ESSAYS ON OPTIMAL SPECTRUM MANAGEMENT FOR EXPANDING WIRELESS COMMUNICATIONS

by

LEO FULVIO MINERVINI

A thesis submitted in partial fulfilment of the requirements for the degree of

Doctor of Philosophy

University of Warwick, Warwick Business School

December 2010

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Acknowledgements

This thesis is the outcome of a long journey, which took me to many places, both physically and intellectually. I am grateful to many persons whom I met during this journey. Without their help, trust and encouragement, I would never have been able to reach this milestone.

My deepest praise and most sincere gratitude go to Prof. Martin Cave. His guidance, mentorship and support have been invaluable, even after he left WBS. I am indebted to Prof. Paul Stoneman, who offered his help and advice during the final stages of this thesis. His insightful comments are gratefully acknowledged. I also would like to thank panel members at my completion reviews for their comments: Dr. David Finnegan, Prof. Qing Wang and Dr. Nick Webber, as well as Dr. Chris Doyle and Dr. Xavier Lemaire from the Centre for Management under Regulation.

I am also grateful for useful discussions with Dr. Roberto Ercole, Dr. Mauro Martino, Dr. Anil Shukla, and a number of participants at academic conferences and research projects, where I was privileged to present my thoughts and papers. This work would have been much harder without their interactions.

Special thanks go to Dr. Jonathan Cave, Dr. David Cleevely and Dr. Arturas Medeisis for their time and constructive feedbacks on different parts of this work.

I would also like to thank my colleagues, classmates and friends. Special thanks go to Barbara, Luca, and Mark for their constant support and encouragement.

I wish to express my gratitude to Prof. Diego Piacentino for his `nudge` at the very beginning of this journey, as well as for his support and challenges to my own thinking on many occasions during these years.

Last, but not least, my family deserves special mention. I acknowledge with deep gratitude their love, support, patience and understanding.

Declaration

To the best of my knowledge, all the work in this thesis is original. No part of this thesis has been submitted for a degree at another university. All work is entirely my own. None of this thesis has been previously published anywhere.

Summary

Wireless communications are experiencing an unprecedented expansion. The increasing mobility of the communication society and the pace of technological change are growing pressure for more spectrum to support more users, more uses and more capacity. Thus, spectrum management has become an extremely important part of wireless communications. A few regulators are changing their traditional 'command and control' approach. Nevertheless, many features of optimal spectrum management are still widely discussed. This work is aimed at contributing to that discussion.

The key insight is that spectrum management can benefit from more liberal spectrum sharing. This work set out to answer three main research questions: (i) whether there is a theoretical framework which can be used to analyze and guide spectrum policy reform, when moving from a traditional 'command and control' regime to a market-inspired one; (ii) whether it is possible to design a plausible mechanism which can promote efficient allocation and assignment of spectrum commons; (iii) whether (and how) technological developments could enable band sharing methods outside the traditional management framework and without harmful interference.

The literature on transition economics and policy was used to help answer the first research question. Evidence from liberalizing countries was positively analyzed to discuss reforms of spectrum allocation and assignment methods. Most countries have adopted strategies that gradually change their spectrum policies and started by using more liberal methods to assign spectrum. It is also argued that future spectrum reforms might benefit from insights presented in the transition economics literature.

A translation of a model on cartel quotas under majority rule is proposed to answer the second research question. The work verifies, firstly, that an analogous set of properties is satisfied under our assumptions and that the median-index theorem applies, mutatis mutandis, to our setting. Thus firms bidding to acquire spectrum commons contribute a minimum amount of their wealth; the sum of contributions offered is then compared to other bids for the same spectrum, which is allocated to the highest bidder.

The last research question considers novel ways of spectrum sharing that might be enabled by technological developments. The work explores contributions, from various research areas, regarding management of scarce resources. Those contributions are discussed with respect to shared spectrum access. It is suggested that spectrum management might benefit from methods which enable the management of pooled (intermittent) demands for access, especially methods in line with fair sojourn protocols.

Chapter 1. Spectrum management: an introduction

1.1.- Radio spectrum for wireless communications: debate and issues

Radio spectrum[1] (henceforth, spectrum) is a vital input into an ever widening range of uses (see, e.g., Richards *et Al*. 2006; Cave *et Al*. 2007a; Hazlett 2008; Ofcom 2010a). Technological developments in electronic communications systems, coupled with individuals' desires to communicate with each other and have timely access to information, wherever they are, have brought an increase in demand for wireless communications and, consequently, in derived demand for spectrum (see, e.g., Benkler 2002; Cave 2002; Hazlett 2003; Webb 2007). However, spectrum can accommodate only a limited number of simultaneous users (see, e.g., Hatfield 2003; ITU 2006a). Therefore, it is crucial to develop appropriate technical, economic and regulatory

[1] Radio spectrum depicts that part of the electromagnetic spectrum used to transmit voice, video and data; it uses frequencies from 3 kHz to 300 GHz and is segmented into bands of infinitely re-usable frequencies (see, e.g., ITU 2000; Hatfield 2003: 1-2; Ofcom 2004: 8).

solutions to avoid artificial spectrum scarcity,[2] while keeping safeguards against harmful interference (ITU 2001a, 2005a).

Optimal spectrum management depends on mechanisms and incentives in place to promote efficiency in its allocation to different uses. Spectrum regulators have played a pervasive role for decades, especially by deciding the allocation of scarce spectrum resources to a variety of commercial and public services, such as radio and television broadcasting, private and commercial radio services, defence and public safety. In fact, until the late 1990s, the dominant approach to spectrum regulation has been based on 'command and control', with spectrum use determined almost entirely by regulatory fiat and enshrined in administrative licences.[3] This has resulted in a rigid spectrum management framework (see, e.g., FCC 2002a; Ofcom 2004; Chaduc and Pogorel 2008).

The debate on the limitations of this framework has a relatively long history indeed.[4] As early as 1959, Ronald Coase proposed, in his critique of the administrative approach, a market allocation of radio spectrum rights

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[2] See, e.g., Akyildiz *et Al*. (2008), Benjamin (2003), Benkler (1998), Cave *et Al*. (2007a), Coase (1959), Hazlett (2001), Levin (1966), Noam (1995) among academic contributions; FCC (2002a), ITU (2001a) and Ofcom (2004) among papers delivered by regulators; and Vodafone (2006) for perspectives from a wireless industry operator.

[3] Licences confer the right to transmit at a specific frequency to a licence holder exclusive of others, with the expectation that license holders will be able to transmit their signals without any harmful interference, as licences also set power limits, temporal and spatial boundaries, *etc*. (see the literature cited above, esp. ITU recommendations).

[4] For instance, the *Journal of Law and Economics* devoted a special issue to spectrum management problems in 1998 (vol. 41, no. 2).

(Coase 1959). Then the US regulators asked if that was "a big joke" (Hazlett 2001). The thesis that spectrum management needs more flexibility (to accommodate technological developments and new demands) has gained widespread currency recently and has been at the heart of the so called "property rights vs commons" debate (see, e.g., Faulhaber and Farber 2003; Baumol and Robyn 2006; Hazlett 2006, 2008a). This has led to some strong calls from industry experts and leading academics for a radical overhaul of traditional methods of spectrum management, through the use of market-based (or market-inspired) solutions.[5]

Some regulators (e.g., Ofcom in the UK, FCC in the US and ACMA in Australia) have taken bold steps towards a more liberal spectrum management regime. Nevertheless, many features of future spectrum management are still greatly discussed.

This work is aimed at contributing to that discussion; in particular, it set out to answer three main research questions:

(i) is there a theoretical framework which can be used to analyze and guide spectrum policy reform when moving spectrum management from a traditional 'command and control' regime to a market-inspired one? National and international regulators very often seem to have managed spectrum in response to contingent pressures and this has resulted in a

[5] See the literature cited above, esp. Faulhaber and Farber 2003; Baumol and Robyn 2006; Hazlett 2006, 2008a; see also Vodafone 2006 and Wik Consult 2005, 2008.

piecemeal approach to spectrum management (sometimes even in liberalizing countries); optimal spectrum management could be promoted by a more clear-cut strategy to its liberalization;

(ii) is it possible to design a plausible mechanism which can promote efficient allocation and assignment of (shared) spectrum commons? Some spectrum bandwidth for (shared) unlicensed use has been traditionally offered by regulators, but usually without safeguards against harmful interference, and without use of market-based mechanisms to determine the value of allocated frequencies. New technologies and demands are bringing about increasing interest for collective use of bandwidth (with no harmful interference); optimal spectrum management includes consideration for the problem of efficient expansion of spectrum commons;

(iii) what methods can be used to share spectrum with no harmful interference (or even `spectrum tragedies`; Hazlett 2005) by new spectrum-using technologies, which are challenging the traditional 'command and control' framework? In general, the traditional approach has divided spectrum along three fundamental dimensions, i.e. frequency, time and space; however, new technologies promise to enable spectrum use in various ways, which differ widely from traditional ones in some cases. Recognition that spectrum is a shared input, which can be used collectively, suggests

need to explore management methods (perhaps already implemented in similar circumstances) that could improve spectrum use.

1.1.1.- Outline of this work

The key insight is that spectrum management can benefit from more liberal spectrum sharing. After the short introduction to the current discussion about optimal spectrum management and main research questions addressed here, this chapter looks, firstly, at the role of spectrum in the value chain and shows that spectrum can be used as an input for a wide range of services and applications. Next, this chapter reviews the key tools for spectrum management - i.e. spectrum allocation, assignment and interference management – and discusses changes, suggested by market-inspired approaches, to the traditional spectrum management regime. Finally, it presents a brief overview of new technologies, including those in their early stages of development, and discusses some of the implications for spectrum management.

Chapter 2 carries on the review and the discussion begun in the introduction, with a closer look at specific themes of market-inspired spectrum regimes. It considers in more detail a number of ingredients of optimal spectrum management promoted by regulators who are changing their spectrum framework from 'command and control' to a more liberal one.

The chapter reviews the literature on spectrum auctions, secondary trading and liberalization of spectrum uses. It then discusses the issue of "unlicensed" spectrum[6] and public sector use of spectrum. The chapter sets out to provide key information on recent developments towards a more market-inspired spectrum management regime and a map to locate the analyses that will be developed in the three core chapters, which follow the methodological presentation for this research (Chapter 3).

Chapter 4 analyzes strategies and tactics of spectrum management reform. It proposes the use of models from the literature on the economics of transition from planned economies to market economies (see Dewatripont and Roland 1995) as a theoretical framework for the case of spectrum liberalization. The chapter presents spectrum reforms in a number of countries and uses them as case studies. The chapter discusses the empirical finding that reforms have proceeded along paths which differ from those suggested by arguably relevant theory; it also discusses hurdles to the implementation of a few market-inspired mechanisms for spectrum management (with technological innovation playing a relevant role) and how spectrum reforms might best be managed.

[6] This is also known as licence-exempt spectrum (esp. in the UK), or class licensed spectrum (esp. in Australia). Some commentators refer to such arrangement as spectrum commons. Here unlicensed spectrum is used to refer to spectrum whose users do not hold an administrative licence for exclusive access.

Chapter 5 then addresses a more specific topic, namely the problem of collecting funds by a few commercial spectrum operators who are willing to negotiate access and use together some bandwidth in a shared manner. A number of innovative technologies offer new opportunities to exploit spectrum resources collectively, with limited (and often tractable) interference problems. Starting from a study on cartel quotas (see Cave and Salant 1995), a majority vote solution is proposed to allocate spectrum for collective use and to assign it via auctions.

Chapter 6 investigates those instances where some bandwidth is shared among a few operators, including the public sector, using various (novel) technologies and network architectures. In those circumstances, it is crucial to have mechanisms which can deal with possibly large and heterogeneous demands of spectrum access, in order to avoid congestion and interference. A number of management arrangements and their implications are proposed and discussed.

Chapter 7 concludes and proposes some possible avenues for further research.

1.2.- Spectrum in the value chain

Spectrum is an input for the provision of an increasing number of radio frequency services. Before the advent of radio broadcasting at the beginning of the 20th century, spectrum was used mainly by point-to-point applications (such as fixed services) that enjoyed open access to the ether. Today spectrum is used to provide a wide range of wireless services; a look at any national table of frequency allocations can illustrate how regulation of spectrum access has accommodated a great number of spectrum uses, especially in frequency bands between 300 MHz and 3.5 GHz.[7]

In the early days of broadcasters' services – radio services first and, then, also TV broadcast services - access to spectral resources was heavily disciplined by regulatory authorities (Hazlett 1998). The goal of spectrum regulation should be the same as that of other economic regulation, namely to advance the long-term interests of end-users. Most observers agree that this is best achieved by competition, but the nature of competition in the value chain can be very varied, and there may be uses for which competition is not feasible or desirable, such as military use, radio-astronomy and emergency services use (Cave 2006; Wik Consult 2008; EC 2009).

[7] For European countries, cf. data available at www.ero.dk .

Figure 1 shows a typical vertical structure of production of wireless broadcasting and communications (to the extent that a distinction between them can be maintained).

Figure 1 - Spectrum in the wireless service value chain

Value Chain	Examples
Content	Programmes, file-sharing
Physical assets	Towers and masts
Spectrum: Wholesale / Retail	Licensees, intermediaries, commons
Transmission	MVNOs, broadcasting transmission
Reselling	Air time
Retail (end-users)	Mobile telephony, broadcasting services

Source: Cave (2006: 221).

Different degrees of vertical integration or separation can accommodate many (spectrum) sharing opportunities, for example:

- the same physical assets and transmission capabilities allow a range of programming to be sold or shared. Equally, content can reach end-users via

many platforms; for instance, television content can be delivered to viewers in the retail market by employing three main broadcasting technologies, i.e. terrestrial, satellite or cable television (see, e.g., Adda and Ottaviani 2005);

- access to spectrum can be achieved in numerous ways via commons, direct licensing, underlays or overlays,[8] or using intermediaries such as band managers or operators of real time access regimes (Bazelon 2003; Bykowsky 2003; Cave and Webb 2003c);

- physical assets, spectrum and other resources can be used to provide entry or access points nearer the end-user (for example MVNOs and other resellers typically use existing wireless network infrastructures and capacity to offer their services).

1.3.- Traditional key tools for spectrum management

Traditional spectrum management involves a layering of mechanisms, starting at the international level with the ITU planning process through national planning processes and down to licensing and interference management (ITU 1998, 2001b, 2001c, 2005a). In these processes, regulators

[8] Spectrum underlay techniques seek coexistence between two or more users of the same channel (or spectrum swath) by enabling transmissions with very low power by secondary users that will not interfere with systems with higher power densities deployed by a primary user. Spectrum overlay techniques are based on an intrude-and-avoid principle such that a secondary user transmits signals only when the channel is not occupied by the primary user. See also Section 1.4 below.

use three fundamental tools to manage spectrum: (i) interference management; (ii) spectrum allocation; (iii) spectrum assignment.

Those tools are likely to continue to play a key role for spectrum management; however, regulatory decisions have become increasingly unsatisfactory and arbitrary in recent years (Cave 2006). There is widespread agreement that more flexibility has to be introduced in their deployment and one option to achieve this is to substitute market-inspired mechanisms for administrative management wherever possible (Coase 1959; Levin 1966; Melody 1980; Rosston and Steinberg 1997; Spiller and Cardilli 1999; Hazlett 2001; Cave 2002; Kwerel and Williams 2002; Benjamin 2003; Faulhaber 2005).

This will be addressed in the following sections, by describing the role of those three key spectrum management tools, the limitations arising from the command-and-control approach and the potential advantages of a more flexible framework.

1.3.1.- Interference management

Interference management under 'command and control' has been carried out by a rigid definition of technical conditions to be met[9] and licences have provided a major tool for interference management. In addition, regulators

[9] See, for instance, Eurostrategies-LS Telecom (2007).

have also introduced guard bands between spectrum allocations to different services and have established a hierarchy of users, whereby primary users' operations enjoy the right to be free from interference caused by secondary users (Falch and Tadayoni 2004; Peha 2009).

The limitations of this approach to interference management have become a major regulatory issue, especially in those countries that are reforming their spectrum management regimes (see Wik Consult 2005; McLean Foster & Co. 2007 for surveys). However, the more flexibility allowed, the higher the risk of harmful interference and, consequently, the more crucial the definition of spectrum rights, which is intertwined with the development of market-mechanisms (cf. Ofcom 2006a).

Interference management under a market-based approach is likely to be aimed at fully protecting spectrum users; this protection would be the outcome of a negotiation process among those entitled to spectrum rights (Cave and Webb 2003b). In a less radical way, parameter-based interference management, that outlines the objectives to be achieved (for example in relation to permissible out-of-band emissions), and yet still leaves the licensee with flexibility as to how best to meet these parameters, is preferable to the traditional approach of tightly prescribing technical conditions.

In reducing the relevance of the 'command and control' framework, spectrum policy is also moving towards an expansion of licence-exempt

spectrum (Benkler 1998; Noam 1995; Buck 2002; Werbach 2004; Lehr 2005; Best 2006; Brito 2007; Horvitz 2007). License-exempt spectrum was originally designed to accommodate experimental uses. However, the success of many of these experimental applications (for instance, WiFi) have seen them extended to commercial use without shifting to other parts of the spectrum.

Interference management for unlicensed spectrum usually involves only power limits and perhaps also the protocols to be deployed (Weiser and Hatfield 2006). Therefore, unlicensed users are not protected from interference (or the administrative level of protection is minimal) and avoidance of interference needs to be arranged in a decentralized way (Santivanez *et Al*. 2006). This has raised major concerns on the viability of open access to spectrum (Buchanan and Yoon 2002; Cave and Webb 2003c; Hazlett 2005; Baumol and Robyn 2006). Technology developments such as beaconing systems and cognitive radios can reduce harmful interference and therefore they should help make (decentralized) interference management easier (FCC 2002b).

1.3.2.- Spectrum allocation

Spectrum allocation refers to the process of deciding what type(s) of service(s) can use a particular spectrum band. At the highest level, spectrum is allocated by ITU through the Table of allocations, which is contained in the

Radio Regulations. Those allocations are regularly updated at World Radio Conferences held every three to four years. In general, national spectrum regulators derive national spectrum plans from the ITU Table of allocations, albeit local variations are possible. More detailed planning arrangements contribute to the allocation process below the national plan of frequency allocations (ITU 2001c, 2001d; Cave 2002; Chaduc and Pogorel 2008).

Implementation of proposed changes of spectrum allocations might take several years using this negotiated approach to spectrum management, which has been criticized for being very slow, unduly restrictive and unable to keep pace with technology and demand developments in wireless communications. Allocation of spectrum should as far as possible be responsive to market conditions rather than imposed by central fiat (De Vany *et Al*. 1969; Falch and Tadayoni 2004; Entman 2004; Cave *et Al*. 2007b). In this way allocation policy would support efficient use of spectrum in the economy (Hazlett and Muñoz 2004). That is, it would enable and support spectrum being employed in the most highly valued uses.[10]

But the advantages of more flexible spectrum allocations have to be balanced against the advantages of harmonisation (ECC 2006; UMTS Forum 2006). In the past, centrally prescribed usage of spectrum has been crucial in a number of occasions, notably in Europe for the development and rapid

[10] To some extent, this is a matter that can be handled by assignment tools—if licensees have the flexibility to change the use to which their spectrum is put (see below).

uptake of 2G mobile phone services, using the Global System for Mobile communication (GSM) standard. However, it would be preferable for these advantages to be realised by market mechanisms wherever possible, as there are also cases of regulatory failures—for example, in Europe, there has been little take-up for TETRA mobile services in the 870-876 / 915-921 MHz band since the decision was ratified in 1996; in Australia, Local Multipoint Distribution Services (LMDS) never proved to be commercially viable in the allocated spectrum at 27 and 28/31 GHz. Moreover, the trajectory of wireless technology is making harmonisation less necessary than in the past, as modular designs and software defined radios make it increasingly feasible to realise the fundamental advantages of harmonising spectrum, namely scale economies and interoperability (ECC 2006).

1.3.3.- Spectrum assignment

Spectrum assignment refers to the process used to decide who gets access to spectrum. To control access to spectrum and prevent harmful interference, the 'command and control' approach was generally accompanied by a licensing regime. Under 'command and control', this has been implemented by administrative mechanisms, some of which involve regulatory discretion

(e.g. beauty contests).[11] If demand for spectrum access is considered unlikely to exceed spectrum supply, spectrum has historically been assigned on a first-come first-served basis. In the US, spectrum lotteries had formerly been used in assigning spectrum for which there was excess demand, in lieu of administrative discretion. However, those lotteries have proven inefficient and were abandoned. High demand for particular frequency bands has suggested, in recent years, the introduction of market-based mechanisms—notably auctions—to assign spectrum (McMillan 1998; Klemperer and Binmore 2002; Kwerel and Williams 2002; Illing and Klüh 2003; Maasland and Moldovanu 2004; Salmon 2004; Cramton *et Al*. 2010).

1.4.- New technologies and their implications for spectrum management

New technologies show great promise in how to make more effective use of spectrum.[12] Developments in spread spectrum technologies (including UWB), software-defined/ cognitive radios (SDR/CR) and smart antennas

[11] Beauty contests are based on comparative selection and may involve hearings or the submission of detailed applications which are then scored according to rules devised by the radio administrator. The winner of a beauty contest is the applicant achieving the highest score.

[12] The literature on those themes is vast; see, e.g., *IEEE Communications Magazine*, vol. 46(4) of April 2008 for a collection of studies on cognitive radios, mobile ad hoc networks and sensor networks; Webb (2007) for discussions and predictions on future wireless communications technologies; see also the deliverables available at http://www.sportviews.org/, the website of the Sportviews (Spectrum POlicy and Radio Technologies Viable In Emerging Wireless Society) project.

have raised particular interest (ITU 2005b, 2006b). These technologies have a potential to increase spectrum efficiency in many ways, including a higher level of frequency reuse and sharing by means of both underlay and overlay techniques. Furthermore, mesh networks have the prospects of diminishing the power required of transmissions, by virtue of their use of multiple short hops at low power levels rather than one long hop at a higher power (Plextek *et Al*. 2006).

