily detected by receiving devices and used to perform network identification and frequency acquisition. In this way, cyclostationary signatures permit DySPAN devices to achieve rendezvous and coordination without prior knowledge of system operating frequencies or the need for a static channelization scheme.

The dissertation first outlined the advantages of cyclostationary signal analysis when applied to the challenge of DySPAN rendezvous and coordination. While this signal processing technique holds many key advantages, there are a number of significant drawbacks typically associated with its use. These drawbacks were identified and in Chapter 5, the use of subcarrier mapping to embed cyclostationary signatures was presented as an effective mechanism for overcoming these drawbacks. The dissertation outlined transmit and receive architectures for the generation, detection and analysis of cyclostationary signatures and showed how these can be incorporated in existing Orthogonal Frequency Division Multiplexing (OFDM)-based transceiver systems.

The use of these cyclostationary signatures was examined in the context of three key applications relating to network rendezvous and coordination. The applications addressed were signal detection, network identification and frequency acquisition. In Chapter 6, computer simulations were used to analyse the performance of systems employing embedded signatures in these areas and to examine the key trade-offs associated with their use.

In the area of signal detection, simulations were used to examine the trade-offs that exist between signature overhead and signal detection performance. In addition, the impact of signal observation time on detection performance was explored. These simulations showed that by using an overhead of just 3 mapped subcarriers, a signature may be embedded in a transmitted waveform and detected at signal-to-noise ratio (SNR) levels of greater than -5 dB. At an SNR of 5 dB, it was shown that an observation time of just 16 OFDM symbol durations is required to achieve a detection rate of 99% for an associated false alarm rate of 1% when a 3-carrier signature is employed. Detection of embedded cyclostationary signatures under frequency-selective fading conditions was also addressed. The use of a robust multi-feature signature was proposed in order to provide frequency diversity. Using these robust signatures, it was shown that excellent detection performance can be achieved for a wide range of multipath channel models.

A key advantage of cyclostationary signatures embedded using subcarrier set mapping is the ability to create unique signatures and use these to perform waveform and thus network identification. The dissertation examined the use of signatures in this way and showed that, using cylic frequency as an identifier, the number of unique single-feature signatures which may be embedded in an OFDM-based waveform is equal to $N - 2M + 1$ where N is the total number of subcarriers used in the waveform and M is the size of the mapped set. Using the minimum signature separation, computer simulations were used to show that an identification rate of 95% can be achieved for 4 unique signatures at an SNR of 5 dB and under frequency-selective fading conditions using an observation time of 30 OFDM symbol durations.

The third key application identified in the dissertation for embedded cyclostationary signatures was that of frequency acquisition. It was shown that upon detection of a signal containing an embedded cyclostationary signature, a receiving device may use that signature to estimate the carrier frequency of the signal. Computer simulations were used to show that under frequency-selective fading conditions, an embedded signature may be used to perform carrier frequency estimation to within a single subcarrier spacing. At SNR levels at or above 5 dB, these simulations showed that an accuracy level of at least 95% can be achieved.

By developing the novel concept of an embedded cyclostationary signature for multi-carrier waveforms and illustrating its use in a range of applications, the dissertation demonstrated the strength of this approach when employed to overcome the challenge of network rendezvous and coordination in emerging DySPAN systems.

Transceiver Prototype Development

Computer simulations were used in the dissertation to illustrate the power of cyclostationary signatures when employed in DySPAN systems. However, the third key contribution of this dissertation showed the practical utility of this approach by describing the implementation of an OFDM based transceiver prototype using embedded cyclostationary signatures for rendezvous and coordination.

Chapter 7 outlined a highly flexible general purpose processor (GPP)-based platform for DySPAN experimentation developed at the Emerging Networks strand of Centre for Telecommunications Value-Chain Research (CTVR) based at the University of Dublin, Trinity College. The dissertation described the implementation of a prototype DySPAN transceiver using this platform, highlighting the key design decisions which were made and outlining the reasons behind those decisions. In this way, the dissertation provides an insight into the key challenges associated with the use of cyclostationary signatures in real-world systems. In addition, variations of the main transceiver design were discussed. These variations illustrate the manner in which signatures can be used to achieve different goals when employed under different operating conditions.

In describing the implementation of a prototype transceiver, the dissertation highlighted the importance of a component-based design in managing system complexity through encapsulation and abstraction. Furthermore, the benefit of a highly reconfigurable platform architecture was clearly shown in the context of system testing and design variations.