New spectrum-using technologies may have a relevant impact across the value chain of spectrum-based services, by enabling a more efficient use of spectrum either directly or indirectly. For instance, spread spectrum technologies are likely to bring about great benefits in increasing spectrum efficiency directly, by using frequencies more intensely; smart antennas promise better performance at both transmitter and receiver levels, and generate opportunities for enhanced spectrum efficiency by building on the techniques to receive and send signals over frequencies without suffering harmful interference; mesh networks enhance the scope for commons, provided that increases in equipment costs do not outweigh savings in spectrum use; SDR/CR technologies are expected to change significantly the way spectrum is used today, particularly as high-level cognitive radios promise to enable more frequency reuse and more flexible uses of the same hardware and infrastructure (Qinetiq 2006), thus contributing to spectrum

efficiency in a variety of ways (see, e.g., Minervini 2007; Fette 2009). Moreover, those technologies might be implemented together (e.g. in mesh network architectures such as ad hoc networks) to offer a wide range of new opportunities for spectrum-based services.

The traditional regime for spectrum management is that of one frequency to one user (bound to provide a particular service using individually licensed apparatus). Technological innovations promise to enable access to spectrum resources using techniques that either do not fit the traditional regime, or would be highly constrained by such regime. Thus a crucial issue is how to achieve the benefits of flexibility in the context of the more sophisticated technologies.

A technology such as CR relies upon using agility to make greater use of given frequencies by pooling intermittent demands to achieve a greater utilisation rate. Other things being equal, this process occurs more efficiently on a larger scale, subject to the increasing cost and technical complexity of ranging over more spectrum. Therefore, CRs are likely to aggregate demand; this will capture the benefits of scale, possibly involving intermediation, such as a band manager selling access to a range of frequencies (Cave and Webb 2003a; Cave 2006).

Two remaining issues concern underlays and overlays (see, e.g., Baumol and Robyn 2006). Underlays are exemplified by UWB, which

operates under the noise floor[13] of other services. In principle, UWB could be utilised in at least three ways. First, one or more separate geographical licences could be carved out beneath any existing noise floor and assigned on an exclusive basis; or, the same space could be carved out, and made licence-exempt; or, an obligation could be imposed on any prospective user of UWB to negotiate an arrangement with all licensees under whose noise floor it proposed to operate. The last option would almost certainly fail because of the transaction cost incurred in negotiating with countless licensees (Cave 2006). Finally, there is the question of overlays, or access by users to spectrum licensed to others. In principle, this could be made generally available. Indeed, the European Commission's proposals on spectrum reform[14] seem to contemplate such a general right of access, when they state that "a new system for spectrum management is needed that permits different models of spectrum licensing (the traditional administrative, unlicensed and new marked-based approaches) to coexist so as to promote economic and technical efficiency in the use of this valuable resource. Based on common EU rules, greater flexibility in spectrum management could be introduced by strengthening the use of general authorisations whenever possible" (EC 2006: 7).

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[13] The noise floor is the measure of the signal created from the sum of all the noise sources and unwanted signals within a measurement system.

[14] Revisions to the Framework were agreed in November 2009 (see Directive 2009/140/EC).

The rest of this work is intended to contribute to the development of that new system for spectrum management.

Chapter 2. Review of the literature on market-inspired methods

2.1.- Spectrum policy trends in liberalizing countries and market-inspired methods of spectrum management

Traditionally, spectrum regulators have established, to a large extent, how radio frequencies can be used for wireless communications (cf. Chapter 1). The 'command and control' framework has been, and in many countries remains, the predominant method of spectrum management. However, there is a general consensus on the need to move spectrum management towards a more flexible regime, in particular in order to avoid inefficiencies brought about by decades of administrative allocation of radio frequencies (cf., e.g., ITU 2001a; Cave 2002; EC 2007; Pogorel 2007).

'Command and control' is no longer the sole approach to spectrum regulation. Three models - exclusive use, commons,[15] and administrative

[15] Unlicensed spectrum and commons have been used as synonymous in the spectrum-allocation debate. However, on one hand, unlicensed spectrum describes an access regime (for spectrum that is owned by the state and allocated administratively); on the other hand, a commons refers to a property regime where a resource is owned by a group of individuals (cf. Hazlett 2006). Moreover, the use of the term 'common property' - to refer to property owned by a community, the government or no one - has led to wider confusion in the analysis of legal regimes, particularly for natural resources (Ostrom and Schlager 1992).

'command and control' - have become the usual taxonomy to describe different spectrum management options, especially following the FCC's Spectrum Policy Task Force report (FCC 2002a), which has influenced spectrum regulation in the US.

While the traditional approach was aimed at controlling interference, recent policy trends have focused on the issue of establishing a framework where spectrum can be put in the hands of those who value it the most. Indeed, consideration that spectrum is a valuable resource has become crucial.[16] Therefore, spectrum auctions and (secondary) trading have been introduced in the regulatory toolkit in many countries, together with some (cautious) measures to deregulate change of spectrum use – although liberalization of use has been pursued in a lower number of countries.[17]

In this section, the case for a major extension of market forces in spectrum management is briefly considered (for extensive reviews of markets vs. administrative methods, see, e.g., Cave 2002; FCC 2002a; Ofcom 2004; EC 2005a; Cave *et Al*. 2007b). The context of the discussion is a management regime in which licences are issued for the exclusive use of one firm or organisation. Under a market system, this is subject to change of

[16] Issues encountered in estimating both licensed and unlicensed spectrum values in the absence of markets are discussed in Minervini (2008).

[17] See Chapter 4 for an analysis of liberalization of spectrum assignment and allocation in a few countries.

ownership and/or change of use – whereas 'command and control' sets constraints on spectrum assignment (i.e. who is entitled to use radio frequencies) and, more crucially, tight restrictions on spectrum allocation (i.e. how radio frequencies can be used).

In some countries (e.g. the US, the UK and Australia, but also developing countries such as Guatemala and El Salvador) spectrum policy is shifting away from the traditional methods of spectrum management and is increasingly relying on market-inspired methods (McLean Foster & Co. 2007). These methods have been adopted to assign spectrum, both at the primary level (auctions) and at the secondary level (spectrum trading); in addition, relaxation of constraints on uses and technologies (liberalization) is being pursued in countries which have been leading recent policy trends. Moreover, the case for an expansion of spectrum bandwidth for collective use has also attracted more attention than in the past. However, spectrum liberalization measures have had little impact on public sector spectrum so far, compared to progress with the use of market-inspired methods for commercial spectrum. These spectrum liberalization issues are reviewed in this chapter.

2.1.1.- Spectrum auctions

Spectrum auctions have been the most prominent of the market-based mechanisms to be deployed in many countries. In those auctions, a government sells the right to use specific segments of spectrum in some geographic areas (see, e.g., Illing and Klüh 2003). Until the late 1980s, spectrum rights (i.e. licences) had been assigned applying many different ways, but only beauty contests (comparative selection procedures) explicitly accommodate a competitive element (OECD 1993). Nevertheless, beauty contests sometimes open the door to favouritism and corruption (Cave and Valletti 2000).[18] Auctions by themselves do not make a fundamental change in spectrum management, because they usually operate in a framework of 'command and control' over the use of the licence which is being auctioned. Thus they introduce a competitive element into the assignment process, but do not necessarily introduce flexibility into spectrum use (Valletti 2001). However, a combination of auctions with secondary trading and liberalisation (see below) does amount to a genuine market-inspired reform.

[18] For instance, in the UK, in preparing for the auction of 3G licences, the regulator stated: "Government should not be trying to judge who will be innovative and successful", thereby suggesting that market-based mechanisms should be preferred to administrative methods (http://www.ofcom.org.uk/static/archive/spectrumauctions/documents/faq2.htm); with regard to the pricing of 3G spectrum, the Telecom Regulatory Authority of India (TRAI) stated that "the auction route is superior to the beauty contests and the fixed fee approaches" (TRAI 2006: 54)

There are a number of different auction formats that can be used to assign spectrum licences, ranging from simple first-price sealed-bid auctions through to complex combinatorial package bid auctions (Klemperer 2004). Since the first spectrum auctions, in New Zealand in 1989 which used a Vickery (or second-price) auction (Mueller 1993), the international trend in spectrum auctions has been to apply more sophisticated auction formats, such as combinatorial (clock) auctions,[19] so that licence assignment processes are more likely to achieve the objective of economic efficiency.

While auctions typically focus on the price for spectrum rights, competitive assignments are sometimes designed with a focus on revenue shares or royalty payments. In 2001 such an approach was adopted in the Hong Kong 3G auction, which was predicated on a need to guarantee a return on the use of spectrum to the community and to avoid possibly large upfront costs (Yan 2001).

[19] The combinatorial clock auction is a two stage auction. The first stage is a multiple round, open clock auction where bidders have the opportunity to bid on their most preferred package of lots in each round. The second stage is a combinatorial sealed bid auction where bidders have an opportunity to express their preferences for packages of lots by bidding best and final offers. Bidders have the opportunity to bid best and final offers on all combinations of lots for which they were eligible to bid during the clock stage. This allows bidders to express their willingness to pay for combinations of lots which they would be happy to win even though they did not bid on them during the clock stage of the auction. A combination of these bids may allow the auctioneer to assign more of the available spectrum than was achieved at the end of the clock stage of the auction, and hence achieve a more efficient assignment (see, e.g., Ofcom 2007a, with regard to a combinatorial clock auction for the L-band spectrum).

Spectrum assignment via auctions has raised a few concerns. In particular, it has been argued that bid prices necessarily result in consumers paying more for services reliant upon radio spectrum, and that auctions, particularly those where bids ascend over time, encourage bidders to over-value spectrum, resulting in spectrum prices being too high (cf. Binmore and Klemperer 2002). However, the first argument is fallacious. In well designed auctions, bidders are required to pay for spectrum up front and, for successful bidders, the cost of spectrum bandwidth will be a sunk cost, which does not influence market prices. For instance, in a paper by Kwerel (2000) the author shows, firstly, that prices for mobile services did not vary as widely as prices for radio spectrum and, secondly, that there was no statistically significant correlation between auction fees and the prices paid by consumers for mobile services (see also Cable *et Al*. 2002; Hazlett 2004). Nevertheless, auction prices are a cost and do matter for those businesses buying spectrum: they can make all the difference between a successful business model and a failure.

The second argument—that is, auctions, particularly those where bids ascend over time, would encourage bidders to over-value spectrum—is also built on shaky grounds. This scenario is exceptional and it is unclear whether

bidders in spectrum auctions would over-value frequencies simply because of auction design (Cramton and Schwartz 2000).[20]

At least in some auctions, the cause of high prices may also be due to artificial scarcity arising out of the out-dated 'command and control' approach to spectrum management (Cave 2002): the limited spectrum often available via administrative decisions, for high value applications (such as mobile telephony), inevitably leads to high prices at auction.

Therefore, a number of studies have discussed the relative advantages of auctions compared to other methods to assign spectrum, and have analyzed the features and implications of different auctions formats. However, the competitive assignment and allocation of spectrum for collective use by a group of players (against exclusive use by one service provider, i.e. the auction winner) has not yet been addressed. Research has so far considered collective spectrum use (e.g. Mott MacDonald *et Al*. 2006), or administrative allocation of licence-exempt spectrum (e.g. Indepen *et Al*. 2006), or competitive allocation to individual auction winners (e.g. Illing and Klüh 2003).

[20] In Europe, a lot of research has been carried out investigating the big differences in the outcomes of the numerous 3G European auctions of years 2000-2001 (EC 2002a; Klemperer 2002).

2.1.2.- Secondary trading in spectrum

Historically, spectrum trades have not been possible between users entitled to rights on spectrum. Hence, in order to assign frequency bands to a different user, spectrum had to be returned to the spectrum manager and then re-assigned—a much more rigid mechanism than secondary trading, with very high transaction costs (Hazlett 2003; Analysys *et Al*. 2004).

Spectrum trading should contribute to a more efficient use[21] of frequencies (Coase 1959; Melody 1980; Hazlett 2001; Cave 2002; Faulhaber and Farber 2003). It complements the introduction of market-based mechanisms for primary assignments of spectrum, i.e. auctions (Valletti 2001). Auctions can be usefully applied to ensure that spectrum is purchased by those who value it the most (Illing and Klüh 2003; Janssen 2004). However, secondary trading of spectrum ensures that, if the valuation of spectrum change over time, resulting in the present spectrum holder's valuation being lower than that of someone else, spectrum can flow from one use to another.

[21] Economists describe efficiency more precisely and three related concepts are often used: (i) Pareto efficiency (which has three components: allocative, productive and dynamic efficiency) is where resources are allocated across consumers and firms so that no firm or consumer can be made better off without making some other body worse off; (ii) informational efficiency (where prices accurately reflect underlying value – usually of concern in financial markets); and (iii) operational efficiency (where markets work efficiently from an institutional perspective). A market can be said to be 'fully efficient' when all three efficiency criteria are satisfied.

Efficiency is usually achieved when the users of spectrum tend to be those with the highest valuations for the spectrum. A trade will only take place if the spectrum is worth more to the new user than it was to the old user, reflecting the greater economic benefit the new user expects to derive from the acquired spectrum. To facilitate transfers, it is crucial to establish a swift and inexpensive mechanism with transaction costs as low as possible—otherwise if transaction costs are too high compared to the potential efficiency gains, these efficiency gains will not be realised (Cave and Webb 2003b). However, the vast quantity of important details, which have to be agreed, means that legislation cannot be far-reaching in the specification of actual arrangements.[22]

To promote spectrum markets, it is useful to provide some information about spectrum use. The availability of databases of licences for spectrum use may play a great role: databases could provide operators with sufficient information to understand who their neighbours will be, for what purpose they are currently deploying their spectrum, and the interference limits to which they are subject.[23]

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[22] There are a variety of market mechanisms that can be used to trade spectrum, including, e.g., bilateral negotiations, brokerage and exchange; it is also possible to combine more than one of these approaches (Analysys *et al*. 2004).

[23] In Europe, the Commission has recently published a decision to harmonise the availability of information on the use of radio spectrum through a common information point and by the harmonisation of format and content of such information; see Commission Decision 2007/344/EC of 16 May 2007 on harmonised availability of information regarding spectrum use within the Community.

Finally, departure from 'command and control' towards a (decentralized) market-based approach to spectrum management has to be matched with the development of an effective dispute resolution process (public or private). Such a resolution process would arbitrate on problems arising from transgressions of interference rights and responsibilities by one party or another. It would also deal with the inevitable but rarer cases where, despite both parties adhering to their licence conditions, there is nonetheless unacceptable interference to their activities (Goodman 2004; Faulhaber 2005; Baumol and Robyn 2006; Weiser and Hatfield 2008; Hazlett 2008b).

Spectrum trading is arguably a more potent market-based mechanism than auctions, as it makes the gravitation of spectrum to its most efficient use a permanent feature of the allocation system. Yet in practice its impact has been modest so far. Several possible reasons have been suggested, with each likely to have had some influence (Weiss 2006; Xavier and Ypsilanti 2006).[24] Nevertheless, an analysis of spectrum trading in conjunction with other market-inspired methods which feature in spectrum reform strategies may provide further insights.

[24] Some of those reasons are closely related to features of spectrum markets (e.g., insufficient information, inadequate development of private band managers, etc.); a second set of reasons is more closely related to the regulatory framework (e.g. uncertainties due to phased liberalisation of spectrum use, lack of alignment of licence terms and conditions, etc.).

2.1.3.- Liberalization and flexibility of spectrum use

Liberalising moves (such as removing or lowering restrictions on use, and encouraging spectrum sharing) will improve the flexibility of spectrum use. This, in turn, should increase efficiency and confer greater economic benefits on society (Valletti 2001; Hazlett 2003; Lie 2004; Hazlett and Muñoz 2004). However, the costs of interference, or of preventing interference, may also rise. As returns to a market tend to increase with its scale (because in a larger market there is more scope for mutually beneficial transactions), the total return to expanding flexibility—measured, for example, by the number of bands over which secondary trades with flexibility of use can be effected—will grow. Assuming that interference costs can be restrained, spectrum policy should promote maximum flexibility (and very limited 'command and control'). At some point, it is possible that the marginal costs of flexibility exceed their benefits. In this situation, the optimal degree of flexibility lies somewhere between zero and maximum possible flexibility. The challenge facing spectrum policy makers is to determine how quickly to introduce flexibility and by how much. However, there are no signs yet from the experience of countries using market methods, that interference costs might, at the margin, outweigh the benefits of flexibility.

2.2.- Marketed licences and the commons

Traditionally, a small number of frequencies sat alongside spectrum licences assigned by administrative methods to provide unlicensed access to users of particular apparatus, or for experimental uses. These frequencies include those used for television remote controls, Bluetooth short range communications etc., as well as spectrum utilised for short-range broadband access using standards such as IEEE 802.11 or WiFi. In the UK, for example, such licence-exempt spectrum amounts to 4-6% of the total.

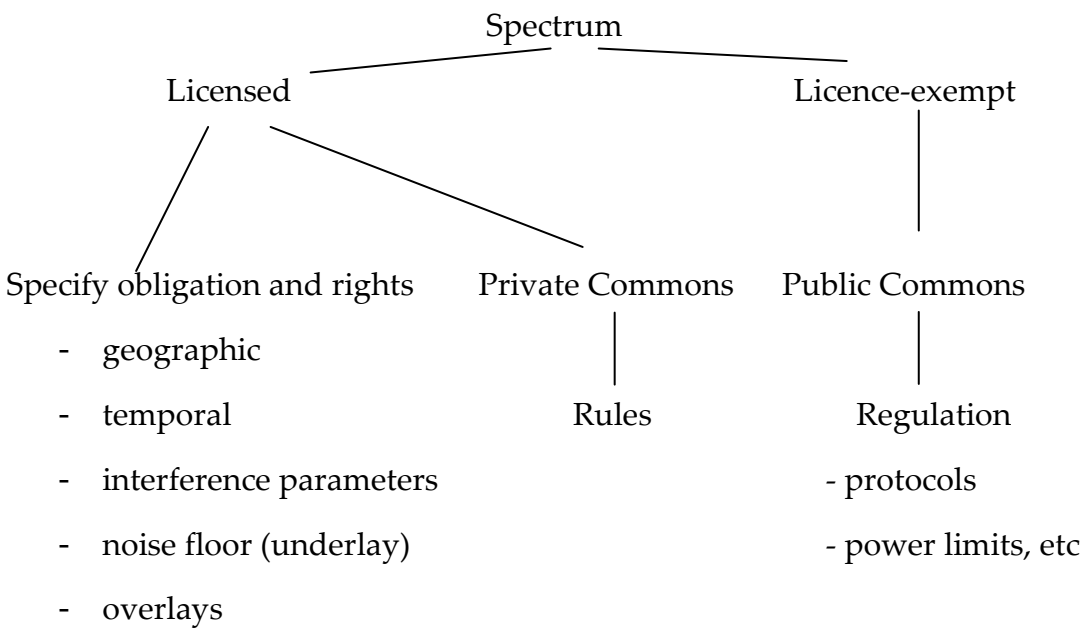
While several commentators have proposed a major expansion of the commons (e.g. , Benkler 2002; Werbach 2004), others regard it as best suited to short range applications where rivalries between operators for spectrum are more limited (e.g., Hazlett 2001; Faulhaber and Farber 2003; Cave and Webb 2003c; Baumol and Robyn 2006). However, drawing the line over time between the universal licensed and unlicensed spectrum is highly problematic, and historically has been done using administrative fiat in two dimensions - in the basic decision to assign a frequency for unlicensed use, and in the choice of restrictions imposed on its use (Hazlett 2006).

In the past, spectrum regulators have made decisions on unlicensed spectrum on administrative grounds,[25] but this is arbitrary and

[25] They have carved the radio frequency spectrum into a number of bands and allocated most of them to licensed uses. Thus, on the one hand, regulators have divided licensed (*Continued on next page*)

unsatisfactory. In a market environment, it would be better to introduce some form of market competition between the two modes of frequency management (Cave 2006). Figure 2 illustrates the allocation decision between licensed spectrum, some of which may be utilised for 'private commons' and licence-exempt spectrum.

Figure 2 - Licensed vs. unlicensed spectrum



Source: Cave (2006: 224).

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spectrum in a few fundamental dimensions (geographic area, frequency, time), and have set interference parameters (e.g. power limits) to protect licensees against harmful interference from other spectrum users. On the other hand, access to unlicensed spectrum has been governed primarily by setting power limits, imposing standards (such as listen-before-talk) and using protocols (either polite, as they check for frequency occupancy by other transmissions before acting, e.g. IEEE 802.11 - or impolite, e.g. IEEE 802.16). In addition, technological developments and increased demand for wireless spectrum recently have led regulators to consider new ways to share spectrum by means of underlay and overlay techniques.

Administrative decisions suppress market mechanisms, but regulators lack the information or incentives to judge on the (marginal) value of spectrum allocated to different kind of uses. Therefore this task should be left to competitive market forces - unless market failures can be demonstrated – and should not be performed by adopting the popularity of some wireless services as a proxy. For instance, rapid diffusion of WiFi hotspots that use unlicensed spectrum should not suggest *per se* to open more unlicensed spectrum; notably, WLANs providers, who use such unlicensed spectrum, usually exclude nonsubscribers (Kwerel and Williams 2002; Hazlett 2006).

2.3.- Public sector use of spectrum

Historically public sector users have been gifted substantial amounts of radio spectrum to provide services in the public interest, such as defence, public safety and emergency services. Therefore, in many jurisdictions, the public sector holds a vast bulk of valuable frequencies. In the UK, for example, public sector spectrum use accounts for just under half of all spectrum use below 15 GHz. Military use of spectrum, particularly for radar and communications, accounts for most of public sector use. The strategic nature

of defence applications means that sometimes little is known in detail outside the immediate agencies concerned about how the spectrum is deployed.

Under the 'command and control' regime, public sector organisations, especially national defence departments, were accorded high priority in spectrum use and they were allocated spectrum for an indefinite period. But as demand for commercial spectrum grew, attention became increasingly focussed on the issue of whether public sector bodies crowded out commercially valuable private sector spectrum users (Cave *et Al.* 2007a).[26]

Eliminating the boundary between private sector and public sector spectrum markets is a bold, if logical, step, and one that many spectrum regulators are as yet generally unwilling to take (see, e.g. EC 2006). However, a few countries have taken bold steps to promote efficient use of spectrum by public sector bodies. In the US, the National Telecommunications and Information Administration and other federal departments were required to improve efficiency of the use of spectrum in 2003.[27] In the same year, the UK Government commissioned an independent audit of public sector spectrum holdings to inquire whether there is scope for re-allocation from public to private sector or within the public sector.[28] Furthermore, the British regulator

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[26] Significant returns of spectrum to the regulator were made in recent years by the French and UK Ministries of defence.

[27] See http://www.ntia.doc.gov/osmhome/spectrumreform/index.html.

[28] See http://www.spectrumaudit.org.uk/. Recently, the Australian spectrum regulator has commissioned a similar investigation into the use of spectrum by the public sector.

has applied administrative incentive pricing to sector users, including defence, to expose the public sector to market influences (Indepen *et Al*. 2004).

Chapter 3. Methodology

3.1.- General methodological considerations

The introduction has presented the topic and the main research questions of this work. The questions that are asked influence what needs to be done to answer them (cf., e.g., Punch 1998: 245). Moreover, it is sometimes suggested that if research questions are well enough focused or refined, they will effectively determine the methods used to answer them; however, in practice, there will be alternative techniques which can be used and researchers need to think about which methods are practicable given the time and other resources available (Blaxter *et Al*. 2001, esp. 80 ff.).

Several methods were used in this work on a few problems of spectrum management. The task of this chapter is to illustrate and justify the particular research methods used to answer the various questions presented in the introduction (cf., e.g., Blaxter *et Al*. 2001; Clough and Nutbrown 2007).

A pragmatic stance was generally adopted. This is briefly discussed in this chapter, as philosophical ideas influence the practice of research and need to be identified, although they remain largely hidden (Creswell 2003: 4).

Thus, methodological choices, which guided and shaped this research and its outcomes, might be judged in the light of pragmatism.

Pragmatists believe that, instead of methods being important, the problem is most important; therefore, researchers use all approaches to understand the problem (Tashakkori and Teddlie 2009).[29] According to Peter Clough and Cathy Nutbrown (2007), there is not a great deal to say about methods as such; methods only arise in the service of quite particular needs and purposes: "if the work ultimately has significance for us, it is because its quite particular purpose has been achieved; and to do this, it will have called on the construction of quite particular tools [..]. It is actually this particularity which it becomes the task of methodology to explain" (*ibidem*: 29).

The rest of the chapter is organized as follows. After an overview of pragmatism and use of mixed methods in research, the following sections discuss in more detail the research methods chosen to answer the research questions and the mixing of different ingredients, including methods, models and data collected for analyses.

[29] "Research design is governed by the notion of 'fitness for purpose'. The purposes of the research determine the methodology and design of the research" (Cohen *et Al*. 2000: 73, quoted in Clough and Nutbrown 2007: 33). See also Newman *et Al*. (2003: 169-70), who argue that "[o]ne's purpose provides a way to determine the optimal path to studying the research question".

3.1.1.- Pragmatism and the use of more than one research method

Burke R. Johnson and Anthony J. Onwuegbuzie (2004: 18) argue that "the project of pragmatism has been to find a middle ground between philosophical dogmatisms and scepticism and to find a workable solution [..] to many longstanding philosophical dualisms about which agreement has not been historically forthcoming".[30] Thus all research projects may be considered mixed, at least to some degree. This is also supported by the difficulty (or impossibility) of placing all components of a research project (e.g., type of questions, nature of data, role of values) on one absolute end of a continuum of philosophical orientations (Creswell 2003: 94; Newman *et Al*. 2003: 169-70; Tashakkori and Creswell 2007).[31]

Mixed methodologists do not think that research paradigms are associated with research methods in a kind of one-to-one correspondence. In mixed methods research "the investigator collects and analyzes data, integrates the findings, and draws inferences using both qualitative and quantitative approaches or methods in a single study or programme of

[30] The paradigm contrast tables evolved during the past 20 years. The initial two-columns paradigm table (constructivism, positivism) became a four-column table in Guba and Lincoln (1994) and then a five-columns table in Lincoln and Guba (2000). Tashakkori and Teddlie (1998) compared four paradigms (positivism, postpositivism, pragmatism and constructivism), whereas Tashakkori and Teddlie (2009) add the transformative perspective as a fifth paradigm.

[31] See also Hantrais (2009, esp. ch. 5), where the focus is on combining methods in international comparative research.

inquiry" (Tashakkori and Creswell 2007: 4).[32] Researchers who work from a mixed-methodology approach acknowledge the importance of both "striving for objectivity and taking steps to counter our subjectivity, and of the reality that not all stories are equally supported by the observable facts" (Clemons and McBeth 2009: 174). Indeed, the compatibility thesis supports the view that combining quantitative and qualitative methods is a good thing and denies that such a wedding is epistemologically incoherent (Howe 1988: 10). Moreover, it is contended that the mixed methods approach fits researchers who enjoy both the structure of quantitative research and the flexibility of qualitative inquiry (Creswell 2003: 23).

From this stance, mixed methods/ methodologists[33] present an alternative to the quantitative and qualitative traditions. However, the quantitative and qualitative traditions appear more settled and their methods better established than the mixed tradition (cf. Clemons and McBeth 2009, esp. ch. 6). Recently, 19 different definitions of mixed methods research from experts in the fields have been presented in Johnson *et Al*. (2007); five

[32] The authors discuss several ways to mix methods from the two traditions, thus presenting a spectrum of combinations of the two (see Tashakkori and Teddlie 2009).

[33] Tashakkori and Teddlie (2009) maintain that "until we get a greater *consensus within the mixed methods community* concerning what constitutes *mixed methodology* in broad terms [..], then the term *mixed methods* is more appropriately used" (p. 21, italics in original).

common themes emerged, including what is mixed, when the mixing is carried out, the breadth of the mixing and why the mixing is carried out.[34]

3.2.- Data collection and analysis

The following sections present a more detailed account of the analyses carried out. They discuss the different methods used to answer different research questions. A broad definition of data is used in this work to embrace regulatory documents, legislation, reports, academic literature and formal models selected for their relevance with regard to research purposes.

3.2.1.- Uses of formal models

This work makes extensive use of formal models, which are used in various ways (including the mixing with more qualitative data) for different purposes and research questions. Moreover, most of those models appear in the economics literature. The following discussion looks at the (fundamental) models used in this work and briefly describes how those models where

[34] The authors arrived at a broad definition of mixed methods research as "the type of research in which a researcher or team of researchers combine elements of qualitative and quantitative research approaches [..] for the purpose of breadth of understanding and corroboration" (Johnson *et Al*. 2007: 123).

used in the analyses. A short review of advantages and disadvantages of formal modelling is presented at the end of this section.

The chapter answering the first research question contains an analysis which is based on a paper by Dewatripont and Roland published in the American Economic Review in 1995. That paper uses formal economic modelling in order to study alternative policies for transition economies. Parts of Dewatripont and Roland's work are used to set up a thematic framework within which the data can be sifted and sorted. Researchers who adopt a more deductive approach use theory to guide the design of a study and the interpretation of results (Neuman 2003: 65). Devising and refining a thematic framework is not an automatic or mechanical process; it involves both logical and intuitive thinking; it also involves making judgements about meaning, about the relevance and importance of issues, about implicit connections between ideas (Ritchie and Spencer 1994: 180). All these activities rely crucially on the researcher's role.

The scope of the paper by Dewatripont and Roland is wider than our work in two respects at least: their analysis is referred to a whole economy gradually moving (or shifting, in the case of a big bang strategy) from central planning to a market based economy; their analysis also takes into account aspects of political economy, as they study, for instance, the relationship between majority voting systems and reversal of policies adopted in the past.

Our work looks at spectrum management reforms and does not investigate issues of political economy.

An alternative could be to develop from first principles a formal model to provide a positive or normative analysis of spectrum management reform. However, our aim is to look at policies carried out by liberalising countries and study them within a plausible thematic framework. The formal models proposed by Matthias Dewatripont and Gérard Roland seemed to offer a ready-made framework to analyse reforming strategies and tactics with regard to spectrum management.[35] Thus mixed methods in this part of research involved a two-stage design: stage one is the identification of a formal model to be used in the analysis of spectrum policy reform; and stage two is the study of a series of international cases from international practices. The two parts of the study were not designed to validate each other; they bring about different elements of analysis, so the relationship between them is not one of confirmation or contradiction, although they contain similar themes (cf. Mason 1994: 109; Gerring 2007: 39-43; Yin 2009: 130-1).

The chapter answering the second research question is based on a translation of a model proposed by Jonathan Cave and Stephen W. Salant and published on the American Economic Review in 1995. Use of formal

[35] In addition, in order to conduct a valid ex-post cost-benefit or cost-effectiveness study, a programme must have been in operation long enough to have had an impact, and the programme must be able to be measured in quantitative terms (cf., e.g., Patton and Sawicki 1993: 385).

modelling, to suggest a plausible mechanism to allocate and assign a spectrum commons via an auction, is the core research activity carried out here, after having identified Cave and Salant's work as a useful point for departure. This followed some previous study (as part of this research) of other formal models, putting forth the idea of matching behaviour, originally proposed by Joel Guttman (1978, 1987), and a discussion about Guttman's work with Jonathan Cave. There are relevant differences between Cave and Salant's model and the model proposed here: their model was the outcome of a positive analysis, carried out to understand and explain situations of likely collusion in a number of industries, where output seemed to be subject to restrictions imposed by producers. In our model, we start from Cave and Salant's work to find out whether, at least in theory, we can conceive of a mechanism to enable purchase of spectrum commons by a group of private players, who are likely to be competing against other (groups of) players in an auction to get bandwidth for their business. The mechanism proposed aims at obtaining from group participants a minimum amount of money to be used for a collective bid (instead of a maximum amount of output as in the collusive setting studied by Cave and Salant). In those circumstances, involving economic public goods, the difficulty is that of estimating, and making effective, unlicensed spectrum users' derived demand for spectrum, in the same way that, say, mobile operators can express their derived

demand. The root cause of the problem is that of establishing the willingness to pay of a (large) number of non-rivalrous spectrum users. This is subject to the well-known difficulty that respondents have an incentive to falsify their estimates. A number of formal mechanisms have been developed to deal with such problems (e.g. the Clarke-Groves mechanism, reviewed in Campbell (1995: 283-94)).[36] These mechanisms do, however, encounter problems associated with the fact that they do not yield a balanced budget. Other techniques, less sophisticated in terms of incentive properties, such as conjoint analysis, may be required to establish the aggregate valuation of unlicensed spectrum from willingness to pay for the services it can offer. Since a spectrum commons is typically regulated to produce a range of mutually exclusive or co-existing services, a range of options may have to be established, in circumstances where consumer understanding of them may not be strong (Cave 2006).

Chapter 6, answering the third research question, draws deliberately on a number of models from various research areas, as one of the purposes of that chapter is to establish, among available mechanisms designed to share scarce resources, those mechanisms which can be useful when pieces of spectrum (e.g. spectrum commons) are used to deliver a number of services

[36] They have the feature that any respondent whose reported valuation tips the decision to buy into the positive has herself to pay a surcharge equal to the difference between the price and all other participants' preferences for the alternative option. This removes any incentive to report distorted valuations.

to many users. Patton and Sawicki (1993: 239) argue that "we often fail to find a solution to a problem because we do not recognize that our seemingly new problem is really an old problem [..]. The idea is that we can relate what we know about one problem and its solution to other problems and their solutions".[37] There are at least three research themes which seem are relevant for analyses of shared spectrum management and allocation: (i) the recent literature on the so called price of anarchy; (ii) some work on the features of a few protocols (for online and offline data processing); (iii) the more traditional literature on (economic) public goods. Even when they do not offer a ready-made solution for spectrum sharing problems, they still may present useful results and insights for (future) spectrum specific refinements and quantitative analyses.

Formal models consist of "a clear analytic statement of a theory with mathematical equations or logical propositions that are independent of evidence or observation, the derivation of observable implications of the theory and the testing of these implications in some appropriate manner" (Wible 1994: 147, quoted in Mayer 1996: 191). Thomas Mayer (1996) presents a discussion of the benefits and limitations of formal models. He argues that

[37] The so called synectics process, which is intended to provide new perspectives on a problem and to suggest possible solutions, is briefly discussed (see Patton and Sawicki, 1993: 240-1). Synectics uses four types of analogy, including direct analogy (which involves searching for solutions among solutions to other problems), and symbolic analogy (which involves thinking of solutions that are aesthetically satisfying rather than technologically accurate).

one great benefit of formal modelling is that one can check the logic of ones' deductive chain better if this chain is set out explicitly; in addition, modelling facilitates dipping into the "great storehouse of ready-made logical chains" offered by mathematics and makes it easier for the reader to grasp what is being said; if readers disagree with the author, they can see why they differ and what assumptions it is that causes them to reject the argument (Mayer 1996: 192-3). One disadvantage of formal modelling is that often, though not always, it increases the time and effort required to read the paper. With regard to errors, it is argued that formal modelling can prevent errors that might result from less careful informal modelling, but formal modelling can also generate errors, both errors made by the author and the error made by readers when they accept erroneous conclusions (*ibidem*: 193).[38] Therefore formal models should be used with circumspection and "both the authors and readers should be on guard against the dangers of linear thinking by stepping back from time to time and looking at the problem under discussion in a more rounded way" (*ibidem*: 201).

[38] The author's full arguments about benefits and limitations of formal modelling are in Mayer (1996); see also the literature cited therein, Schotter (1996) and Hausman (1989).

3.2.2.- Collection and analysis of regulatory documents, legislation and literature

Research was carried out almost entirely as desk work. Besides research and work on formal models available in the literature, a fundamental role was played, firstly, by national and international regulators' documents and norms; secondly, by contributions in the (academic) literature. Information and evidence for this research was collected almost entirely using secondary data available in public documentation and, especially for evidence about non-English speaking countries, academic literature.[39] Some of the literature used is authored by experts in the field of spectrum management and consultants for spectrum regulatory bodies and governments. In addition, this work benefitted from attendance and participation in meetings of experts and workshops on spectrum issues. These events offered the opportunity to get up-to-date information about policy, technology and research developments regarding spectrum management, including access to papers unavailable in the published literature (e.g., because still circulating in the form of working papers).

A great amount of secondary data was thus used in the analyses. This is particularly evident in the more qualitative parts of the work, i.e. those parts where formal modelling is not the main research strategy/ method (as it is in the chapter proposing and analyzing a mechanism to purchase

[39] See, e.g., Yin (2009) on strengths and weaknesses of those sources of evidence.

spectrum commons collectively), but a useful ingredient for subsequent analyses. There, the challenge – and, to some extent, the purpose – was to provide some coherence and structure to the cumbersome data set, while retaining a hold of the original materials from which it derived (cf. Ritchie and Spencer 1994: 176). In this process, writing memos and notes on the documents greatly helped tracing the work done (cf. Creswell 2003: 190). Moreover, in those parts of the work, data analysis was not a discrete element of the research process which could be neatly separated from the other phases of the project; instead it can be argued that data analysis was integral to the way in which questions were posed, sources of information selected and data collected (Burgess *et Al*. 2001: 143). Research design, data collection and analysis were largely simultaneous and continuous processes (Bryman and Burgess 1994: 217; cf. also Creswell 2003, esp. 190 ff.). This helps understand the decision to do the analysis without computer software, as the use of software would have separated data collection and analysis more sharply; moreover, content analysis in this work is not intended to provide quantitative information about the documents and the literature used. On the contrary, a neater distinction between data collection and analysis can be traced in the work taking its steps from Cave and Salant (1995): after having identified their research paper and judged its usefulness

for our research question, the transfer (with necessary changes) of that model to our setting and further analysis of the implications were carried out.

3.2.3.- Use of case studies for spectrum policy analysis

The following chapter presents an analysis of spectrum policies adopted in a few liberalizing countries.[40] It mixes theoretical propositions from the theory of transition economics and multiple case studies (see, e.g., Gerring 2007 and Yin 2009) to discuss international experiences of spectrum management reform (Yin 1992).[41]

Therefore, the study shares the crucial view that modernizing spectrum management has similarities with the abandonment of `Gosplan regulation` (Faulhaber and Farber 2003), and the assertion that "[r]eforming spectrum policy is like reforming planned economies" (Kwerel and Williams 2002: 40) is taken as the starting point of this research. The literature on transition economics and policy offers theoretical analyses of the expected payoffs under big-bang and gradualist approaches. That literature is used to

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[40] There is no single, agreed upon way for conducting policy analysis (cf., e.g., Patton and Sawicki 1993: 46). Very few analysts would argue that their work is value free (*ibidem*: 32).

[41] See Yin (1992, 2009); this research attempts to take on board two suggestions, *inter alia*, offered by the author in his discussion of programme evaluation: i) "many evaluations must go beyond assessing outcomes and must test relationships between processes and outcomes"; ii) "evaluations benefit greatly from any exposition of a demonstration project's 'theory'" (Yin 1992: 124). For a discussion of advantages and disadvantages of case studies see also Blaxter *et Al*. (2001).

analyse recent spectrum management reforms, which incorporate greater reliance on market-inspired mechanisms and increased flexibility to promote efficient use of radio frequency bandwidth in a number of countries (see Trochim 1989). There is thus a fundamental assumption about the possible extension of the transition literature to spectrum policy reform: reforms of spectrum management and planned economies are conceived as reforms which share a crucial attribute (Sartori 1970; Collier and Mahon 1993), i.e. they both imply a transition from centralized administrative decisions on resource allocation to (more) decentralized market-based/ market-inspired methods to allocate resources.

The literature on transition economics used in the analysis is particularly concerned with the sequencing of reforms: it offers theoretical guidance about which parts of reform packages should be adopted in the early stages and which other parts should be adopted in later stages, according to specific circumstances.[42] Thus, this research focuses on the timing of events which represent milestones of spectrum policy reform in liberalizing countries. Purposely selected case studies are used as a means to account for what is judged to be important information about spectrum

[42] There are also circumstances when sequencing is not optimal and a big-bang strategy should be adopted, i.e. the reform package should be implemented as a whole and without delay. In addition, the literature on transition economics is also concerned with the 'political economy' of reforms.

policy reforms in various countries.[43] In a discussion about multicase narratives, Abbott (1992: 73) argues that "population/ analytic approaches seem to reject too much important information [..]. Among the important information rejected by population/ analytic approaches is the narrative sequence of events in the various cases". The passage of time is integral to qualitative research. Qualitative researchers note what is occurring at different points in time and recognize that when something occurs is often important (Neuman 2003: 148). Moreover, Carl V. Patton and David S. Sawicki (1993: 24) argue that descriptive analysis is often incorporated into prospective policy analysis; in order to design and evaluate new policies, the rationale for and the impact of past policies should be understood; therefore implemented policies must be monitored and evaluated in order to decide whether to continue or modify them and to generate information that will be useful when similar policies are proposed. Case studies are helpful to provide a context within which policy can be discussed. "For outcome evaluation purposes, the most useful case studies are those which are set up to provide directly comparative studies of similar regulatory initiatives in different places" (Stern 2010: 236).

[43] Abbott also argues that "[t]here are different types of universal narratives, which can be ranked from strictly to loosely specified. At the highly specified end of the continuum are stage theories, where we believe in a common sequence of unique events

As often acknowledged, "researchers have very different views on the case study method. Some researchers may see the case study method as an alternative to 'mainstream' or positivist research methods and may be critical of an attempt to emulate the natural science model in data collection and analysis" (Gibbert *et Al*. 2008: 1473). In the positivist tradition, criteria of reliability and validity (which embraces internal, external and construct validity) are commonly used to assess the rigour of case study (Gibbert *et Al*. 2008; Yin 2009). Those criteria are taken into account in developing the analysis. Qualitative researchers tend to use a "case-oriented approach [that] places cases, not variables, center stage" (Ragin 1992: 5): they examine a wide variety of aspects of one or a few cases, and their analyses emphasize contingencies in "messy" natural settings. This work aims to avoid, with regard to spectrum policy reform, being "left to swim in a sea of empirical and theoretical messiness" (Sartori 1970: 1053). The analysis also intends to judge the plausibility of that theory for spectrum policy reform (Hammersley 1992).[44]

The liberalizing (group of) countries considered are the United States (US), European countries members of the European Union (EU), the United Kingdom (UK), Australia, New Zealand, Guatemala and El Salvador. Their spectrum policies are the case studies for this research. There are other

[44] "Judging a theory plausible is not a test of it, since there may be many competing plausible explanations" (Hammersley 1992: 177).

countries which have introduced some market-based mechanisms to manage their spectrum; however, the cases selected are spectrum policy reforms which present the greater differences from the traditional model of command-and-control regulation. Other countries (e.g. India, Canada, Nigeria and Japan) have taken actions to enhance spectrum efficiency, but those actions have been by and large limited to the introduction of spectrum auctions for its assignment, whereas crucial decisions of spectrum management are still left in the hands of national regulators. Conceptually, the selected cases are thus viewed, by and large, as objects (Ragin 1992): cases are based on existing definitions present in research literatures (i.e. they are general rather than specific); moreover, they are considered empirically real and bounded (i.e. a realist rather than a nominalist stance is preferred).

The analysis of spectrum policy reforms is carried out grouping the data collected (on the various reviews and actions taken by liberalising countries) in two major bundles of reforms.[45] The first bundle of liberalising measures includes changes in mechanisms of spectrum assignment, which may be further divided into primary and secondary assignment methods. The relevant changes are those moving spectrum regulation towards more market-based mechanisms; therefore primary assignment refers crucially to

[45] A. Abbott argues that "[i]n the single-case narrative, each step need only be told; it need not be conceived as a version of a more generic type of event [..] [whereas] issues of conceptualization of events in multicase narrative research [..] concern aggregating occurrences into conceptual events" (Abbott 1992: 75-6).

the use of auctions (whereas beauty contests are conceived as a more traditional command-and-control method) and secondary assignment refers to the introduction of forms of spectrum trading (see Analysys *et Al*. 2004). The second bundle of liberalising measures includes changes in the degree of decentralization of decisions on spectrum allocation (i.e. decisions on the services provided using spectrum as an input) and other spectrum usage rights.[46]

[46] I.e. the issue of technology and service neutrality. Liberalisation of spectrum usage rights may be extended to include liberalisation of spectrum assignment; however spectrum auctions and secondary trading are usually addressed separately from spectrum allocation, because the problems involved differ. Moreover, in the following analysis, licence-exempt spectrum and spectrum commons are considered as measures of spectrum allocation liberalisation, although specific technical issues of spectrum use in those cases usually suggest a separate discussion (by academics, consultants and regulators: see, e.g., Faulhaber 2005; London Economics 2008; Ofcom 2004, 2005).