Experimental Transceiver Analysis

The fourth contribution of the dissertation involved the presentation of experimental results obtained using real-world signals transmitted over the air and received by our transceiver prototypes. Computer simulations serve to provide a number of key insights into the use of cyclostationary signatures for DySPAN rendezvous and coordination and to illustrate the main trade-offs involved in their use. However simulations attempt to model real-world operating conditions and so can only provide an approximation to real-world performance. By describing experiments using a prototype transceiver and presenting results, the dissertation examined the performance of cyclostationary signatures embedded in over-the-air OFDM-based waveforms and showed that this approach provides a practical solution for real-world DySPAN systems.

Chapter 8 outlined experiments used to assess the performance of cyclostationary signatures when employed for signal detection, network identification and frequency acquisition. By mirroring a number of the tests carried out using simulations, these experiments permitted comparisons to be drawn between performance achieved using modelled signals and results obtained under real-world conditions.

In each application it was shown that experimental results closely matched those obtained through simulation. When employed for signal detection, a 3-carrier signature was found to provide a detection rate of 98% for an associated false alarm rate of 2% using an observation time of 16 OFDM symbol durations at an SNR of approximately 5 dB. In the area of network identification, signatures were shown to permit identification of four unique signatures with an accuracy rate of 100% at or above 3 dB using an observation time of 30 symbol durations. In this case, experimental performance exceeded that obtained using simulations due to the frequency-selective fading models employed in those simulations. When used to achieve frequency acquisition, it was shown that signatures embedded in over-the-air signals permitted receiving devices to estimate the carrier frequency of those signals to within a single subcarrier spacing with 95% accuracy at 3 dB SNR when an observation time of 30 symbol durations was used.

9.3 Future Work

In developing the concept of intentionally embedded cyclostationary signatures for multi-carrier DySPAN systems, this dissertation highlighted a number of further areas in which this approach may be used and in which future work may be carried out. This section addresses each of these areas in turn.

Enabling Increased Flexibility in DySPAN Systems

This dissertation focused primarily upon the introduction of operating frequency flexibility in emerging DySPAN systems and the challenge of rendezvous and coordination which this entails. By developing the novel concept of cyclostationary signatures for OFDM-based systems, it was shown that this form of flexibility may be incorporated in practical systems while supporting the robust establishment and maintenance of communications links between devices. Cyclostationary signatures make this possible by permitting a form of physical layer signalling to be achieved between heterogeneous devices. Using this concept of physical layer signalling, it may be possible to support further flexibility in these systems.

One area in which such flexibility would be valuable is signal bandwidth. While the spectrum sculpting capabilities of reconfigurable OFDM-based systems are widely recognized, little research has been devoted to the issues of rendezvous and coordination in such systems. Operating frequency flexibility permits a DySPAN system to transmit a waveform using idle white space spectrum. However, signal bandwidth flexibility would permit that system to dynamically tailor the bandwidth of that waveform to the properties of that white space spectrum. In addition, by supporting bandwidth flexibility a DySPAN system can optimize spectrum use efficiency by only using that bandwidth which is required for communication at a given time and place. In this way, remaining bandwidth may be occupied by other systems.

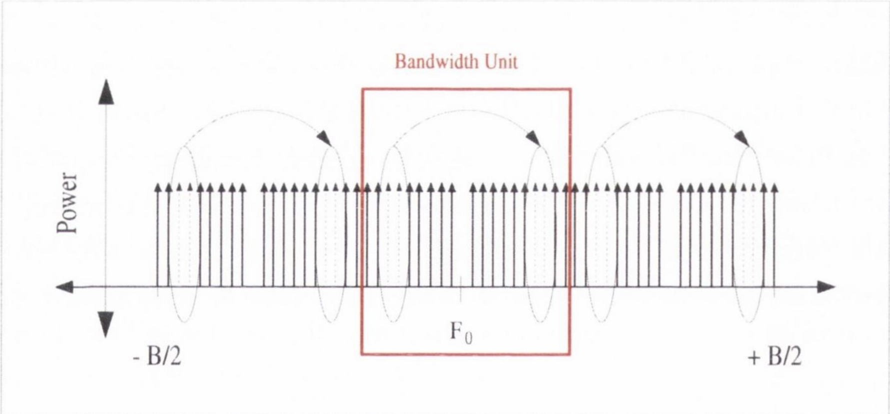


Fig. 9.1: Generation of a signal using multiple units, each containing an independent cyclostationary signature.