Chapter 4. Reforming spectrum management: re-thinking practice

4.1.- Introduction

Traditional administrative methods to regulate radio frequencies are currently unsatisfactory; in particular, those methods tend to create artificial gaps between spectrum supply and demand.[47] Some spectrum regulators have changed their policies to accommodate new technologies and increasing demand for wireless services; however, spectrum management reform has not proceeded along the same path everywhere.

A variety of liberalisation programmes and specific actions have been proposed.[48] Contributions to the debate on modernizing spectrum policy can be placed along a continuum, ranging from proposals of big-bang strategies, aiming at a radical and quick change of spectrum management methods, to slow and incremental adjustments, very close to the administrative

[47] Cf. Chapter 1, Section 1.

[48] For a survey of the literature see Cave *et Al*. (2007b).

approach. For a rapid transition to market allocation of spectrum, in 2002 two economists working at the US FCC proposed to reallocate restricted spectrum to flexible use and to conduct large-scale two-sided auctions of spectrum voluntarily offered by incumbents, together with any unassigned spectrum held by regulatory authorities (Kwerel and Williams 2002). Thus a rapid and efficient restructuring of spectrum rights and use could be facilitated by ensuring that most spectrum was up for sale at the same time.[49] According to their proposal, 438 MHz of spectrum in the 300 to 3,000 MHz bandwidth could be restructured in as little as 2 years, significantly reducing spectrum shortages for high demand uses. However, this big-bang auction never happened.

At first glance, most reforming countries seem to have adopted gradual and incremental strategies; a number of market-inspired mechanisms, such as auctions and trading, have been introduced, or at least proposed, over time. Noteworthy exceptions seem to be Guatemala and El Salvador, as those two small countries in Latin America have conducted an extensive programme of spectrum rights auctions during a relatively short period of time (Hazlett *et Al*. 2006).

[49] The authors also proposed to provide incumbents with incentives to participate in such auctions, by immediately granting participants flexibility and allowing them to keep the proceeds for the sale of their spectrum.

The aim of this chapter is to analyze spectrum policy reforms which are taking place in liberalising countries, and to contribute to the discussion on determinants and circumstances of effective reforms intended to increase reliance on decentralized methods for spectrum assignment and allocation. This is done using theories developed through analyses of transition economics (from planned economies to more market-based economies), as this work shares the crucial view that modernizing spectrum management has similarities with the abandonment of 'Gosplan' regulation and elaborates on the assertion that "[r]eforming spectrum policy is like reforming planned economies" (Kwerel and Williams 2002: 40).[50] A few questions are of particular interest here: whether, and under what conditions, big-bang strategies have to be preferred to gradualist strategies in the move from 'command and control' to market-based approaches for spectrum management; whether, and to what extent, theoretical findings elaborated in the area of transition economics provide a useful theoretical framework for spectrum policy reform; and whether, and to what extent, experience with spectrum management reform in liberalising countries matches theoretical models of successful reform.

[50] Cf. Chapter 3. This analysis moves from the economic literature investigating the transition of former communist countries from planned economies to market economies; it is based especially on Dewatripont and Roland (1995).

The rest of this chapter is organized as follows. Section 2 reviews the existing literature on spectrum management which has dealt closely with the problem of identifying models of spectrum policy reform. Section 3 introduces a selection of propositions elaborated in the literature on transition economics, which are then used as analytical tools for spectrum policy reforms. Section 4 reports the most relevant evidence from the case studies (namely, Europe and the UK, the US, Australia, New Zealand, Guatemala and El Salvador), focussing on two key dimensions of spectrum liberalization policy, i.e. allocation and assignment. Section 5 closes this chapter with a discussion, from both positive and normative perspectives, of spectrum policy reforms analyzed in the previous sections.

4.2.- Previous contributions on spectrum policy reform frameworks

There is a vast literature about general and specific themes of spectrum management reform, which involves many different issues of transition from a strictly administrative regime to a more liberal one (cf. Chapters 1, 2). Liberalization of radio frequency use may be implemented to various degrees; therefore, various strategies and tactics may be adopted by spectrum regulators. Because the aim of this chapter is to analyze strategies and tactics adopted by liberalising countries (and contribute to the discussion), the focus in the following literature review is on a few analyses

which discuss possible frameworks for the transition from 'command and control' to a market-based (or, at least, market-inspired) regime. The selected contributions - which are considered of greater relevance - are, in chronological order, the ones by Kwerel and Williams (2002), Wellenius and Neto (2007) and Hazlett and Muñoz (2009). The following discussion will highlight some major findings of those studies; it will also compare and contrast those findings.

The first analysis, which is briefly considered here, is in Kwerel and Williams' paper of 2002, where a big-bang strategy is advocated (Kwerel and Williams 2002). The authors argue that liberalization of spectrum policy can be broken down into two component parts: i) the flexibility given a particular licensee to use the spectrum allocated to its licence, whereby more flexibility cedes additional property rights to wireless spectrum holders; ii) the process whereby spectrum is allocated or reallocated from one category (or service) to another, thus permitting spectrum to be bid out of a given deployment and used in another one without special regulatory action.[51]

Those two component parts of spectrum policy liberalization match, to some extent, two of the three benchmark models of spectrum regimes suggested by Hazlett and Muñoz (2009). The first component, i.e. part (i), may be matched with Hazlett and Muñoz's model of spectrum assigned to

[51] Cf. Hazlett and Muñoz (2009: 265, fn 14).

firms (their 'model II'), whereby "[t]he regulatory authority allocates spectrum to licenses, which are then distributed to firms (through auctions or beauty contests), and it does not constrain the services that firms may supply or the technologies employed in accessing this bandwidth" (Hazlett and Muñoz 2009: 265); the second component, i.e. part (ii), may be matched with their model of spectrum assigned by markets ('model III'), whereby "private property rights are assigned to the spectrum resource, wireless firms enjoying full flexibility in the use of assigned airwave space ... [and] spectrum rights can flow between firms" (*ibidem*).[52]

Furthermore, Hazlett and Muñoz (2009: 276) contend that "[p]olicy reform, which entails an expansion of administrative allocations or more general liberalization measures, can be pursued either by independent regulatory actions or via statute". They discuss two alternative scenarios for reform policies and regulatory structures: first, a scenario where policies are instituted by fiat under the administrative allocation system already in place; alternatively, a scenario where statutory reforms may eliminate regulatory discretion and require structural changes. With statutory reforms ('model

[52] The remaining benchmark model ('model I') - i.e. spectrum assigned to services – is close to the traditional command-and-control regime of spectrum management, although with occasional (minor) reliance on market-based mechanisms for spectrum assignment: "[in this model] the regulatory authority assigns spectrum to each operator to provide a specific service, with licenses awarded by either beauty contest or competitive bidding" (Hazlett and Muñoz 2009: 265).

III'), markets would change both spectrum assignments and allocations,[53] and prices would be at levels reflecting efficient spectrum allocations. Thus spectrum would be treated as any other input.[54]

Hazlett and Muñoz are particularly concerned with mobile communications services. They contend that "liberalizing both licences and spectrum allocations can be undertaken in tandem, and many reform efforts have taken this approach" (Hazlett and Muñoz 2009: 275). Moreover, they note that one proposal in this direction is the big-bang strategy advocated by Kwerel and Williams.

Primary spectrum assignments via auctions and secondary spectrum trading are both liberalizing actions. However, Spiller and Cardilli (1999: 67) argue that "[a]lthough pundits and scholars alike have attached much importance to the shift towards auctions, it is unclear whether auctions by themselves are that important regulatory change". Spectrum trades usually have only little impact on spectrum efficiency if trading is not accompanied by spectrum rights enabling change of use - i.e. change of allocation, before or after a trade (e.g. Valletti 2001; Analysys *et Al*. 2004). With regard to

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[53] Liberalization of spectrum allocations in this sense may include allocation (and assignment) of spectrum in the hands of the regulator as well as refarming - both driven by regulatory action. The analysis in Kwerel and Williams can be extended to include allocations of unlicensed spectrum (and commons). Those inclusions would be within existing regulatory structures (cf. 'model II').

[54] Marginal cost is decreasing in capital and spectrum; these two inputs are substitutes (Reed 1992).

trading, Hazlett and Muñoz note that use of spectrum secondary markets is "sometimes associated" to policy changes.

Finally, Wellenius and Neto (2007) outline three of the many options that may be considered for spectrum policy: (i) do nothing; (ii) move as fast as possible; and (iii) improve piecemeal at the margins. They argue that "whenever country conditions permit, it is preferable to move quickly. The benefits from spectrum management reform are likely to be larger when an aggressive agenda is pursued [..]. Radical solutions may be easiest to implement when spectrum management is least developed" (*ibidem*: 54).[55] The authors also contend that "[n]ew solutions are likely to be tried first in situations on which there is experience elsewhere and the risks are low, or where risks are higher but payoff in terms of economic or social benefits is large [..]. This more gradual transition may be preferred in mature markets" (*ibidem*: 55).

[55] The authors argue that "the rights approach will yield the greatest economic efficiency gains and least risk of anti-competitive behaviour if all spectrum is placed on the market at once and at the same time restrictions on use and technology are lifted" (Wellenius and Neto 2007: 54; cf. Kwerel and Williams 2002). Nevertheless, they write "[t]he spectrum rights approach [..] is not equally well suited to manage all parts of the spectrum nor in all country conditions. The main limitations that may arise relate to insufficient liquidity, lack of individual spectrum rights, high transaction costs and inefficiencies, international constraints, market failures, and conflict with public policy" (Wellenius and Neto 2007: 18-9).

4.3.- The transition from command-and-control to market-based mechanisms: theoretical models of transition economics

Liberalizing countries are introducing market (-inspired) mechanisms in various areas of spectrum management, thus moving from 'command and control' to a more flexible regime. This section discusses possible strategies and tactics for such transition, using the literature on transition economics as a theoretical framework (esp. Dewatripont and Roland 1995; see also Wallsten 2002; Nsouli *et Al*. 2005); in particular, it contrasts big-bang reforms and gradual reforms and suggests that gradualism is likely to be a better approach to spectrum reform than big-bang strategies.

The defence of a big-bang strategy is often based on the complementary nature of reform packages (i.e., smaller parts which represent sub-divisions of a major reform) - e.g. spectrum auctions and liberalization of radio frequency uses. However, reform packages being strongly complementary does not necessarily strengthen the case for big-bang transitions: it may, on the contrary, give gradualism an additional advantage, by building constituencies for further reforms (because an appropriate sequencing of reforms would provide demonstrated success to build upon). The case for gradualism thus crucially hinges on correct reform sequencing. Moreover, a big-bang strategy involves high reversal costs,

which are often an obstacle to start a reform programme (cf. Dewatripont and Roland 1995).

Spectrum reform involves a considerable amount of uncertainty; crucial information will only become available later (in liberalization programmes): for instance, what technologies will actually become available and marketable, what levels of harmful interference will be suffered, what services and applications will be in (high) demand and what will the wireless network be like. With such issues at large, gradualism makes reforms easier to start, because it gives an additional option of early reversal at a lower cost after partial uncertainty resolution. It is not a coincidence that gradual reform packages tend to start earlier (Dewatripont and Roland 1995).

A gradualist approach involves a sequential implementation of minimum bangs, i.e. a simultaneous implementation of a minimum set of reforms that can be implemented independent of other reforms without failure. Therefore, a gradualist approach assigns different parts of a reform programme into packages; within each package, there is usually strong interdependence and simultaneous implementation is likely to be better. This is in contrast to a piecemeal approach, which implements different parts of a reform package in many steps without regard to possible strong interdependences (Wei 1997).

The literature on transition economics and policy offers formal analyses of the expected payoffs under a big-bang approach and a gradualist reform. A number of results, which are listed below, could assist in the design, implementation and analysis of spectrum reforms (cf. Dewatripont and Roland 1995; Roland 2002):

a) gradualism has advantages and disadvantages compared to a big-bang strategy. A crucial advantage is to save on reversal costs, by giving an option of early reversal, when the prospects for further reform look disappointing. Disadvantages may derive, firstly, from a period of partial reform (which can be costly) and, secondly, from an unnecessary delay in the implementation of the whole reform package (when the expected payoff of a big bang approach is positive);[56]

b) 'informativeness' of sequential reforms is key to decide as to whether a gradualist approach is better than a big-bang one.[57] If reforms can proceed quickly, gradualism is the best strategy when information is likely to become available at a later stage (for instance, information on actual operation of devices in licence-exempt spectrum, or service options to promote efficient use of some frequency bands);

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[56] Still gradualism dominates if the option value of early reversal is important enough; intuitively, this is true if learning is not too costly, or if it is fast enough.

[57] Informativeness is used "in the sense that learning about one reform tells whether to try another reform or not" (Dewatripont and Roland 1995: 1211).

c) if gradualism is optimal and reforms included in the package differ only in their riskiness, it is optimal to start with the riskier reform, because doing so increases the option value of reversibility (thereby increasing the expected outcome). Arguably, liberalizing spectrum use is riskier - especially in terms of a possible increase in harmful interference - than changing assignment methods (for instance from first-come-first-served to comparative bidding);

d) if the only difference is in the expected outcomes, and reforms do not proceed quickly, it is better to start with the reform with the higher expected outcome. A number of studies have produced a strand of large-scale high-level estimates of the (positive) effects of spectrum liberalization; in general, total benefits of liberalization and trading are expected to be substantially higher than those from trading only. This is largely due to higher innovation and competition from liberalization (cf., e.g., Analysys *et Al*. 2004, which uses a methodology followed in later studies on other liberalizing countries). However, there is still little empirical evidence directly addressing the effects of liberalization on interference (London Economics 2008).

4.4.- International experiences of spectrum reform

This section focuses on several countries which have been in the forefront of spectrum reforms. These countries provide evidence on the major initiatives

aimed at introducing market-based mechanisms for spectrum management. The (groups of) countries selected for this purpose are Australia, the European Union, Guatemala and El Salvador, New Zealand, the United Kingdom and the United States (they are predominantly but not exclusively high income countries). They are not the only liberalizing countries, but their experience with spectrum reform includes the aspects deliberately selected for this study, where the emphasis is on spectrum auctions and secondary trading (i.e. liberalization of assignment) as well as on technology and service neutrality in licence conditions (i.e. liberalization of allocation).

4.4.1.- Europe

Flexibility of spectrum management to enhance efficient use of frequency bands has been a crucial theme in European policy for many years. In December 2004, the Council argued that one relevant ICT policy issue was "to continue assessing different spectrum management models with a view to more flexible and efficient use of spectrum at European and global level, taking into account the development of new and innovative technologies as well as the methodologies which make use of market mechanisms".[58] EU

[58] Council Resolution 10 December 2004, see 15472/04 (press release 345: 14).

policy has been liberalising spectrum assignment and allocation in a number of ways, which are summarised below.[59]

Liberalization of assignment

European countries have used competitive biddings to assign spectrum licences. The most relevant experience with auctions in Europe is the European UMTS/ IMT-2000 licence assignment, which took place in many European member states in 2000-2001. Many studies analysed the European 3G auctions and tried to identify the determinants of its results (e.g. Jehiel and Moldovanu 2001; McKinsey & Co. 2002; Illing and Klüh 2003; Cave *et Al*. 2007a). However, member states took different paths to assign spectrum for 3G licences: only some of them auctioned licences, while others used comparative biddings (beauty contexts) or mixed approaches; spectrum users paid widely different amounts of money for 3G licences (see, e.g., Aegis and Connogue 2001, 37-9).

In Europe, spectrum trading is not mandatory but allowable. Article 9(3) of the *Framework Directive 2002/21/EC* permits member states to allow for the transfer of rights to use radio frequencies between undertakings. In 2003, the RSPG (Radio Spectrum Policy Group) received a request from the EC for an opinion on secondary trading; in November 2004, the RSPG published

[59] For a recent discussion of EU spectrum policy see Cave and Minervini (2009).

their Opinion (RSPG 2004). They adopted a cautious stance with regard to spectrum trading:[60] they favoured a phased approach to secondary trading of rights of use to the spectrum, leaving to individual countries the decision whether to introduce secondary trading and the timing of it. This took into account that some EU countries were introducing secondary trading (e.g. the UK), while other countries were more hesitant. The difference in experience with trading also led the RSPG to consider that European harmonisation of spectrum trading rules should not be pursued at that stage. Last, but not least, the RSPG was sceptical about the application of trading in bands catering for government services (e.g. defence) and safety of life services (e.g., civil aviation), terrestrial broadcasting services and broadcasting-satellite services, and scientific services (e.g. radio astronomy).

Most EU member states have implemented spectrum trading in a number of bands used for commercial services. In February 2009 the RSPG published their Opinion on best practices regarding the use of spectrum by some public sectors in Europe (RSPG 2009) and, with regard to trading, the RSPG considered that spectrum trading is not necessarily applicable in all frequency bands used by the public sector. However, trading offers public bodies the flexibility to enter into leasing arrangements for a limited time (if

[60] The RSPG considered trading to be beneficial in certain parts of the spectrum, subject to the implementation of sufficient safeguards to ensure that potential benefits are not offset by adverse consequences; moreover, the RSPG stated that "European administrations should introduce secondary trading with due care" (RSPG 2004: 4).

they do not wish to dispose of the spectrum permanently) and this could be especially useful for the public sector because of their long time horizons for planning.

Liberalization of allocation

Work aimed at introducing a more flexible spectrum management regime in Europe has gone further than fostering spectrum trading. In May 2004 the EC invited the RSPG to prepare an Opinion on a co-ordinated EU spectrum policy approach for wireless communication radio access platforms, under the acronym WAPECS (Wireless Access Platforms, later changed to 'Policies' for Electronic Communications Services). In its Opinion of November 2005, the RSPG defined WAPECS as "a framework for the provision of electronic communications services within a set of frequency bands to be identified and agreed between European Union Member States in which a range of electronic communications networks and electronic communications services may be offered on a technology and service neutral basis, provided that certain technical requirements to avoid interference are met, to ensure the effective and efficient use of the spectrum, and the authorization conditions do not distort competition" (RSPG 2005: 2-3). Table 1 shows the frequency bands originally identified for WAPECS.

Table 1 - Frequency bands identified for WAPECS

Broadcasting bands	174–230 MHz 470–862 MHz 1452–1479.5 MHz	
Fixed links/point to point (P2P)	5925–6425 MHz, 3600–4200 MHz, 1375–1400 MHz, 1492–1517 MHz, 1427–1452 MHz and 1350–1375 MHz	
Point to multipoint (P2MP)	(without MWS) 3400–3800 MHz, 24.5–26.5 GHz (with MWS) 24.5 GHz–26.5 GHz	
Mobile services	380–400 MHz 410–430 MHz 450–470 MHz 870–876 MHz 880–921 MHz 925–960 MHz	1710–1785 MHz 1805–1880 MHz 1900–1980 MHz 2010–2025 MHz 2110–2170 MHz
Unlicensed bands	1880–1900 MHz (DECT) 2400–2483.5 MHz (RLANs) 5150-5350 MHz (RLANs) 5470-5725 MHz (RLANs)	

Source: RSPG (2005).

The objective is to ensure that spectrum is available for a wide variety of services and applications to comply with the overall policy goal of developing the EU internal market and European competitiveness. WAPECS aims to introduce more flexibility in the use of radio frequency spectrum, taking into account that a number of platforms and technologies may provide mobile, portable and fixed access for a wide range of ECS and

converging applications (e.g., IP access, multimedia, multicasting, interactive broadcasting, datacasting), under one or more frequency allocations (mobile, broadcasting, fixed) deployed via terrestrial and/or satellite platforms. In practice it was suggested that substantial amounts of spectrum, including roughly one third of the spectrum below 3 GHz (the spectrum best suited for terrestrial communications), could possibly be made subject to tradable and flexible use by 2010.

While the RSPG was working on the WAPECS concept, the EC published a communication on market-based approaches to spectrum management (EC 2005a). It proposed a coordinated introduction of spectrum markets across the EU. However, the traditional model was expected to continue to play a relevant role where public interests are at stake (e.g. defence, aviation, scientific research, etc). The EC also contended that lack of flexibility in spectrum management has led to a spectrum bottleneck[61] for new radio technologies; moreover detailed *ex ante* administrative decisions and a requirement for prior regulatory approval have often delayed or even prevented the introduction of new products (EC 2005b). Consequently, the Commission's communication on the *Review of the EU regulatory Framework for ECS* proposed (at 5.1) that "based on common EU rules, greater flexibility in spectrum management could be introduced by strengthening the use of

[61] In 2006, a study by the ERG (European Regulators Group) highlighted a few bottleneck/competition problems in the mobile communications sector (see ERG 2006).

general authorizations whenever possible. When not possible, owners of spectrum usage rights should not be unduly constrained but, subject to certain safeguards, have the freedom to provide any type of electronic communications service ('service neutrality') using any technology or standard under common conditions ('technological neutrality')" (EC 2006).

Moreover, in 2007 the EC stated that the deployment of innovative wireless services and technologies is increasingly hampered by the reservation of certain spectrum bands for narrowly-defined services (EC 2007), thus embracing the principle of technological neutrality and service neutrality for spectrum policy.

In 2008 some member states took actions aimed at introducing market-based approaches into their spectrum management practices: a draft *Frequency Act* allowing secondary trading and technologically neutral use of spectrum was presented to the Danish Parliament; a similar legislative instrument was being discussed in the Netherlands; the Greek Ministry of transport and communications adopted a regulation allowing partial spectrum trading (EC 2009b).

The Commission's proposals have brought to the fore fundamental issues with regard to spectrum management and the design of property rights. In response to this, the European Parliament (EP) published a statement on radio spectrum policy where the principles of technological and

service neutrality where reaffirmed. In its statement the EP "rejects a one-sided market model of spectrum management and urges the Commission to reform the system of spectrum management in such a way as to facilitate the coexistence of different types of licensing models".[62]

4.4.2.- The United Kingdom

Until the late 1990s, the UK applied command-and-control methods to most spectrum used commercially and by public agencies. In its Spectrum Framework Review (SFR) of November 2004, Ofcom set out a new deregulatory approach under which the market, not the regulator, would determine the most appropriate use of spectrum (Ofcom 2004).[63] Ofcom adopts a light-touch approach to regulation and believes it is important to reduce restrictions on spectrum usage as far as possible. The liberalisation process was launched in 2005 in three license sectors: business radio, fixed wireless access and fixed links. As a rule, Ofcom is proceeding cautiously, by

[62] The EP also "considers that the administrative method of allocating spectrum rights could be supplemented by Member States opening up more frequencies to unlicensed, and therefore possibly shared use, and by allowing spectrum trading on condition that this opening up does not harm the continuity and quality of services concerned with public information and safety". Excerpts from texts adopted by the European Parliament at the sitting of Wednesday 14 February 2007, P6_TA(2007)0041, *European Parliament resolution towards a European policy on the radio spectrum* (2006/2212(INI)). Recently, the ECC has reviewed the various terminologies that are commonly used to qualify the type of licensing regime applied in the regulation of spectrum use in Europe (ECC 2009).

[63] The SFR followed Professor Cave's review of spectrum management (see Cave 2002).

initially only considering individual areas, and then dealing with changes to licence conditions in those sectors only. The extent and date of liberalisation will thus vary from licence class to licence class, depending, for example, on the practical viewpoint, the complexity of the coordination required and the ability of users to solve interference issues.

Liberalization of assignment

In its SFR, Ofcom indicated that their preferred method of spectrum assignment to operators - particularly where demand is likely to exceed supply - is by way of auction. A caveat was included that, where there are strong policy reasons for an auction not to be used, then alternative allocation methods would be considered. The UK has carried out a few spectrum auctions using the simultaneous ascending auction method (as in the auction for 3.4 GHz FWA spectrum). In 2008 Ofcom released spectrum in the so-called L-band at 1452-1492 MHz and this was Ofcom's second combinatorial clock auction.[64] In June 2009, the government's action plan for the information society, known as Digital Britain,[65] announced that the government may implement a proposal from an independent spectrum

[64] Its result is in sharp contrast to the first combinatorial clock auction (the 10-40 GHz auction); several of the bidders failed to bid on the largest profitable package in the clock stage (see Cramton 2008).

[65] See http://www.berr.gov.uk/whatwedo/sectors/digitalbritain/index.html .

broker to hold part of the 2.6 GHz auction together with the award of the 800 MHz digital dividend band.

Spectrum trading was introduced in the UK at the end of 2004 as a key element in Ofcom's programme of market-based reform. Since then, trading has been progressively extended to a broad range of licences. The holders of certain wireless telegraphy licences, granted by Ofcom under section 8 of the *Wireless Telegraphy Act 2006*, are allowed to transfer all or part of their rights and obligations to another party. Under the *Trading Regulations*,[66] Ofcom has introduced trading options which offer flexibility to parties interested in trading rights: in addition to an outright total transfer (where all the rights and obligations of a licence transfer from one party to another), the regulations permit concurrent or partial transfers – in concurrent transfers, rights and obligations under the licence become rights and obligations of the transferee, while continuing to be rights and obligations of the person making the transfer; in partial transfers, only some rights and obligations under the licence are transferred (partial transfers may be outright or concurrent).

Trading volumes in the UK have been low since trading was first permitted, particularly at the beginning. By August 1, 2007, only five extra-group trades had been accomplished (and this has been a source of concern

[66] See http://www.ofcom.org.uk/radiocomms/ifi/trading/tradingguide/tradingguide.pdf . The *Trading Regulations* give effect to Article 9 of the *Framework Directive 2002/21/EC*.

to the regulator). In April 2008, Ofcom's information note on key spectrum initiatives reported the following number of trades (Ofcom 2008a), as of November 2007 (Table 2).

Table 2 - UK trades as of November 2007

Licence class	**Licences on issue, March 2007**	**Licences traded**	**Percentage of licences traded in licence class since trading began**
Fixed links	365	7	2%
Business Radio CBS	563	3	1%
Broadband Fixed Wireless Access	14	6	43%
Business Radio Public Mobile Data	4	1	25%
Concurrent spectrum access	12	1	8%

Source: Ofcom (2008a: 13).

Ofcom noted that, although some of these trades were "administrative" (e.g. transferring licence holdings within a group of companies or occurring as a result of corporate takeovers), "there is value even in these forms of trades" (Ofcom 2008a: 13).

The Transfer Notification Register (TNR), which provides information on licences traded or in the process of being traded, shows information on hundreds of licences traded after November 2007.[67] In addition, Ofcom has recently conducted work on simplifying spectrum trading in the UK, as features of its trading regime may be imposing unnecessary regulatory burdens.[68]

Administrative incentive pricing

A distinctive feature of UK spectrum management is the use of administrative incentive pricing (AIP) for public sector spectrum holdings. The underlying principle of AIP is that, where spectrum is in excess demand in its current use or could feasibly be used to address excess demand from some alternative use, spectrum is assigned to those who value it most highly. Where spectrum is not priced in a market, as in the case of public sector holdings, AIP takes into account the opportunity cost of spectrum and introduces payments for spectrum usage; this brings about better incentives compared to traditional administrative fees (Cave *et Al*. 2007a, esp. ch. 12). Recently Ofcom has published a statement on applying spectrum pricing to the maritime sector (Ofcom 2010c) and has proposed to extend AIP to more

[67] Access to the UK TNR is available at http://spectruminfo.ofcom.org.uk/spectrumInfo . Most trades involved business and radio licences.

[68] The *Trading Regulations* specify a six-stage process for executing trades; see Ofcom (2009, 2010a).

licence classes, in addition to cases of public services where AIP is already in use (e.g. defence).[69]

Liberalization of allocation

Ofcom, as noted above, is shifting UK spectrum policy towards a flexible system of spectrum management. Therefore, the regulator has been developing spectrum usage rights (Ofcom 2006a). In 2006 Ofcom introduced two different ways to liberalise specific groups of licences. Firstly, by means of changing existing individual licences. In this case, licence holders can apply for a change to the usage conditions or requirements with regard to the technical parameters for their license(s). This gives Ofcom greater control of the interference potential, but creates insecurity for the applicant for the outcome is uncertain, and it also involves high administrative costs. The second course of action is to change generically the license conditions. This type of approach is aimed at making license conditions as flexible and technology-neutral as possible. It creates greater investment security and is associated with lower transaction costs for those concerned (*ibidem*). For instance, 205 MHz of spectrum in the 2010-2025 MHz and 2500-2690 MHz bands (known as 2.6 GHz) were released on a technology and service neutral basis. However, the definition of technology-neutral and use-neutral

[69] See Ofcom (2010d); see also the results of the 2005 independent audit of spectrum holding and further initiatives at www.spectrumaudit.org.uk .

emission rights brings up complex issues.[70] Periodical revisions of spectrum usage rights were planned and carried out since 2006. In particular, Ofcom is liberalising 900 MHz and 1800 MHz spectrum for UMTS (Ofcom 2010e); the regulator is also liberalising licence-exempt spectrum access (cf., for instance, Ofcom 2006b and, recently, Ofcom 2010f, 2010g).

4.4.3.- The United States

In the US, liberalised spectrum management primarily relates to non-government spectrum, whereas the framework for government spectrum, especially for military use, continues to be 'command and control'. Liberalisation of non-government spectrum is being carried out gradually.

Liberalization of assignment

The US were initially reluctant to use market mechanisms to assign spectrum to operators, preferring to use comparative hearings or even a lottery system. Comparative hearings (or beauty contests) have been conducted for many decades, whereas lotteries were experimented only briefly in the early 1980s to assign cellular telephone licences, in an attempt to avoid issues attached to

[70] For instance, there are a number of potential uses of the 2.6 GHz spectrum including mobile broadband wireless services; each licence is tradable and various types of trade are permitted; see Ofcom (2008b) and Ofcom's consultation about liberalisation in the 900 MHz, 1800 MHz and 2.1 GHz spectrum bands (Ofcom 2009b).

comparative hearings.[71] In 1985, when the FCC first asked permission from the US Congress to auction spectrum licences, the Congress denied that request. In 1993, having seen the success of other countries (notably New Zealand and India[72]) in raising government funds, and with a pressing need to reduce the budget deficit, the US government espoused market-based mechanisms to assign spectrum (Kwerel and Rosston 2000): the *Omnibus Reconciliation Act* provided the FCC with the statutory authority to conduct spectrum auctions and, since 1994, the FCC has been running auctions.[73]

With regard to secondary assignments (i.e. spectrum trading) and further liberalization measures of spectrum management, the US government has long recognised that secondary markets can potentially serve as at least a partial correction to misallocation of spectrum in the hands of operators who do not use it to deliver the most valuable services. The SPTF Report (FCC 2002b) expressed its support for a clear definition of tradable property-like rights for spectrum (*ibidem*, esp. 55-8) and two alternative models of spectrum reuse were promoted: on the one hand, a

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[71] Hearing processes to uncover the value structure of firms over the available licences are very complex and may take a long time to allocate licences. With lotteries, hundreds of thousands of applications were submitted; it took many years for operators to obtain enough contiguous cellular licences to form businesses.

[72] India is not included in this survey. A discussion on spectrum auctions and policy in India can be found in Prasad and Sridhar (2009).

[73] As of July 1, 2009, the U.S. Government had realized $52.6 billion in license revenues (FCC 2009).

secondary markets model; on the other hand, an easements[74] or underlay model. In the former model, the licensee would determine what rights it is willing to sub-license, if any, and to whom; in the latter, the regulator would determine what rights if any must be provided to third parties. The SPTF also recommended the use of secondary market mechanisms, perhaps complemented by limited use of easements imposed by the regulator,[75] "to facilitate access to licensed spectrum for opportunistic, non-interfering devices that operate above the temperature threshold" (i.e. the energy limit that can exist in a band).[76]

Further measures to promote spectrum leasing have been discussed in the US. The SPTF advocated improvements in the FCC's regulations for spectrum leasing to facilitate spectrum trades;[77] they also considered that it might in some cases be appropriate to enable some private entity (a band

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[74] Under U.S. law, an easement is a limited right to use the property belonging to another, especially to gain access. Here, an easement would confer limited rights to use spectrum licensed to another user.

[75] In the literature, see for example Faulhaber (2005), who argues in favour of easements to enhance spectrum access, and Baumol and Robyn (2006), who raise concerns on the effectiveness of arrangements which are not based on market mechanisms. See also the discussion in Cave (2006: 228-31).

[76] The FCC proposed the model "interference temperature" for quantifying and managing interference in a specific band, by providing a cap on the total radiofrequency energy that could exist in the band. This model would focus on the actual radio frequency interference environment confronted by receivers, rather than on transmitter operations (FCC 2002a). The model might promote more liberal spectrum allocations.

[77] Webbink, then the Deputy Chief of the FCC's Office of Plans and Policy, argued that spectrum trading should be subject to few if any restrictions; that prior notification of the FCC should not be required; and that the FCC should eliminate most technical restrictions on usage except to the extent necessary to address interference (Webbink 1980).

manager or frequency coordinator) to manage opportunistic secondary users on the primary licensee's behalf.[78] FCC procedures for spectrum leasing were substantially liberalised by the *First Report and Order* in October 2003 (FCC 2003). That ruling enabled "most wireless radio licensees with 'exclusive' rights to their assigned spectrum to enter into spectrum leasing arrangements". The policies affected both mobile and fixed services (FCC 2004a). The *First Report and Order* provided two modes of liberalised arrangements. The first mode is spectrum manager licensing, where the licensee retains both *de jure* control (i.e. legal control) and effective *de facto* control (i.e. working control) over the leased spectrum. The ruling enabled leases without prior FCC approval within the perimeter drawn by a licence: in this mode, it is the licensee that is primarily accountable to the FCC for compliance with spectrum-relevant legal and regulatory obligations. The second mode is the *de facto* transfer mode, where the licensee retains *de jure* control, but transfers *de facto* control to the lessee; although this is a fast track approval process, prior FCC approval is still required.

[78] There has been no wide-scale implementation of the easements (or underlay) approach. Existing licensees are understandably uncomfortable with the risk of interference, and also with the risk that easements would lead to a "squatter's rights" problem—that once someone began to take advantage of an easement, it would be difficult or impossible to evict them later (Kwerel and Williams 2002). There are, however, instances where the FCC permits unlicensed devices to operate in licensed spectrum without first obtaining the permission of the licensee - UWB is a conspicuous example.

The *Second Report and Order* further liberalised the process (FCC 2004b). Most notably, it made overnight processing of lease applications available to a wide variety of lease arrangements where the parties certify that the arrangement does not raise any of a specified list of potential concerns (such as foreign ownership, license eligibility, or competition issues). The *Second Report and Order* (Section 88) also attempts to clear the way for cognitive radio and similar forms of opportunistic use of spectrum.

Liberalization of allocation

By and large, the US spectrum access regulation has focused on power limits to constrain spectrum use and 'harmful interference' among users; with regard to the issue of licence technology and service neutrality, the US approach has been to have only a minimum of constraints on spectrum access and licences:[79] unless precluded by international agreements, licensees are free, for the most part, to provide any service (e.g. fixed, mobile, private, common carrier) and free to deploy any technology they may see fit. For many services, including Personal Communication Services (PCS), constraints usually regard only power limits.[80] However, those limits may

[79] Technical constraints deal largely with mitigating the effects of harmful interference.

[80] The FCC limits essentially power radiated into adjacent frequency bands in the same geographic area, power radiated into adjacent geographic areas in the same frequency band and power radiated inside the assigned band for each class of station; see, e.g., Sutherland (2007).

greatly (or even excessively) restrict the range of services permitted in a radio frequency band (see criticisms in Hazlett 2001, 2008a).

4.4.4.- Australia

Australia began a series of major policy reforms in the early 1990s, when the government published the results of a spectrum policy review (BTCE 1990), which advocated, firstly, a greater emphasis on a market-based system of spectrum management to replace the previous complex and inflexible web of inter-layered regulation, and, secondly, a gradual introduction of a mixed market/ administrative system, with tradability of spectrum restricted to commercial applications. Afterwards, Australia has carried on its liberalizing efforts in a number of directions. In its *Five-year Spectrum Outlook 2009-2013* (*Outlook*), ACMA (Australian Communications and Media Authority) has recently analysed spectrum demand and set work programmes for the next five years. The *Outlook* states that ACMA will seek to set conditions of use that will allow and encourage spectrum licensees to move spectrum to its highest value use(s) with a minimum of regulatory intervention (ACMA 2009a). ACMA's *Outlook* considers that the highest value use of spectrum will change over time and "[t]his requires a regulatory system that has the flexibility to enable licensees to adapt spectrum access and usage to both market requirements and technological advances" (ACMA 2009a: 11).

Liberalization of assignment

Considerable amounts of spectrum have been made available to the market over the last 15 years in Australia, starting with the auction of MDS spectrum (2.3 GHz) in 1994. A number of broadcasting and open narrowcasting[81] licences were auctioned by the then Australian Broadcasting Authority (ABA) between 1996 and 2005. Revenue from auction of broadcasting licences amounted to about $693 million, with another $4 million realised from sale of open narrowcasting licences by the ABA. However, auction activity has slowed drastically since 2001 with the collapse of the *dotcom* boom.[82]

With regard to secondary markets for spectrum, Australia was one of the very earliest countries to allow spectrum trading. Apparatus licences[83] became tradable in 1995. Trading of spectrum licences was a fundamental element of the *Radiocommunications Act 1992*; however, the first spectrum licences were not issued until 1997. Spectrum blocks owned by licensees are

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[81] Open narrowcasting services are broadcasting services whose reception is limited in at least one of a number of ways specified in section 18 of the Broadcasting Services Act 1992; see http://www.acma.gov.au/WEB/STANDARD/pc=PC_90044 .

[82] See www.acma.gov.au .

[83] The *Radiocommunications Act 1992* provided for a new, comprehensive system of licensing. A *spectrum licence* represents the more market-oriented form of licensing; it authorises the operation of (non-specified) devices within a defined spectrum space and licence conditions, is fully tradable, can be divided and aggregated, is issued for periods of up to 15 years. An *apparatus licence* (the traditional command-and-control type licence) generally authorises the operation of a transmitter or receiver at a particular location. A *class licence* provides open access to spectrum on a shared basis: anyone can use equipment in class licensed bands, as long as they comply with the conditions.

represented in standard trading units (STUs), which are the smallest spectrum units recognised by the regulator and cover a predetermined geographic area and frequency band. STUs can be combined vertically, to provide increased bandwidth, or horizontally, to cover a larger area. In some cases the bandwidth is as small as 0.0125 MHz (cell size varies by location according to the population density).[84] Notwithstanding the introduction of STUs, the rate of trading has been quite slow. The Productivity Commission produced figures in its 2002 Radiocommunications report (PC 2002) purporting to show that the rate of trading in spectrum and apparatus licences was similar to annual turnover rates in the residential property market (PC 2002: 150).

In November 2008, ACMA published data on secondary market activity for spectrum licences (Table 3) and apparatus licences (Table 4).[85]

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[84] See http://www.pc.gov.au/__data/assets/pdf_file/0004/27256/sub028.pdf; see also ITU (2004).

[85] Both spectrum and apparatus licence trade/ transfer data is likely to greatly over-estimate the level of trading taking place. The Productivity Commission (PC) itself noted that many transfers were among related parties. The PC also identified a number of possible reasons for the slow supply of spectrum traded in secondary markets. See ACMA (2008, 2009b).

Table 3 - Trading in spectrum licences 1998 to financial year 2007-2008

Year	**MHz Traded**	**Total Licences Traded**	**Percentage Turnover Rate***
1998-1999	136	50	13.8
1999-2000	85	22	5.4
2000-2001	879	47	7.7
2001-2002	598	51	8.4
2002-2003	24	54	8.8
2003-2004	1315	24	3.6
2004-2005	50	6	1.0
2005-2006	5534	119	18.7
2006-2007	120	24	3.5
2007-2008	130	28	4.1
Total Trades		**425**	

Source: ACMA (2008: 11).
**Note: Turnover rate is the number of licences traded each year compared to the total number of spectrum licences on issue.*

Table 4 - Trading in apparatus licences since 2004

Licence	Standard transfers (percentage turnover)				
	01/01/04 to 30/06/04	**2004-05**	**2005-06**	**2006-07**	**2007-08**
Point to point	171 (0.9)	296 (0.8)	207 (0.6)	377 (1.0)	149 (0.4)
Point to multipoint	69 (2.3)	61 (1.0)	37 (0.6)	92 (1.5)	55 (0.9)
Land mobile system	615 (2.7)	497 (1.1)	731 (1.6)	649 (1.4)	694 (1.5)
Ambulatory	57 (1.1)	192 (1.8)	132 (1.2)	73 (0.7)	228 (2.1)
Paging system	8 (0.5)	32 (1.0)	29 (0.9)	27 (0.8)	19 (0.6)
Broadcasting service	6 (0.2)	152 (2.0)	302 (4.0)	17 (0.2)	143 (1.9)
Narrowband Area Service	10 (5.9)	15 (4.4)	49 (14.5)	64 (18.9)	7 (2.1)
Narrowcasting Service	79 (7.6)	127 (6.1)	54 (2.6)	80 (3.8)	114 (5.5)
Total licences transferred*	**1284 (1.5)**	**1794 (1.1)**	**1948 (1.2)**	**1628 (1.0)**	**1685 (1.1)**

Source: ACMA (2008: 12).
**Note: Total licences include non-assigned licences such as amateur, where a transfer is essentially the transfer of a call sign issue.*

Liberalization of allocation

Spectrum licensing has created additional flexibility.[86] Nevertheless, spectrum licences fall short of an ideal of technology or use neutrality - in

[86] Some examples are the introduction of the wireless broadband service (in part of the spectrum licensed band used elsewhere for 3G mobile telephony) and the introduction of a land mobile network for the Western Australia police force using the spectrum licensed 500 MHz band; Telstra was able to introduce a new W-CDMA 3G network into the 850 MHz (*Continued on next page*)

practice, technical frameworks for spectrum licences are designed with an intended use in mind.[87] Outside of the spectrum licensed system, apparatus licences remain very service- and technology-specific. Indeed, the degree of neutrality has receded in later spectrum licence band releases compared with the earlier ones. The Productivity Commission reported in 2002 that the deployment of spectrum licences has proceeded more slowly and has been applied in far fewer bands than was envisaged. It noted that spectrum licensing had been applied in only 13 of the 84 bands initially assessed by the regulator as being suitable for this licensing approach, around 30 percent of the spectrum covered by these bands (PC 2002). There has been relatively little progress since. ACMA's *Outlook* has recently stated, *inter alia*, that the creation of a new licence framework, which combines the characteristics of each of the existing licences types, may provide the necessary flexibilities to accommodate wireless access services into the future (ACMA 2009a). ACMA has investigated such a concept - called the 'private park' (this would be similar to class licensing arrangements for the 2.4 and 5.8 GHz bands, where

band, previously used for CDMA and CDMA2000 services, without the need for band re-planning or spectrum rule changes.

[87] See PC (2002). In 1996, the 1.9 GHz Band Plan stated that its primary purpose was "to facilitate the introduction in Australia of new systems known generally as cordless telecommunications services (CTS). By not specifying particular CTS systems, the Band Plan supports the competitive philosophy of technology neutrality"; see http://www.acma.gov.au/web/standard/pc=PC_285

each licensee could use the entire spectrum band and interference would be controlled by specifying conditions of use).

4.4.5.- New Zealand

New Zealand has been reducing command-and-control regulation for many years and its spectrum policy counts various market-based mechanisms introduced to improve spectrum management. The *Radiocommunications Act 1989* established a licensing regime which shares similarities to that in Australia. There are three licensing systems that apply to spectrum in New Zealand: i) the management rights regime (MRR), which is applicable to spectrum used primarily for commercial purposes; ii) the radio license regime (RLR), earlier known as apparatus licensing (an administrative assignment process which applies to spectrum used for applications in the public interest); and iii) general user licenses (GULs), for low powered devices such as garage door openers and WiFi.