One possible approach for supporting bandwidth flexibility in DySPAN systems would be to define a minimum unit of bandwidth to be used by devices within the system. Transmitted signals would comprise one or more of these bandwidth units in a similar manner to the channel bonding approach proposed for the Institute of Electrical and Electronics Engineers (IEEE) 802.22 standard described in section 3.2.3. However, while the centre frequencies of IEEE 802.22 channels are typically fixed, the use of physical layer signalling would permit flexible bandwidth signals to be transmitted at any operating frequencies. Where each bandwidth unit comprising a transmitted signal contains an embedded signature, those signatures could be independently detected by a receiving device and used to estimate the overall signal bandwidth and carrier frequency. In this way, control information could be obtained and a communications link could be established. Fig. 9.1 illustrates this approach and shows how a signal can be generated from a number of bandwidth units, each with an embedded cyclostationary signature.

A second area in which waveform flexibility would prove useful is in the subcarrier spacing adopted in OFDM-based systems. In defining the subcarrier spacing to be employed in an OFDM-based system, the designer of that system makes an important trade-off between inter-symbol interference (ISI) and inter-carrier interference (ICI) robustness. A small subcarrier spacing results in a large number of subcarriers and hence a long symbol duration. With this long symbol duration, a longer cyclic prefix may be used for a given degree of overhead, providing increased robustness to ISI. However, a large subcarrier spacing increases the distance between adjacent carriers, reducing the effect of ICI. It may be possible to use embedded cyclostationary signatures to determine the subcarrier spacing used in a given waveform. In this way, physical layer signalling could be used to support subcarrier spacing flexibility in OFDM-based systems. Thus, those systems would no longer be optimized for fixed expected levels of ISI and ICI but could dynamically optimize the waveform used according to the channel conditions experienced at a given time and place.

Alternative Detector Designs for Cyclostationary Signatures

This dissertation proposes the use of a signature detector designed primarily using a time-smoothing approach to cyclic feature detection. As discussed in Chapter 5, this approach permits the processing requirements of signature detection to be evenly distributed over time and allows the use of a short fast Fourier transform (FFT). However, one limitation of this approach is the need for prior knowledge of the overall OFDM symbol duration used by the transmitter. As discussed in Chapter 4, in order to preserve the cyclostationarity of a signal when performing time-smoothing, averaging windows of signal samples must be symbol synchronous. In order to ensure that symbol transitions are synchronized between averaging windows, the OFDM symbol duration must be known and the averaging window size must be an integer multiple of that duration.

One approach which can be used to overcome this need for prior knowledge of the symbol duration involves the use of a detector design based on the use of frequency-smoothing. Such a design would involve the buffering of a large number of received signal samples followed by the use of a very large FFT and subsequent smoothing. In this way, a bursty processing profile is required however time-averaging windows are not used and the issue of symbol synchronization does not arise.

Alternate Uses of Cyclostationary Signatures

The focus of this dissertation has been upon the issue of network rendezvous and coordination in emerging DySPAN systems. Embedded cyclostationary signatures have been shown to be a practical and effective tool for overcoming this challenge. However, it may be possible to employ cyclostationary signatures in addressing a second challenge typically associated with DySPAN systems: that of low-power primary signal detection.

In order to share a spectrum band with a high-priority primary user without causing harmful interference, a DySPAN device must be capable of reliably detecting the transmissions of that primary user. It has been shown that cyclostationary signal analysis may be used to achieve improved detection performance over equivalent radiometric approaches at low signal power levels [68]. However in order to realize these advantages, the signal of interest must contain cyclic features which can be identified and used for detection.

One approach for facilitating low-power detection of primary transmissions would be to embed a cyclostationary signature in those transmissions which could be leveraged in a receiver to perform detection. In this way, the high-priority primary user could aid a secondary DySPAN system and reduce the possibility of harmful interference. Ideally, dynamic spectrum access by a secondary user should not require any aspect of the primary system to be changed. Thus, this approach may not be possible for currently deployed wireless systems. However, it could be incorporated in future systems which are granted high-priority spectrum access in a shared band.