Liberalization of assignment

Under the *Radiocommunications Act 1989*, the Ministry of commerce is provided with the authority to transfer portions of the spectrum to private management. Thus auctions have been used to sell spectrum since 1989,

when the first sealed-bid, second price tender system was used (the so-called Vickrey auction, with the bidder who submitted the highest bid winning the auction and paying the second highest offer price).[88] The *Radiocommunications Act* also allowed spectrum transfers in some cases.

The Ministry of economic development (MED) published a review of radio spectrum policy in 2005 (MED 2005b). This provided an assessment of the spectrum strategy implemented by means of the *Radiocommunications Act* in 1989 and identified areas for prioritisation in the coming years. In particular, this review noted that the level of trading had been low and mainly confined to FM and AM radio broadcasting licences (where a great deal of consolidation happened through takeover). In addition, trades had not involved a change in use. The small size of the market in New Zealand, entry barriers to sectors using radio spectrum (notably in mobile telecommunications) and availability of alternative spectrum in the RLR licensing framework were identified as factors limiting secondary spectrum trading. The MED has recently completed a major technology platform upgrade to the online public register of radio frequencies in order to ease

[88] In New Zealand spectrum auction design and methods have changed over the years. Drawing from experiences in other countries (especially in the US), New Zealand adopted the simultaneous ascending auction in 1996 and has used it for a number of auctions. In 2004 outcry auctions were used for the allocation of three spectrum licences that had been unsold in a previous simultaneous ascending auction (MED 2005a). In September 2009, MED (2009a) reported a reduction in government revenues from auction and spectrum sales activity ($0.249 million).

doing business (MED 2009a): this may facilitate transparent access to information on spectrum holdings and spectrum trading. The MED also proposed the development of a process for facilitating requests by prospective radio users to free up unused spectrum by cancelling or transferring radio licences.[89]

Liberalization of allocation

Technological and economic developments in the ICT area since the MRR was first introduced in 1989 have recently led the MED to review the way spectrum is managed under the longstanding administrative RLR. A discussion document was published in March 2009 (MED 2009b); as a result of the inquiry, no major changes were proposed by the MED. The Ministry for communications has agreed that the MED continue the RLR in its current form and consider congestion problems on a case-by-case basis. The Ministry also intends to explore options for minor improvements to the regime, including ongoing reviews of demand trends, coupled with a more systematic and forward-looking approach to enabling new technologies as they emerge.[90]

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[89] See http://www.rsm.govt.nz/cms/policy-and-planning/current-projects/radiocommunications/spectrum-management-in-the-radio-licensing-regime .

[90] *Ibidem*.

4.4.6.- Guatemala and El Salvador

Guatemala and El Salvador are two small Central American countries (with populations of 12,728,111 and 6,948,073 respectively) which decided in 1996-97 to adopt a simple but effective form of spectrum market which, in the case of non-public sector spectrum, gave private parties exclusive control over use of bandwidth and confined the regulator to defining, issuing and protecting spectrum rights (Ibarguen 2005; Hazlett *et Al*. 2006).

In Guatemala, before the enactment of the 1996 *Ley General de Telecomunicaciones* (General Telecommunications Law), spectrum was licensed by the state. The 1996 Law introduced the so-called *titulos de usofructos de frecuencias* (TUFs, also known as usufructs), which are the most salient feature of spectrum reform in Guatemala, as they established property rights over spectrum. TUFs can be leased, sold, subdivided or aggregated at will, and last for 15 years (renewable on request). A physical TUF is a paper certificate listing the frequency band, hours of operation, maximum transmitted power, maximum power emitted at the border, geographic territory and duration of right. The *Superintendencia de Telecomunicaciones* (SIT), an independent regulatory body established in 1995, is responsible for the registry of TUFs and is conceived as an administrator to enforce specified rules. "Essentially, the SIT is empowered to respond to private claims for spectrum access (TUFs) and to adjudicate disputes over

airwave rights" (Hazlett *et Al*. 2006: 7). The system is designed to have interference problems solved first by private negotiation and then private arbitration, if necessary (Ibarguen 2005). Regulation is thus restricted to setting aside bands for use by the state and adjudicating interference disputes which are not resolved by mediation. According to Ibarguen, one of the prime movers behind the reform, "one of the reasons for the vitality of the TUF market may be that interference problems have been negligible. Telgu (the largest private spectrum owner) has reported just one interference problem since 1996" (*ibidem*: 548).

In 1997 El Salvador adopted the *Ley de Telecomunicaciones* (Telecommunications Law) which brought about a reform similar to the one introduced by the *Ley General de Telecomunicaciones* in Guatemala. As a result, in Guatemala and El Salvador the management process was switched from a top down to a bottom up one. Any person or firm could request title to frequency bands not assigned to other users, and those and existing assignments became usufruct titles, offering the right to use and enjoyment by the right holder and not subject to being reclaimed by the government.

Following the enactment of the law, 3,985 TUFs have been auctioned between 1996 and 2004 with more than 75% of them auctioned between 1997 and 1999.[91]

[91] *Superintendencia de Telecomunicaciones de Guatemala*, 2006.

Spectrum trading is allowed in Guatemala and El Salvador. The sale of a TUF is accomplished by its endorsement by the seller, the buyer registering its new rights with the independent spectrum body. However, in Guatemala, change of use is permitted on transfer, whereas in El Salvador change of use is not allowed. In a recent study the authors note that "in Guatemala the regulatory authority has had difficulty buying back spectrum rights bands now needed for unlicensed use in keeping with new international recommendations to enable development of wireless broadband service using WiFi and WiMax technologies" (Wellenius and Neto 2007: 23).

4.5.- Discussion

In the previous section, liberalizing strategies and tactics adopted in a few countries were succinctly surveyed and individually discussed. The focus was on two major areas of spectrum management reform towards market-based methods of spectrum use:

(i) changes in the mechanisms to assign spectrum to users, either at the primary assignment stage (notably by means of auctions) or at the secondary assignment stage (i.e. trading); and

(ii) changes in the framework governing the allocation of spectrum to services, by means of reductions, as far as possible, of administrative constraints on spectrum use (especially in the form of a complex web

of technical restrictions set by regulatory fiat) and decentralization to (licensed) spectrum users of decisions regarding more or less ample bundles of spectrum rights.

This section discusses evidence from case studies using propositions about transition economics as theoretical lenses (cf. Section 3 above); those propositions about transition from administrative methods to market-inspired ones are thus contrasted with data on spectrum policies in the countries surveyed above. Table 5 below provides a synthetic overview.

Table 5 - Liberalization measures and timing in the areas surveyed

Part 1	Major liberalization measures and timing		
	Liberalization of assignment		Liberalization of allocation
	Spectrum auctions	Spectrum secondary trading	
Europe	2000-2001, 3G spectrum auctions	2002, Framework Directive	2005, communication on a market-based approach to spectrum management; 2006, Review of EU regulatory framework for ECS; 2007, European Parliament's resolution on spectrum management

Part 2	Major liberalization measures and timing		
	Liberalization of assignment		Liberalization of assignment
	Spectrum auctions	Spectrum secondary trading	
UK	2000, first auction	2004, Spectrum Framework Review	2004, Spectrum Framework Review; 2006, spectrum usage rights; 2010, licence-exempt spectrum
USA	1994, first auction	2002, SPTF report; 2003, First Report and Order; 2004, Second Report and Order	In principle technology and service neutral spectrum
Australia	1994, first auction	1995, apparatus licences; 1997, spectrum licences	1997, spectrum licences
New Zealand	1989, *Radiocommunications Act*		
Guatemala	1996, *Ley General de Telecomunicaciones*		
El Salvador	1997, *Ley de Telecomunicaciones*		

Strategies which guide spectrum management reform in those countries differ substantially. On the one hand, most countries appear to be

moving gradually, from 'command and control' to more decentralized decisions of spectrum management. Reforms usually started from changes in the mechanisms to assign spectrum to users, rather than expansions of private property-like methods to manage spectrum rights. This has happened in European countries (including the UK), Australia[92] and the US - although traditionally, in the US, the approach with regard to licensees' rights has been more liberal than elsewhere. New Zealand can be included in this group of countries: the *Radiocommunications Act 1989* modernized spectrum management with regard to assignment and allocation, but use of auctions was the first major market-based measure implemented. On the other hand, a few countries have pursued liberalization of spectrum management by simultaneously acting on aspects of spectrum assignment as well as allocation (e.g. Guatemala).

Theoretical analyses show that gradualism has advantages and disadvantages compared to a big-bang strategy (cf. Section 3 above). Using the results from the theory of transition economics for an assessment, it can be argued that, by and large, countries which have been following a gradual approach to spectrum management reform may have chosen an appropriate

[92] Australia did introduce spectrum licences (which are more flexible compared to apparatus licences) and made them tradable in 1997, but their use has not met regulators' expectations.

strategy.[93] However, a few aspects deserve further discussion. Those countries represent a fairly good number of the most developed economies, with a long history in wireless electronic communications using radio spectrum. Therefore, spectrum use legacy is likely to pose many constraints – including the presence of vested interests[94] - on the implementation of reforms, which may show greater degrees of complexity, compared to countries with less developed economies and different (shorter) histories in electronic communications. The considerable amounts of consultation and analyses carried out by regulators, who have adopted a gradual reform strategy, seem to support this point. Thus the theoretical relationship between the speed of transition and `informativeness` appears relevant: in areas such as the UK and the US, the implementation of a gradual spectrum management reform has favoured collection of information about the effects of various reform actions on current circumstances. This might also provide, normatively speaking, useful inputs for future tactics. Indeed, the case of Australia offers evidence which supports the view that gradualism may be better than big-bang strategies in the management of transitions from 'command and control' towards market methods: liberalization of spectrum

[93] Success of a policy is often difficult to define and measure, because various parties have different goals and perspectives (cf. Patton and Sawicki 1993: 364 ff.).

[94] The literature on transition economics considers issues of political economy, which are not investigated here. In the case of spectrum liberalization, mobile operators and broadcasters may have strong interests and incentives in keeping close to traditional spectrum management; their customers' welfare needs consideration too.

rights has proved more complex than initially envisaged; therefore Australian regulators have in some circumstances slowed down the liberalization process, or even reverted back to more centralised management of spectrum rights, at least in some frequency bands.

Nevertheless, theoretical propositions about the role of `informativeness` in carrying out reforms cannot be used, given available data, for precise positive assessments, because data on advantages and disadvantages (benefits and costs) is lacking.[95] Existing analyses of costs and benefits of spectrum policy reforms do not examine reversal costs, which are relevant in the formal analysis suggested in the literature on transition economics. Moreover, it is not possible to collect empirical data about the counterfactual case, because the choice for gradualism excludes big-bang strategies in any given country. Thus, it is difficult to assess what would have happened in the case of more rapid reforms (or vice versa) looking at the data collected. Recently, European regulators have analysed a few spectrum policy options and stated that "there would seem to be a need for further economic analyses of the costs and benefits of the various options available, e.g. measuring the value of windfall gains and the costs of any decrease in competition" (ERG and RSPG 2009: 24).

[95] A review of studies which have provided estimates of costs and benefits of more liberal spectrum regulation can be found in London Economics (2008). In Europe, an influential report was prepared for the EC by Analysys *et Al*. (2004).

A few studies provide, however, *ex ante* valuations of net benefits (expected outcomes) from lifting constraints attached to licences, and show substantially high figures. This might imply that gradual or incremental moves towards liberalized spectrum management are not the best choice, if change is proceeding too slowly and considerable benefits are not enjoyed for some time,[96] especially because of partial reforms which have changed only assignment methods quickly. The cases of Guatemala and El Salvador seem to provide evidence that fast moves towards markets for spectrum rights can be successful liberalisation strategies (cf. Ibarguen 2005; Hazlett *et Al*. 2006). However, the apparently good outcomes of spectrum policy reform in those two small countries, which are close to each other,[97] do not allow generalizations to countries that do not share similar features and contexts (Yin 2009: 43-4; Gerring 2007: 43-50, 76-80).

In those countries where spectrum management reform has embraced a (cautious) gradual approach, liberalization moves have proceeded incrementally. In general - once decisions to use market mechanisms to assign spectrum were made - the introduction and implementation of auctions and secondary trading happened at relatively early stages (although

[96] See London Economics (2008); see also Hazlett (2008c) for an analysis of cellular licences and Wellenius and Neto (2007) for the case of spectrum policy reform in developing countries.

[97] Dewatripont and Roland (1995) also consider that countries look at what others do in deciding their reform strategies. It can be argued that El Salvador has followed the strategy adopted in Guatemala.

spectrum trades have been fewer than usually expected); liberalization of licence conditions towards technology and service neutrality has proved complex and slow. By and large, this might be explained taking into account that liberalization of assignment is a relatively easier action, compared to liberalization of spectrum use with regard to services and technologies (which requires thorough analyses of possible harmful interference).[98] In addition, it can be argued that governments have relatively strong incentives to introduce auctions soon, as auctions provide funds to cover public expenditure. However, the theoretical analysis suggests that, in those circumstances, gradualism may not be preferred to big-bang strategies, because delays in the implementation of the various components of a comprehensive spectrum management reform package may be too costly, especially in the case of significant benefits associated to liberal licence conditions.

Theoretical propositions also point out that, if gradualism is optimal and reforms included in a package differ only in their riskiness, it is optimal to start with the riskier reform. The data seem to support the view that, *coeteris paribus*, liberalizing licence conditions and establishing property-like private rights over spectrum is riskier than changing mere assignment procedures (either primary or secondary ones). Accordingly, from a

[98] On a continuum of liberalization measures, ordered in increasing degree of complexity, one might locate auctions, secondary trading and service/ technology neutrality.

normative perspective, spectrum policy should start from the former rather than the latter (when gradualism is chosen). Furthermore, the theory shows that, if the only difference is in the expected outcome and reforms do not proceed quickly, it is better to start with the reform with the higher expected outcome. Thus, there is an additional reason suggesting that starting from liberalizing licence conditions might be a better way to manage the transition from 'command and control' towards market methods: available research shows much greater benefits from spectrum liberalization of licence conditions rather than trading of spectrum licences (London Economics 2008).

In conclusion, the countries surveyed in this study have gone through different experiences of spectrum management and their approach to reform varies. They have proceeded at different speeds, using different strategies and tactics. There is no unique recipe of spectrum policy reform, as shown by the cases analyzed above.[99] By and large, it seems plausible that radical solutions may be easiest to implement when spectrum management is least developed (Wellenius and Neto 2007). The cases of small countries like Guatemala and El Salvador may be regarded as evidence supporting this claim.

[99] As noted by two authors in a recent paper, "[t]hese idiosyncratic spectrum policies illuminate possible paths to liberalization, an important normative exercise left for later research" (Hazlett and Muñoz 2009: 276).

The theoretical propositions elaborated in the area of transition economics might add a few more specific insights to the debate and analysis of spectrum policy reforms, especially with regard to comparative advantages and disadvantages of big-bang or gradual reform strategies as well as issues of sequencing (for gradual reforms). In particular, the theoretical framework proposed for the analysis might enable elaborations of spectrum management reform based on more clear-cut elements, such as expected outcomes, riskiness, reversal costs and `informativeness` of gradual *versus* fast liberalization measures. Thus it can be argued that future spectrum liberalization moves might benefit from this analysis – for instance, the issue of reversal costs, currently neglected, might be a relevant issue to be taken into account for decisions about how to best manage spectrum policy reform. One might also imagine that, in the future, a country could use Dewatripont and Roland's work as a normative guide for spectrum strategy and policy.

Chapter 5. Competing to purchase spectrum commons

5.1.- Introduction: the problem of using the market to allocate spectrum commons

The crucial point of spectrum management reform is to change the regulation of radio frequencies to direct spectrum to the most valuable uses. One way of looking at this is to see it as a process of normalising the treatment of spectrum as an input into a variety of production processes. This can be done by applying a market-based approach to radio frequency access wherever possible.[100]

The introduction of spectrum auctions to assign frequency bands for 3G mobile communications brought market forces and prices into the area of spectrum management, as many countries worldwide have recently used market mechanisms to assign rights over radio frequencies. However, the process of spectrum allocation was not delegated to the market and auction winners could secure spectrum for exclusive access to their licensed bands. In particular, the problem of efficient allocation of spectrum for unlicensed

[100] Cf. the discussion in the previous chapters, esp. Sections 1.1 and 2.1.

operations has not received much attention so far. Actually, a major difficulty with market-based allocation of "unlicensed" spectrum (i.e. radio frequencies that can be used on a non-exclusive basis) is to aggregate individual demands for it in the same way as licensed service providers, such as mobile operators, can express their (derived) demand for radio frequencies (Cave 2006; Mott MacDonald *et Al*. 2006).

The aim of this work is to suggest a mechanism – alternative to administrative fiat - to allocate and assign spectrum commons for unlicensed operations, notwithstanding the practical difficulties involved in the use of markets for their provision. Therefore, the rest of this chapter is organized as follows. Section 2 provides a review of solutions proposed in the literature from two perspectives: on the one hand, it discusses briefly mechanisms suggested to allocate spectrum for unlicensed operations; on the other hand, it looks at the literature on the efficient provision of public goods and considers models of "matching behaviour". Section 3 introduces our basic model, which is a translation of Cave and Salant's model on cartel quotas under majority rule to our problem (Cave and Salant 1995), assuming crucial knowledge about participants. Section 4 explores that translation by verifying, firstly, that an analogous set of properties is satisfied and that the median-index theorem (*ibidem*) applies – *mutatis mutandis* - to our setting. This might contribute to overcome some of the difficulties involved in the

implementation of matching behaviour, as – by using a majority vote - firms bidding to acquire a spectrum commons must contribute a minimum amount of their wealth; the sum of contributions offered for a spectrum commons is then compared to bids for spectrum for exclusive access. Hence spectrum flows to the most valuable use. Section 5 closes this chapter.

5.2.- The problem of collecting funds for spectrum commons: a review of previous proposals

The traditional allocation of unlicensed bands by administrative fiat is "arbitrary and unsatisfactory" (Cave 2006: 224). An alternative approach was used by Indepen, Aegis and Ovum (2006) in their report for the UK regulator, under its licence-exemption framework review (Ofcom 2007b): the consultants attempted to attribute a value to licence-exempt spectrum by a cost-benefit analysis of services that might develop in unlicensed access bands.

In February 2008, a completely different approach, built around spectrum auctions, was proposed by the FCC (Federal Communications Commission, i.e. the US spectrum regulator); the FCC published two working papers by Bykowsky, Olson and Sharkey (2008a, 2008b), which contribute to the design of market mechanisms to allocate unlicensed spectrum. Bykowsky *et Al*. suggest a clock auction to efficiently allocate

available radio frequency bands between licensed services and unlicensed operations; in particular, taking into account public goods characteristics of spectrum bands allocated to unlicensed uses, the authors suggest a model where participants' bids are summed up, if those bids are submitted for the unlicensed spectrum rule (thus creating an open platform[101] for devices and applications); therefore each spectrum block up for auction will be governed by the licensing rule that gets the highest (aggregated) bid. The authors assume that bidders submit offers for the provision of spectrum under Nash-Cournot behaviour and then compare the outcomes of their simulations with the Pareto efficient equilibrium. However, the solution to the incentive problem – that is to induce bidders to get as close as possible to the efficient outcome - is outside the scope of their work. Economic theory has suggested sophisticated mechanisms to implement an efficient allocation of public goods (for surveys, see: Green and Laffont 1977; Groves and Ledyard 1987; Laffont 1987). The general results are technically impressive, but the proposed solutions are frequently rather complicated and, hence, impractical for producing plausible mechanisms which induce efficient contributions to public goods (see criticisms in Walker 1981: 71; Laffont 1987: 567; Jackson and Moulin 1992: 2; Falkinger *et Al*. 2000: 247). Therefore, several authors

[101] Under an unlicensed access rule, wireless network operators are not allowed to restrict access by radio devices or block software applications; therefore, this rule creates an open platform (whereas a licensed access rule creates a closed platform). This seems to reflect the network-centric service-provision approach (Lehr 2005).

have suggested incentive mechanisms which seem to meet the requirements of simplicity (Falkinger *et Al*. 2000).[102]

Among those incentive mechanisms, some useful ideas for the efficient allocation of unlicensed spectrum may be found in the literature on voluntary collective action (see, e.g., Olson 1965 and the references in Stigler 1974), which is not concerned with the problem of demand revelation directly and does not involve coercion solutions. In particular, a voluntary collective action approach to the optimal provision of public goods is based on mutual subsidization by agents of their contributions to the public good. This approach, which is aimed at increasing voluntary contributions to the provision of a public good by "matching behaviour", was originally suggested by Joel Guttman in 1978 (Guttman 1978).[103] Matching behaviour is "a strategy that makes an agent's contribution to the provision of a public good conditional on the contributions of his counterparts in order to induce them to contribute as well. Unconditional contribution induces free-riding and thus is suboptimal" (Guttman 1986: 172). Guttman's setting is a two-stage non-cooperative game: the first stage of the game is played to choose simultaneously the matching rates (m_i) – i.e. the rate at which each firm i will

[102] For some of those mechanisms, for example the compensation mechanism (Varian 1994a) and the Falkinger mechanism (Falkinger 1996), their effectiveness has been tested in experiments (Bracht *et Al*. 2008).

[103] See Guttman (1987) for a list of references to his works on matching behaviour. See also Danzinger and Schnytzer (1991). A related mechanism is the compensation mechanism (Varian 1994a, 1994b).

subsidize the sum of the flat contributions offered by the other firms, which are as yet undetermined; given the matching rates chosen in the first stage, the second stage of the game is played to determine, again simultaneously, the autonomous flat contributions (a_i) – i.e. the amount of money which each firm will provide to acquire bandwidth, in addition to the money contributed by the matching mechanism. Therefore, firm *i*'s final contribution x_i is given by:

$$x_i = a_i + m_i \sum_{j \neq i} a_j$$

where:

a_i = firm *i*'s flat contribution;

$\sum_{j \neq i} a_j$ = sum of the flat contributions offered by firm *j*, $j \neq i$;

m_i = firm *i*'s matching rate.

The total contribution *X* to the provision of spectrum for unlicensed operations would be the sum of individual contributions by the *n* firms:

$$X = \sum_1^n x_i = \sum_i a_i \left(1 + \sum_{i \neq j} m_j \right).$$

Any of the firms solves a maximization problem, that can be stated as follows:

$$\max \ \pi_i = f(X) - x_i,$$

where f is an appropriate twice continuously differentiable function, which captures the benefits to firm i associated to total contribution X; x_i can be regarded as i's cost to participate in the provision of the good.