In examining the use of cyclostationary signatures for DySPAN rendezvous and coordination, transmit and receive architectures were optimized to reduce overhead, required observation time and computational complexity. However, in order to examine the use of signatures for low-power signal detection, these designs must be revisited with the goal of optimizing detection performance. For example, a greater level of signalling overhead may be acceptable to embed a high-powered signature in the transmitter while in the receiver a much longer signal observation time might be considered.

Cyclostationary Signature Use on Alternative Platforms

One of the key contributions of this dissertation is the description of a prototype transceiver using cyclostationary signatures implemented upon a GPP-based software radio platform. An area for possible future work would be to extend this implementation to a number of alternative platforms.

By implementing a transceiver using cyclostationary signatures upon a field programmable gate array (FPGA)-based platform, some of the dynamic reconfiguration advantages of the GPP-based implementation may be lost. However significant improvements in performance could be gained. These improvements could be leveraged, for example, to permit rapid analysis of wide frequency bands for signature-containing signals. Alternatively, an FPGA-based platform could be employed to perform full cyclic frequency analysis of a signal of interest for embedded signatures.

Retaining the flexibility of a GPP-based platform, advanced processor architectures could be employed to achieve the performance typically associated with FPGA-based platform. One such system is the Cell broadband engine [115] developed jointly by IBM, Toshiba and Sony and currently used in the Playstation 3 games console. The Cell architecture combines a power processor core with eight 'synergistic processing elements' which are used for parallel data processing. These processors are connected by a high-speed bus, permitting very large amounts of data to be passed rapidly between them. By employing the Cell architecture and implementing highly parallelized algorithms for the generation, detection and analysis of cyclostationary signatures, it may be possible to realize a highly reconfigurable system for general cyclostationary signal analysis as well as cyclostationary signature detection.

9.4 Conclusion

Since work on this dissertation began, some significant developments have taken place in the areas of spectrum regulation and DySPAN technology. Together, these changes are bringing dynamic spectrum access closer to a reality.

In the area of spectrum policy there have been important advances in a number of countries including the UK and the US. Specifically, the coming switch from analog to digital broadcast television in these countries promises to make significant swathes of highly-valued spectrum available for reallocation and reassignment. Termed *the digital dividend*, these spectrum bands provide an attractive trade-off between signal propagation and capacity and would be highly suited to systems providing broadband data connectivity. Recognizing the benefits of emerging dynamic spectrum access technology, a number of regulators have taken steps to examine the use of DySPAN systems in these bands.

In the UK, the Office of Communications (Ofcom) has identified two categories of spectrum which will be available for reallocation following the digital switch-over [117]. It has termed these categories *cleared* and *interleaved* spectrum. Cleared spectrum becomes available due to the increased efficiency of digital broadcast technology. As less bandwidth is required to support broadcast television services using digital technology, the additional spectrum currently used for analog services will become available following the switch-over and can be reallocated on a countrywide basis. Interleaved spectrum, on the other hand, becomes available within the spectrum bands to be allocated to digital television broadcasters. Although thirty two 8 MHz channels will be allocated for digital television, only six of these will be used for the preferred service in any one location. As a result of this multiplexing scheme, a number of idle channels may be available for use at any time in that location. While Ofcom has chosen to allocate *cleared* spectrum using auction mechanisms, it has proposed to allow license-exempt use of *interleaved* spectrum by DySPAN systems capable of detecting idle channels and using them while reliably avoiding the creation of harmful interference.

Similarly, in the US, the analog-digital switch-over scheduled for February 2009 will result in a dividend of both cleared and interleaved spectrum. Cleared spectrum bands covering 108 MHz of spectrum are currently being allocated in auctions expected to raise over $20bn. However, proposed use of interleaved or *white space* spectrum has been subject to intense lobbying over the past number of years. Use of interleaved spectrum by DySPAN systems is strongly advocated by the Wireless Innovation Alliance with partners including Dell, Google and Microsoft [118]. On the other hand, serious concerns about potential interference with broadcast services have been raised by the incumbent broadcasters. In order to examine the capability of DySPAN systems to reliably detect digital television broadcasts and avoid the creation of interference, the Federal Communications Commission (FCC) began testing white space DySPAN devices in August 2007 [119]. Depending upon results of these tests, unlicensed use of interleaved spectrum by DySPAN systems may be permitted.

Also in the US, in February 2008, the FCC announced the designation of a testbed for spectrum sharing innovation. Intended to provide a venue for demonstrating techniques for sharing spectrum between federal and non-federal users, the testbed comprises 10 MHz of spectrum in the 470-512 MHz band. Researchers can apply to use the testbed and will follow a three-phase program to test and evaluate DySPAN systems and techniques.

Each of these regulatory steps is significant in encouraging and promoting DySPAN research and development. At the same time, considerable technological advances in the area of dynamic spectrum access are also being made. In Dublin in April 2007, the second IEEE international symposium on New Frontiers in Dynamic Spectrum Access Networks took place. A major focus of this event were the demonstration sessions where both academic and industrial researchers displayed devices and systems capable of DySPAN operation. These included contributions from Motorola, Shared Spectrum Company and Qinetiq as well as the CTVR Emerging Networks research group based at University of Dublin, Trinity College, the University of Kansas and Virginia Tech University. In addition to their demonstrations in Dublin, the Shared Spectrum Company carried out extensive tests of their spectrum sharing equipment in Fort Hill A.P. in Virginia, showing the ability to identify unused spectrum and use it to form and maintain a network while efficiently using spectrum and avoiding the creation of harmful interference [120].

As changes in regulatory policy are creating opportunities for the development and deployment of DySPAN systems, technical advances are beginning to address many of the challenges associated with these systems.

This dissertation represents a significant step towards the realization of practical Dynamic Spectrum Access Networks (DySPANs). The issue of network rendezvous and coordination has been highlighted as a key technical challenge associated with the development of highly reconfigurable networking systems and the novel use of embedded *cyclostationary signatures* has been proposed as a powerful and flexible tool for overcoming this challenge. In making this proposal, the research has developed a firm foundation upon which to advance the future development of highly reconfigurable, robust wireless networks.

ACRONYMS

ACA	Australian Communications Authority
ACI	adjacent channel interference
ADC	analog to digital converter
AF	autocoherence function
AGC	adaptive gain control
AM	amplitude modulation
API	application programming interface
ARFCN	absolute radio frequency channel numbers
ASIC	application-specific integrated circuit
AWGN	additive white Gaussian noise
BCH	broadcast channel
BPSK	binary phase shift keying
CAF	cyclic autocorrelation function
CCP	cyclic cross periodogram
ComReg	Commission for Communications Regulation
CTVR	Centre for Telecommunications Value-Chain Research
DAC	digital to analog converter
DC	direct current
DDC	digital downconverter
DUC	digital upconverter
DySPAN	Dynamic Spectrum Access Network
DSP	digital signal processor

FCC	Federal Communications Commission
FCH	frame control header
FDD	frequency-division duplexing
FEP	front-end processor
FFT	fast Fourier transform
FM	frequency modulation
FPGA	field programmable gate array
FRC	Federal Radio Commission
FS-CCP	frequency-smoothed cyclic cross periodogram
GDP	gross domestic product
GPP	general purpose processor
GSM	Global System for Mobile
I-Q	in-phase - quadrature
ICI	inter-carrier interference
IDE	integrated development environment
IEEE	Institute of Electrical and Electronics Engineers
IFFT	inverse fast Fourier transform
IID	independent and identically distributed
IO	input/output
IR	infra-red
IRIS	Implementing Radio In Software
ISI	inter-symbol interference
ISM	Industrial, Scientific and Medical
ITU	International Telecommunication Union
MAC	medium access control
MIT	Massachusetts Institute of Technology
NLOS	non line-of-sight
Ofcom	Office of Communications

OFDM	Orthogonal Frequency Division Multiplexing
PAPR	peak-to-average power ratio
PC	personal computer
PCS	personal communications service
PN	pseudo-noise
PPE	power processing element
PSD	power spectral density
PSK	phase shift keyed
QAM	quadrature amplitude modulation
QPSK	quadrature phase shift keying
RC	rendezvous channel
RF	radio frequency
ROC	receiver operating characteristic
SCF	spectrum correlation function
SCH	superframe control header
SDR	software-defined radio
SNR	signal-to-noise ratio
SOI	signal of interest
SPE	synergistic processing element
SPTF	Spectrum Policy Task Force
TDD	time-division duplexing
TDMA	Time Division Multiple Access
TS	timeslot
TS-CCP	time-smoothed cyclic cross periodogram
UN	United Nations
USRP	Univeral Software Radio Peripheral
UWB	ultra-wide band
WiMAX	Worldwide Interoperability for Microwave Access

WLAN	wireless local area network
XML	eXtensible Markup Language

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