The model predicts Pareto optimal provision of a non-excludable public good by identical actors with perfect information, regardless of the number of actors and by two non-identical actors. Moreover, the author finds that "[w]ith more than two non-identical actors, some indeterminacy emerges in the equilibrium, and inefficient equilibria become possible" (Guttman 1978: 254). Hence, Guttman's model offers interesting theoretical results. However, implementation is difficult, because the model is based on a two-stage game that is hard to play effectively, especially when the number of firms grows above a few units (Guttman 1986).

Recently, Gerber and Wichardt (2009) proposed a two-stage mechanism to establish positive contributions to public goods in the absence of strong institutions to sanction free-riders, as in the case of international agreements. The idea of their mechanism is to allow players to take an action, prior to the contribution stage, which renders it a dominant strategy to comply with the agreement (*ibidem*, esp. 430). Players commit to the public good by paying a deposit prior to the contribution stage; if there is universal commitment, deposits are immediately refunded whenever players contribute their specified shares to the public good.

In the following sections, we will assume that some spectrum may be used as commons for collective use with appropriate standards and suggest an approach which – in the spirit of the one proposed by Bykowsky *et Al*. (2008a,b) - is based on an auction mechanism to allocate spectrum efficiently between licensed and unlicensed uses. At the same time - and in the spirit of Guttman's matching behaviour – our approach requires participants who bid for spectrum commons to contribute at least a minimum fraction of their wealth; this fraction is set by majority vote (each firm bidding for a spectrum commons has one vote) and we will show that a translation of the median-index theorem applies to our circumstances. Thus, our envisaged mechanism is such that: (i) in the first stage, potential users of unlicensed spectrum vote on a common minimum percentage of wealth to pay; (ii) in the second stage, unlicensed users bid at least the common minimum percentage for unlicensed use, the auctioneer compares the total of these bids with the highest bid (if any) for licensed use, and provisionally assigns the lot to licensed or unlicensed use accordingly. This continues till there is no excess demand. If the lot goes to licensed use, the winner pays the larger of the next-highest licensed-use bid or the total of the unlicensed-use bids; if the lot goes to unlicensed use, each bidder 'pays' the smallest amount they could have bid without changing the use class.

5.3.- Basic (translated) model

Our basic model is a tentative translation of an earlier model developed by Cave and Salant (1995) on cartel quotas under majority rule; we propose a translation of that earlier model to the circumstances that we are investigating and we will use the following notation:

N number of unlicensed bidders;

w_i bidder *i*'s (non-negative) exogenous wealth, which is assumed to be common knowledge[104] and immediately convertible in assets accepted by the seller – i.e. the auctioneer - at no cost (w_i is a firm-specific scalar);[105]

c_i constant cost of capital (opportunity cost of funds) for firm *i*;

b_i 'individual' bid for unlicensed access, i.e. the amount of assets offered as individual contribution to the purchase of spectrum for unlicensed operations;

B_{-i} sum of individual contributions offered by the n firms, excluding firm *i*, i.e. $B_{-i} = \sum_{j \neq i} b_j$;

[104] For instance, firms` balance sheets are audited by an independent auditor and published; this would provide reliable information about firm *i*`s wealth, as represented in its accounts.

[105] Furthermore each bidder`s wealth is larger than his valuation for the spectrum; a similar simplifying assumption is used, e.g., in Moulin (1992).

F minimum fraction (or percentage) of wealth to pay, chosen by the N bidders by (unweighted) majority-rule voting; hence F will be the same for every player. F is a committee's prior choice and if the committee chooses the fraction F, then firm *i*'s contribution must be no lower than $F\ w_i$.

It is assumed that it is possible to identify the firms which will definitively participate in the mechanism. Firms are then indexed in order of ascending cost of capital; if two firms have the same cost of capital, firms are indexed in order of increasing wealth:

if $c_i > c_j$ or

if $c_i = c_j$ and $w_i > w_j$

then $i > j$

(if $c_i = c_j$ and $w_i = w_j$ then assign indexes arbitrarily).

Firms bidding for unlicensed spectrum are assumed to spend their wealth on contributions to the purchase of a public good input. To avoid free-riding, those firms must join a committee, whose fundamental task is to vote by majority on the minimum fraction F of individual wealth that must be contributed.

Let $B = \sum_1^N b_i = B_{-i} + b_i$ denote the aggregate bid for unlicensed spectrum; then $B \geq \sum_1^N F w_i = F \sum_1^N w_i$. Also, let f(B) denote average benefits (e.g. revenues) attainable by winning aggregate bids B.

Firm *i* is assumed to maximize a profits function, as specified below. For this purpose, *i* has to choose its preferred contribution (b_i) to the collective project, given the contributions offered by other firms and the previously selected fraction F (where $F \in [0, 1]$):

$$\max \quad b_i\,[f(B) - c_i] = b_i\,[f(B_{-i} + b_i) - c_i]$$

s.t.

$$b_i \geq F\,w_i.$$

Each bidder's equilibrium profit π_i depend, *inter alia*, on the prior choice of F; hence they are regarded as induced profits $\pi_i(F)$. Also, equilibrium profits will be zero for every unlicensed bidder if B is less than max { L_k }, where L_k is the amount of money offered by firm *k* who is bidding against everyone else to get spectrum for exclusive licensed access (*k* is not in the group of n firms bidding for unlicensed spectrum and therefore is not in the voting committee):

$$\pi_i = 0 \qquad \text{if} \qquad B < L_k.$$

Assume total benefits TB depend on the amount of capital collected in the following way:

$TB = b_i \cdot [f(B_{-i} + b_i)]$.

Then marginal benefits MB are:

$MB = \partial TB / \partial b_i = f(B_{-i} + b_i) + b_i [\partial f(B_{-i} + b_i) / \partial b_i]$;

in addition assume MB is strictly decreasing.

With MB strictly decreasing, $f(B_{-i} + b_i)$ decreases. If at least one firm is constrained to bid the minimum (i.e. $b_i = Fw_i$) then, as F increases, Fw_i increases too and $f(B_{-i} + b_i)$ decreases. However, π_i (F) will be positive as long as $f(B_{-i} + b_i)$ exceeds c_i .

5.4.- Analysis of the basic model

5.4.1.- Economic equilibrium which would result if the committee had voted for any arbitrary fraction of wealth

Translating Cave and Salant's assumption to our setting, it is assumed that:

- the average revenue function f(B) is strictly decreasing and twice continuously differentiable;
- the total benefit function [i.e., $b_i * f(B)$] is strictly concave;
- if $b_i \rightarrow \infty$ then lim f(B) = 0;

- there would be positive profits if the lowest-cost firm contributed funds whose cost of capital is c_1 [i.e., $f(B) - c_1 > 0$].

Given those benefit assumptions, then a unique Cournot equilibrium - induced by any given fraction F of wealth - exists in pure strategies.

Proofs.

Existence and uniqueness are proved in Appendix (part A).

The equilibrium is characterized by an aggregate bid (B) divided into a vector of individual bids (b_1, b_2, .., b_N) satisfying one of the following conditions for i = 1, 2, .., N:

a) unconstrained bidder: $f(B) + b_i f'(B) - c_i = 0$ and $0 < Fw_i < b_i$;

b) constrained bidder: $b_i = Fw_i$ and $f(B) + Fw_i f'(B) - c_i \leq 0$

(firm *i* would like to contribute less than $b_i = Fw_i$, but – since *i* joined the procedure – it must contribute at least a minimum amount of funds, according to F);

c) outsider: $E[f(B)] - c_o \leq 0$

(this firm is not one of the N bidders for unlicensed spectrum: it is better off if it does not participate in the procedure, because expected average benefit is already so low that the firm would not be able to make a positive profit if it participated; of course, $b_o = 0$).

5.4.2.- Fraction which a regulated committee would select under (unweighted) majority rule

Assume voters (i.e. firms) are foresighted and self-interested. We want to prove that the median-index theorem (Cave and Salant 1995) applies to our setting. The median-index theorem states that – assuming an odd number of voters (N) are to select an alternative from a compact one-dimensional set of alternatives by simple majority rule – every ideal point of the firm with the median index on the committee will be weakly preferred to any other point by a majority of the voters, if the following preference assumptions are met:

1.- continuity, i.e. each voter's preferences can be represented by a continuous real-valued function on the set of alternatives;

2.- unconstrained monotonicity, i.e. each voter's preference function is monotonically decreasing above its cutoff;[106]

3.- nesting of cutoffs and partial agreement, i.e. if voters are indexed so that someone with a higher cutoff has a lower index, then the preferences of any two voters display partial agreement[107] below their cutoff points.

[106] In our setting, a "cutoff" is the wealth fraction which exactly induces firm *i* to contribute the amount of funds that firm *i* would freely choose to maximize its profits (i.e. the constraint is just binding). A unique cutoff is associated with each firm.

Therefore we have to prove – preliminary - that an analogous set of preference assumptions is satisfied in our setting. Given the benefit assumptions above, we will introduce a 'translation' of the regularity condition to our setting. Then, following Cave and Salant (1995), we will show that our benefit assumptions and regularity condition are sufficient for a set of preferences[108] to display the following properties:

a) nested cutoffs;

b) partial agreement;

c) unconstrained monotonicity;

d) continuity.

This will allow us to prove the existence of a Condorcet winner, that is a fraction of wealth to pay which will be selected by some majority of the firms. We will then consider uniqueness of a Condorcet winner.

Let B(F) denote the aggregate equilibrium bid induced by a majority decision to contribute fraction F of wealth. Also, let F_j denote the fraction that would just bind on firm *j*, i.e. *j*'s marginal cost and benefit are equal for $F = F_j$. Thus, given $B_{-j}(F_j)$, F_j is implicitly defined as

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[107] The agreement in preference is said to be partial when no restrictions are placed on the preference if the firm with the smaller index prefers the larger fraction (or vice versa). In contrast, the agreement is said to be complete when firms have the same marginal cost and must therefore rank the two fractions identically (Cave and Salant 1987).

[108] Cave and Salant (1995) start showing properties for the induced preferences and then examine the majority-rule voting behaviour of any set of agents whose preferences satisfy a generalization of those properties. Profit functions describe our (induced) preferences.

$f(B(F_j)) + F_j w_j f'(B(F_j)) - c_j = 0$.

F_j is regarded as *j*'s "cutoff", because it is the fraction which exactly corresponds to the amount of *j*'s wealth that *j* would bid to maximize its profits – whereas, above that fraction, *j* has to contribute more than the amount where its marginal benefit equals marginal cost (*j*'s profit maximization is constrained).

Regularity condition

In Cave and Salant's model, the regularity condition is a crucial one: "[it] is necessary and sufficient for the cutoffs to be nested and […] is sufficient for the existence of a Condorcet quota. When cutoffs are nested, the induced preferences display a property we refer to as 'partial agreement'" (Cave and Salant 1995: 87); in addition to nesting and partial agreement, the preferences display "continuity" and "unconstrained monotonicity" (Cave and Salant 1995: 88).

We will therefore elaborate an analogous regularity condition, for the circumstances that we are investigating. Assume that the following regularity condition holds for each pair of firms *i* and *j* such that i > j:

$f'(B(F_j)) F_j (w_i - w_j) \leq c_i - c_j$.

This is a reduced form of

$f(B(F_j)) + f'(B(F_j)) F_j w_i - f(B(F_j)) - f'(B(F_j)) F_j w_j \leq c_i - c_j$

where – given the selected fraction $F = F_j$ - the first part of the left-hand side is the marginal benefit for firm *i* when firm *i* bids the minimum amount required by the committee ($b_i = F_j w_i$); while the second part of the left-hand side is the marginal benefit for firm *j* (*j* would bid exactly that fraction of its wealth which is required by the committee). The right-hand side is the difference in the costs of capital for firms *i* and *j*.

Then any fraction binding on one firm must also bind on firms with greater indexes: for instance, if F_j is a fraction binding on firm *j* and i > j, then F_j must also be binding on firm *i*. In fact, if F_j is binding on *j*, when $F = F_j$ marginal benefit and marginal cost are equal for firm *j*, but firm *i* would be better off with a fraction F lower than F_j (i.e. $F < F_j$), because when $F = F_j$ firm *i*'s marginal benefit are lower than its cost of capital. Nevertheless it must contribute at least $F_j w_i$. This can be shown by re-writing the regularity condition in the following way:

$$f(B(F_j)) + f'(B(F_j)) F_j w_i - c_i \leq f(B(F_j)) + f'(B(F_j)) F_j w_j - c_j$$

and, given that F_j is just binding on *j*, $f(B(F_j)) + f'(B(F_j)) F_j w_j - c_j = 0$; therefore

$$f(B(F_j)) + f'(B(F_j)) F_j w_i - c_i \leq 0$$

which shows that, when $F = F_j$, for firm *i* marginal benefits are lower than its cost of capital (or, if equality holds, F_j is just binding on *i* as well as on *j*).

If firms face the same cost of capital, but firm *i* has greater wealth than firm *j*, $c_i = c_j$ and $w_i > w_j$; the regularity condition therefore becomes:

$f'(B(F_j))\, F_j\, (w_i - w_j) \leq 0$.

This can be manipulated[109] to get

$f(B(F_j)) + f'(B(F_j))\, F_j w_i \leq f(B(F_j)) + f'(B(F_j))\, F_j w_j = c_j = c_i$

which, again, shows that for $F = F_j$ and $c_i = c_j$ marginal benefits are lower than firm *i*'s cost of capital (or, if equality holds, F_j is just binding on *i* as well as on *j*).

It can be noted that, if firm *i* and firm *j* have the same wealth, $w_i = w_j$ (and $c_i \geq c_j$); then in the regularity condition

$f'(B(F_j))\, F_j\, (w_i - w_j) \leq c_i - c_j$

the left-hand side is equal to zero; therefore the regularity condition holds (by assumption, $c_i - c_j \geq 0$).

The regularity condition also holds in applications where fractions are set equal to the Cournot-equilibrium individual contributions prior to the formation of a (voting) committee: this is the case where no minimum bid is

[109] Recall: $F = F_j$ which is the fraction just binding on firm *j*; hence marginal benefit and cost of capital are the same for firm *j*. Moreover, in this case it is assumed that the difference in the costs of capital is zero – i.e. firms face the same cost. Thus, for $F = F_j$ marginal benefit for firm *j* is also equal to firm *i*'s cost of capital.

required from each player, who can bid as little as he likes (the Cournot contribution).

Is the regularity condition sufficient for the existence of a Condorcet fraction? Cave and Salant (1995: 89) show that "any set of preferences displaying nested cutoffs, unconstrained monotonicity, partial agreement, and continuity must have a Condorcet winner". Therefore, to go on with the 'translation' of Cave and Salant's model, the average benefit assumptions, together with the regularity condition, should be sufficient for the set of induced preferences arising from the Cournot equilibrium to display the following properties:

1) nested cutoffs;
2) partial agreement;
3) unconstrained monotonicity;
4) continuity.

Those properties are translated below to our circumstances.[110]

1) Nested cutoffs.

If i > j , then $F_i \leq F_j$ for any couple of firms; hence cutoffs are nested:

$F_N \leq F_{N-1} \leq \ldots \leq F_2 \leq F_1$

[110] Proofs similar to those elaborated by Cave and Salant will be presented (some of those proofs are relegated to the appendix).

(that is, if firms face different marginal costs of capital, when i > j firm *i* has greater marginal cost than firm *j* - hence firm *i* prefers a fraction F lower than F_j; if marginal cost is the same for both firms, and firm *i*'s wealth is greater than firm *j*'s wealth, then again firm *i* prefers a fraction F lower than F_j)

The 'translated' regularity condition is necessary and sufficient for the cutoffs to be nested:

$f'(B(F_j))\, F_j\, (w_i - w_j) \leq c_i - c_j$ iff $F_N \leq F_{N-1} \leq \ldots \leq F_2 \leq F_1$.

Note that, by adding the implicit definition of F_j and the regularity condition, we obtain that also firm *i* is constrained at fraction F_j :

$f(B(F_j)) + F_j\, w_j\, f'(B(F_j)) - c_j$ (implicit definition of *j*'s cutoff)

$+ f'(B(F_j))\, F_j\, (w_i - w_j) - c_i + c_j$ (regularity condition)

$= f(B(F_j)) + F_j\, w_i\, f'(B(F_j)) - c_i \leq 0$ (*i* is constrained by fraction F_j).[111]

2) Partial agreement.

If two fractions of wealth bind on each of two firms and one firm strictly prefers a particular fraction (case 2.a below) – or is indifferent between the two fractions (case 2.b below) - it is possible, in some circumstances, to

[111] The implicit definition of *j*'s cutoff is $f(B(F_j)) + F_j\, w_j\, f'(B(F_j)) - c_j = 0$; the regularity condition is $f'(B(F_j))\, F_j\, (w_i - w_j) \leq c_i - c_j$ and it is a non-positive number; $f(B(F_j)) + F_j\, w_i\, f'(B(F_j)) \leq c_i$ shows that *i* is constrained at F_j.

deduce that the other firm likewise – and respectively - strictly prefers the same fraction, or weakly prefers one of the two fractions. "The agreement in preference is said to be 'partial' rather than 'complete' since no restrictions are placed on the preference if the firm with the smaller index prefers the larger [fraction] or, alternatively, if the firm with the larger index prefers the smaller [fraction]. In contrast, firms with identical marginal costs must rank the two [fractions] identically even in these cases. Agreement is then said to be 'complete'" (Cave and Salant 1995: 87).

2.a) Strict preference:

for any two firms *i* and *j* such that i < j and any pair of fractions ϕ and F such that $\phi < F \leq F_j \leq F_i$:

if $\phi \succ_i F$ then $\phi \succ_j F$

or

if $F \succ_j \phi$ then $F \succ_i \phi$.

"That is, if the firm with the smaller index strictly prefers the smaller [fraction], then so must the firm with the larger index; reciprocally, if the firm

with the larger index strictly prefers the larger [fraction], then so must the firm with the smaller index" (*ibidem*).[112]

Proof.

Since $\phi \succ_i F$

$\phi\, w_i \{f(B(\phi)) - c_i\} > F\, w_i \{f(B(F)) - c_i\}$;

also, since $c_i \leq c_j$ and $\phi < F$

$-\phi (c_j - c_i) \geq -F (c_j - c_i)$.

Dividing the first inequality by w_i, adding the second weak inequality and multiplying by w_j, we obtain

$\phi\, w_j \{f(B(\phi)) - c_j\} > F\, w_j \{f(B(F)) - c_j\}$

which confirms that $\phi \succ_i F$.

The reciprocal statement can be verified *mutatis mutandis*.

2.b) Indifference:

for any two firms *i* and *j* such that i < j and any pair of fractions ϕ and F such that $\phi < F \leq F_j \leq F_i$:

[112] If firm i strictly prefers F to ϕ and both fractions bind on i, then $F\, w_i \{f(B(F)) - c\} > \phi\, w_i \cdot \{f(B(\phi)) - c\}$. We obtain $F\, w_j \{f(B(F)) - c\} > \phi\, w_j \{f(B(\phi)) - c\}$ by multiplying by the positive number w_j/w_i,. Therefore, if both fractions also bind on firm *j*, firm *j* strictly prefers F too.

if $\phi \sim_i F$ then ϕ weakly $\succ_j F$

or

if $F \sim_j \phi$ then F weakly $\succ_i \phi$.

"That is, if the firm with the smaller index is indifferent between the two [fractions] then the firm with the larger index must weakly prefer the smaller [fraction]; reciprocally, if the firm with the larger index is indifferent between the two [fractions], then the firm with the smaller index must weakly prefer the larger [fraction]" (Cave and Salant 1995: 88).

Proof.

Both statements can be verified *mutatis mutandis*.

3) Unconstrained monotonicity.

If firm *i* is unconstrained and at least one firm is constrained,

$F_N \leq F \leq F_i$

then *i*'s induced profits $\pi_i(F)$ is increasing in F.

4) Continuity .

π_i (F) is a continuous function.

Proofs.

Unconstrained monotonicity and continuity are proved in Appendix (part B).

5.4.3.- Validity of the median-index theorem in our setting

We have shown a translation of the (generalized) preference assumptions required by Cave and Salant's median-index theorem. This theorem has a crucial element in firms' "ideal points". Therefore, we assume that the set of feasible fractions (of wealth to pay) is a compact collection of non-negative elements. Since π_i (F) is continuous and F lies in a compact interval, each firm *i* has an ideal point, denoted I_i, such that π_i (I_i) ≥ π_i (F) for all F. Moreover, by unconstrained monotonicity, $I_i \leq F_i$ (cf. Cave and Salant 1995: 89). Hence Cave and Salant's median-index theorem translates to our setting.

Proof.

Suppose there are N voters (i.e. firms), where N is an odd integer. Denote the median index by m = (N+1)/2. Let I_m be an ideal point of firm m and let F denote any other quota.

If $F < I_m$, voters *1, 2, .., m-1, m* (a majority) would at least weakly prefer I_m. This follows since $F < I_m \leq F_m \leq \min(F_{m-1}, F_{m-2}, \ldots, F_2, F_1)$ and these voters partially agree with m.

If instead $F > I_m$, voters *m, m+1,…, N-1, N* (a majority) would at least weakly prefer I_m.

Recall that the cutoffs of these firms are no larger than F_m and that $I_m \leq F_m$. Any *i* such that $F_i \leq I_m$ must weakly prefer I_m to $F > I_m$ (unconstrained monotonicity). As for any *i* such that $I_m < F_i \leq F_m$, such a firm at least weakly prefers I_m to any $F \in (I_m, F_i]$ (since preferences partially agree) and at least weakly prefers F_i to any $F > F_i$ (unconstrained monotonicity). Hence it weakly prefers I_m to any $F > I_m$ (continuity).

We have thus established the existence of at least one Condorcet winner, namely any ideal point (i.e. fraction) of the voter with the median index. That fraction is unique if two additional mild conditions hold (Cave and Salant 1995: 90):

- the firm with the median index has a single ideal point;
- at this ideal point, the preference of every firm unconstrained at I_m is strictly decreasing.

5.5.- Summary and concluding remarks

Technological change over the past decade has focused attention on spectrum as a valuable economic resource in increasingly short supply and triggered reviews of spectrum policy. Market-based mechanisms have been

introduced to assign spectrum for exclusive usage by individual network service providers. More recently, commercial success of services provided in licence-exempt spectrum bands has stimulated research on the efficient allocation of spectrum for collective use. This chapter contributes to the discussion on the efficient allocation of spectrum resources. It investigates the problem of efficient provision of a spectrum commons and suggests that spectrum can be allocated effectively with a mechanism which builds matching behaviour and the median-index theorem (under majority rule) into an auction where bidders compete simultaneously to acquire spectrum either for (exclusive) sole or collective use.

Our approach requires participants who bid for spectrum commons to contribute at least a minimum fraction of their wealth; this fraction is set by majority vote. Hence our approach is based on crucial assumptions which have a great impact on its implementation, as this implies, in particular, the identification of bidders who will definitively participate in the auction for unlicensed spectrum and truthful reports of their wealth (for instance, the availability of accurate financial audit and other company reports). Under those assumptions, we show that a translation of the median-index theorem applies to our circumstances. Thus, our envisaged mechanism is such that in the first stage, potential users of collective spectrum vote on a common minimum percentage of wealth to pay; in the second stage, those users bid at

least the common minimum percentage for collective use. Then the auctioneer compares the total of these bids with the highest bid (if any) for licensed use, and provisionally assigns the lot to sole or collective use accordingly. This continues till there is no excess demand. If the lot goes to sole licensed use, the winner pays the larger of the next-highest licensed-use bid or the total of the collective-use bids; if the lot goes to collective use, each bidder 'pays' the smallest amount they could have bid without changing the use class.

Chapter 6. Spectrum sharing in composite and opportunistic networks: towards new approaches to future spectrum management?

6.1.- Introduction

Spectrum is a shared resource: it is used for a very wide range of coexisting services and applications, from satellite communications across the world to home WiFi connections, from TV broadcasting to cellular mobile phone services. Traditionally, administrative decisions have divided spectrum into a number of frequency bands.[113] Access to those bands has been governed, to a great extent, by a licensing system, which has coupled bands to services and has offered a means of spectrum sharing as well as protection against (harmful) interference; in addition, individual licence holders have used various methods to further divide their licensed spectrum. Allocation of

[113] Cf. Chapters 1 and 2 above; in the literature, see, e.g., Chaduc and Pogorel (2008).

unlicensed bands for shared access by many independent users/ uses has been somewhat cautious and parsimonious by regulators.[114]

The open access, unlicensed or spectrum commons approaches to managing shared access to spectrum offer many attractive benefits, but pose difficult challenges, one being the design or implementation of mechanisms for handling congestion and allocating resources among users/ uses in times of congestion (Lehr and Crowcroft 2005; Mott MaDonald *et Al*. 2006; Quotient Associates 2007). Congestion handling should avoid, ultimately, a tragedy of the commons in the use of radio frequencies – the argument is that unregulated access to shared spectrum would make it prone, in the absence of exclusive property rights, to too high a level of interference and inefficient use, because too many users and devices would attempt to access it avariciously (Hazlett 2005).

So far spectrum sharing has relied widely on the traditional approach, both in the private sector, where firms have rarely started businesses (individually or with partners) around access to shared spectrum bands, and in the public sector, where incentives to share historically generous spectrum assignments to governments' agencies have been weak (Wik-Consult 2008; EC 2009).

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[114] Softening of regulation for licence exempt devices has been cautious as well (cf., e.g., McLean Foster & Co. 2007, and, recently, Ofcom 2010f).

More recently, technological developments - especially so called "disruptive" ones such as dynamic spectrum access technology (which includes cognitive radios) – enable, or promise to enable, more flexible frequency usage and promote both the vertical disintegration and horizontal integration of the existing wireless market silos (Chapin and Lehr 2007; cf. also Olafsson *et Al*. 2007; Casey 2009; Peha 2009).[115] Those developments have stimulated research in many directions to explore possible ways to increase (re-)use of spectrum, for instance by deploying opportunistic cognitive networks (Bellanger 2010) as well as reconfigurable radio systems in composite wireless networks and cognitive mesh networks in the long term (ETSI 2009, 2010). Various scenarios - with access to dedicated bands for those new technologies and architectures, or with shared access to spectrum used by primary users (as in the case of white spaces[116]), or hybrid solutions - are being investigated, especially to solve engineering issues and figure out new business models.

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[115] Some technologies have not reached the mass market yet; regulatory changes to accommodate them have been under discussion for a few years. In Europe, cf., for instance, Commission Decision of 30 June 2010 amending Decision 2006/771/EC on harmonisation of the radio spectrum for use by short-range devices (the "SRD Decision"), available at http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:166:0033:0041:EN:PDF . The forthcoming World Radiocommunications Conference in 2012 (WRC-12) has cognitive radio regulatory policy on its agenda.

[116] White spaces are unoccupied radio frequencies (in TV bands); see, e.g. Marcus *et Al*. 2006 and Ofcom (2009c). Spectrum usage measurements, in the frequency bands between 30 MHz and 3 GHz, show relatively low utilization of licensed spectrum (FCC 2002b; Ghasemi and Sousa 2008).

This chapter aims to contribute to the current discussion on novel spectrum sharing methods. In particular, it takes a closer look at the issue of having mechanisms (access protocols) for allocating shared spectral resources among users/ uses and handling congestion (if it emerges). It tries to establish, among available arrangements designed to share scarce resources, those which can be useful if pieces of spectrum (e.g. spectrum commons) are used to deliver a number of services to many users. In addition, it figures out some conceptual circumstances marked by access to shared spectrum and qualitatively discusses possible management models and allocation mechanisms.

There are at least three research themes which seem of some relevance for analyses of shared spectrum management and allocation: (i) the recent literature on the so called price of anarchy, mostly developed using a game theoretical approach;[117] (ii) some work on the features of a few protocols (online and offline), usually studied in the area of operations research, but with an emphasis on worst case equilibrium similar to the price of anarchy literature; (iii) last, but not least, the more traditional literature on (economic) public goods, which has investigated the commons under different hypotheses about their costs. Even when they do not offer a ready-made

[117] For a recent application of game theory to spectrum sharing see Berlemann and Mangold (2009: 87-144).

solution for spectrum sharing problems, they still may present useful results and insights for (future) spectrum specific refinements and quantitative analyses.

The rest of the chapter is organized as follows. After a sketch of various circumstances characterized by spectrum sharing (with traditional as well as new technologies), spectrum sharing in the presence of a spectrum manager/ allocation mechanism is analyzed. The analysis is carried out for the case where devices and users have equal access rights to spectrum (with a focus on spectrum commons costs and losses), and for the case where access rights are different (with a focus on management schemes involving cash transfers). Then consideration is given to circumstances where a spectrum manager is absent. The last section closes this chapter with a summary and some concluding remarks.

6.2.- Allocation of shared spectrum without tragedies

When a public or private spectrum commons can be used by devices in the hands of users who have property (or at least access) rights to it, and everyone enjoys the same rights, two circumstances seem of particular interest. The first one is the fully decentralized environment, with no band managing system (BMS, i.e. spectrum manager/ allocation mechanism) regulating access to shared spectrum, hence end users are entirely

responsible for all decisions on spectrum access - crucially, with regard to access timing and spectrum use duration, as well as amount of information transmitted. The other environment is the one where, although access decisions are still taken in a decentralized manner, a BMS system disciplines access to shared spectrum – e.g. by means of an operator spectrum manager (OSM) and a joint radio resource manager (JRRM), possibly deploying cognitive pilot channels or cognitive control channels (ETSI 2010; ITU-R 2010); a multi-radio controller (which arranges scheduling of spectrum access requests issued by concurrent applications, cf. ETSI 2010); or, at minimum, a common protocol imposing a discipline on access (Akyildiz *et Al*. 2008). In the latter environment, should congestion arise, part of the data, which a user would like to transmit, might be diverted to another (opportunistic) network or even blocked by the BMS. In addition, the BMS might implement compensation schemes (possibly aiming at fair and efficient use of shared spectrum). This section deals with this kind of circumstances.

6.2.1.- Management of shared spectrum where devices and users have equal rights of access

In a device centric environment, where spectrum is shared by several devices and users, but regulated by a BMS, mechanisms for handling congestion and allocating resources among users/ uses in times of congestion are crucial. For

instance, this may be the case of a (cognitive) opportunistic system that proactively carries out continuous spectrum sensing (Ghasemi and Sousa 2008, esp. 38).[118] In those circumstances, the most relevant analyses for shared spectrum management are, to the best of our knowledge, those looking at the design and implementation of appropriate protocols (service disciplines) to manage continuously arriving requests for services from a shared scarce resource. This reflects dynamic interaction in the use of the shared resource.

Two papers on scheduling present significant analogies to spectrum commons issues in this kind of environment, although the case of spectrum access may be more complex due to difficulties related to the awareness of other devices and of their operations.[119] The first one is a recent paper by Hervé Moulin (2007), who investigates scheduling problems, including those with arbitrary job size and release time. Compared to the case of identical release time (similar to a static environment), that piece of research may be particularly appropriate for those instances where several devices and users, sharing a spectrum commons, seek access at arbitrarily chosen points in time to communicate their data. A crucial analogy, which is drawn here, is between the scheduling (queuing) problem investigated by Moulin and a

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[118] Intuitively, delay sensitive applications favour proactive sensing (rather than reactive sensing), but this comes at the cost of increased sensing overhead (Ghasemi and Sousa 2008: 38)

[119] In the literature on queuing systems, a line is drawn between observable and unobservable queues; it is shown that agent`s equilibrium behaviour differs (Hassin and Haviv 2003).

shared spectrum management model. Moulin (2007: 877) considers that "in many real life queues involving heterogeneous users, such as the Internet, ignorance of other users' characteristics is the norm rather than the exception. In particular, the arrival of new jobs is subject to unpredictable bursts and lapses, and the service time may differ widely across users". The analysis there is concerned with circumstances where a single server or a finite number of identical servers are shared resources among jobs to be processed. Nevertheless, access to a spectrum commons (or parts of it – for instance, bandwidth channels, each being a shared resource itself) shows, arguably, the same logic of access to a server and thus could be managed similarly: the operations carried out by the server may be carried out, in the case of spectrum, by the BMS, which could be a base station or even a (cognitive) device in the hands of an end user with ad hoc networking capabilities.

Various service disciplines are compared by the `guarantees` they offer to users. A guarantee is the smallest welfare/ utility an agent will reach under the worst possible configuration of other users characteristics (Moulin 2007: 876). In our setting, the guarantee of a particular user of a device can be interpreted as the smallest welfare/ utility[120] under the worst possible

[120] This depends only upon the user's own characteristics, the resources to be shared (the commons), and the number of other users.

configuration of spectrum access timing and data transferred by other users. The focus is on the worst slowdown - i.e. sojourn time (from the beginning of a wireless electronic communication to its completion) divided by service time - which any user may experience, where the maximum is taken over all conceivable characteristics of other users. It is shown that, using a weighted version of the fair sojourn protocol (FSP),[121] the worst slowdown can be capped as a function only of the number of users in the queue at release time (the bounds on slowdown are not improved with multiple servers). In the case of shared spectrum, this suggests that, by implementation of an appropriate protocol,[122] communication delays experienced using devices such as cognitive radios and software defined radios (e.g. in the transfer of data between two devices or in the download of software to change operating parameters) can be capped too. Thus possible reluctance to share a spectrum commons could be reduced.

Sanjeev Arora and Bo Brinkman (2004) study protocols for data transmission over an IP computer network with individual hosts responsible for setting their sending rate appropriately, in the absence of a central

[121] FSP is an efficient protocol Pareto superior to the processor-sharing protocol (PS); it achieves a nearly optimal total sojourn time, while offering to every user a smaller slowdown than PS (see Moulin 2007 and the references there).

[122] One might think of a protocol which is able to count the number of users of the commons at the time when transmission is considered by the device, which might also be projected and programmed in order to store data and refrain from transmissions until a favourable spectrum environment is sensed.

authority which allots bandwidth to the hosts. An analogy between a decentralized IP network used by hosts, and a spectrum commons used by cognitive radios/ software defined radios might be drawn in appropriate settings: similarly to hosts, cognitive radio users would like to send (masses of) data or to download software as fast as possible. However, this would lead to a congestion collapse. Arora and Brinkman propose a model, previously introduced by Karp *et Al*. (2000), to understand the problem of regulating the rate of a unicast flow between two devices. Their analysis points to a crucial issue in a device-centric environment where spectrum is a shared resource: the need to study network algorithms from the hosts' perspectives as well as to study and design protocols (or other arrangements) from the devices' perspectives in a spectrum commons. In order to set appropriate data sending rates, the authors develop an efficient algorithm for bandwidth utilization. Their algorithm is essentially a randomized version of the multiplicative increase, multiplicative decrease (MIMD) strategy, whereby the hosts, so long as they do not experience dropped packets, raise their transmission rates by a multiplicative factor. This is considered an aggressive and non-altruistic strategy (in contrast with other existing protocols).[123] In the case of shared spectrum, one could also develop

[123] For instance, the additive increase, multiplicative decrease protocol increases the sending rate by 1 if the host's packets are getting through the network, whereas it halves its sending rate if the host notices that its packets are being dropped. This protocol has proved (*Continued on next page*)

reputation indexes associated to protocols and shared spectrum environments, in order to inform on "politeness" (cf. Bellanger 2010, where a "good neighbour" approach is considered).

Spectrum commons management: congestion, costs and losses

A few studies about the commons, from an economic perspective, offer additional insights about allocation of shared spectral resources and handling of congestion. They share a concern with the analysis in Arora and Brinkman (2004) and may be related to the growing research on the price of anarchy (discussed below), because they use a very similar approach.

Hervé Crès and Hervé Moulin (2003) observe that, in the case of commons with decreasing returns (increasing marginal costs),[124] the non cooperative equilibrium has too low a level of balking, hence there is overproduction. Thus the problem is the design of a queuing protocol to minimize such inefficiency. Crès and Moulin propose management by means of a congestion factor; they find that, the more crowded the commons, the more random priority outperforms average cost:[125] random priority never overproduces by more than 100%.

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successful in preventing congestion problems on the Internet (Arora and Brinkman 2004: 187-8).

[124] See also Moulin (2003, ch. 6).

[125] With random priority, users are told their number in the queue, and then they decide whether they want to receive the service or not (and pay for it); with average cost, users (*Continued on next page*)

If communications in a spectrum commons are managed (by a band manager) as if they are jobs in a queue – which is the case in congested networks such as the internet –, then this is another indication that bandwidth could be shared by various devices performing a wide range of different functions and services with only limited risks of a `tragedy`.

Moreover, in a recent paper (Juarez 2008) the line of research proposed by Crès and Moulin is developed to consider the case of non crowded commons (instead of crowded ones, as in Crès and Moulin). The author, who presents an analytical approach which moves closer to the price of anarchy literature (than did Crès and Moulin), introduces the concept of worst absolute loss and finds that - if commons are not crowded – random priority (again) performs better than average cost rules.

A crucial aspect of those analyses lies in resource management: it is assumed that decisions are taken at the beginning of a unit of time (which may well be very short), and that no other requests are considered during the processing time. This holds if one can think of a BMS that arranges transmission across a spectrum commons in blocks: for instance, this could be the case of a (cognitive) opportunistic system that, in order to decide the allocation of available spectral resources to its users, carries out periodical spectrum sensing. Use of store and forward protocols, such as those

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decide whether to request the service or not, and if they do, they pay average cost; see, for instance, Juarez (2008: 70).

developed for disruption tolerant networks, could be particularly helpful, because they use bundles of information, i.e. aggregated packages of users information, which can be passed and repackaged until their destination is reached (cf. Cannon and Harding 2007: 103-4).

6.2.2.- Management of shared spectrum where devices and users have different rights (priority) of access

In plausible circumstances, a spectrum commons may be shared by devices (and users) that do not have equal rights of access: some of them may enjoy exogenous rights which entail priority over other users, at least in specified cases. For instance, a commons may be shared by devices in use for general applications and services, as well as by devices in the hands of public agencies which provide defence, national security, public safety or emergency services. When the latter group of devices seek spectrum access, it will normally happen under a priority rule; therefore, communications by other devices will have secondary spectrum access (Webb 2007).

A number of situations may arise: on the one hand, use of spectrum by priority access devices may require use of the whole capacity - thus access by

other devices is, at least temporarily, suspended[126] - an issue of congestion brought about by priority access devices may arise (which would be again the case of spectrum management when devices have equal rights of access); on the other hand, use of spectrum by those devices may leave spare capacity for secondary access devices. In the latter case, spectrum management can be arranged in at least two alternative ways: firstly, communications which cannot be completed during the congestion peak are dropped and it is the responsibility of the device to repeat its access request later (if this is still beneficial for the user); secondly, communications are arranged in a queue by a spectrum commons manager, that will serve the queue (at the end of the congestion peak) – in the meantime, users may decide to leave the queue, which brings about a case with similarities to the online protocols analyzed in Moulin (2007).[127]

If spare capacity is not enough to satisfy all communications demands, rationing may occur among communications which have different access

[126] Queuing systems can be organised using a number of rules; some of those rules include pre-emption. For instance, an emergency service could be arranged using a last-come-first-served rule with pre-emption; therefore, therefore spectrum would be immediately used for that service, and any other service would be interrupted (Hassin and Haviv 2003).

[127] See also Crès and Moulin (2001). In order to check whether priority access devices are using all the capacity, one may think that protocols such as AIMD or MIMD are in operation inside devices (such as CRs) without primary access rights (cf. the discussion above and references to the literature).

rights.[128] In those cases, discrimination among users of shared spectrum is wanted, independently of the size of their demand. The axiomatic literature on distributive justice points out that rationing methods imposing the equal treatment of equals axiom are not appropriate, because a priori discrimination is allowed in our context (cf. Moulin 2000: 644-5). This kind of observation has stimulated research (Moulin 2000) in the area of asymmetric rationing methods, i.e. methods where equal treatment of equals is not compelling and priority rules following a fixed priority ordering are designed. Moreover this research has focused on the case of the discrete rationing model (instead of traditional continuous models), which can be used for general queuing problems, including management of access to a spectrum commons.[129]

Spectrum commons management: the LEDPP rule and other compensation schemes

In spectrum commons with a BMS, if congestion is experienced during a certain period of time, the band manager (on behalf of the wider community

[128] Rationing is used in a variety of contexts, e.g. the inheritance context and the bankruptcy contexts; the cost-sharing of a public good and taxation are two related interpretations; in the network literature, queuing is almost synonymous with rationing (Moulin 2000: 643-4).

[129] Moulin (2000) proposes models which analyze rationing problems involving a finite set of N agents. The author shows that, in the discrete model, the priority rules are the only rationing methods satisfying the three properties of consistency (i.e invariance of the rationing method to certain changes in the set of agents), upper composition and lower composition (i.e. invariance to changes in the amount of resources to be shared among the agents; upper composition pertains to an optimistic assessment of the available resources, whereas lower composition pertains to a pessimistic one).

of potential users who enjoy access rights to the commons) may aim to have a rule (a protocol) which offers spectrum assignments satisfying a given set of desirable properties (or axioms). Recent work by Çağaty Kayı and Eve Ramaekers (2010), in the research area of games and economic behaviour, offers a characterization of Pareto-efficient, fair and strategy-proof[130] allocation rules in queuing games, with monetary transfers à la Groves (1973) set up to compensate agents having to wait.

This approach may be useful to manage requests of spectrum access by a plurality of devices and users, whose demand for communications as well as waiting costs may differ from one another. In those circumstances, the authors suggest using the largest equally distributed pairwise pivotal (LEDPP) rule, which is identified as the only allocation rule satisfying the three axioms imposed. The LEDPP rule selects all efficient queues; sets each agent's transfer considering each pair of agents in turn, making each agent in the pair pay the cost she imposes on the pair, and distributing the sum of these two payments equally (for equal treatment of equals in welfare) among the others (for strategy-proofness).[131] The results in Kayı and Ramaekers

[130] Efficiency requires to maximize total welfare; fairness requires to treat equal agents equally; strategy-proofness requires that an agent should find revealing her unit waiting cost at least as desirable as misrepresenting it.

[131] The authors decompose Pareto-efficiency, on the domain of linear preferences in transfers, into two axioms: queue-efficiency, i.e. queues should minimize total waiting cost, and balancedness, i.e. transfers should sum up to zero; all axioms are satisfied by their LEDPP rule.

(2010) include two relevant extensions (*ibidem*: 230-1): (i) if agents (users) differ in processing time (spectrum capacity per unit of time), the appropriate generalization of the LEDPP still satisfies the axioms imposed; (ii) agents (information transmitted) may be excluded (blocked), but not forced to participate in the rule - that is, voluntary participation is guaranteed.

Nevertheless, in the case of spectrum commons, a few issues related to the implementation of the LEDPP rule seem worth discussing. First of all, the question arises, whether transfers à la Groves can be implemented with low transaction costs and, consequently, whether the LEDPP rule can be economically implemented (here, it is worth noting that some contributions in the literature on spectrum trading suggest spot markets for spectrum resources). Secondly, it seems interesting to extend the LEDPP rule to situations where the band manager of a congested commons is faced (almost) continuously with request of spectrum access by devices and users. Thirdly, the LEDPP rule might be useful when compensations (transfers) are arranged only if waiting time is in excess of some threshold.

Moulin (2007) proposes a scheduling model relevant for a static environment (offline) where the band manager – as randomization is not feasible - can perform cash transfers balancing to zero among users (who, in this model, are characterized by their waiting cost as well as their job size).

The results about the worst slowdown are still the same as those with randomization.[132]

6.2.3.- Anarchy and spectrum commons

In the fully decentralized environment, without a BMS, spectrum sharing (in a commons regime) may result in excessive access, given a priori technical limits, e.g. Shannon's information transfer limit (cf. Webb 2007, ch. 6, esp. 60-1). Recently, a few papers have contributed to the development of a new research line about the so called "price of anarchy", i.e. the extent to which selfish behaviour affects (system) efficiency (Johari and Tsitsiklis 2004: 407-8). This is a performance index for resource allocation mechanisms introduced in the context of congestion games; it has been applied in various areas, including transportation problems, allocation of divisible goods, supply chain management and resource allocation of network bandwidths. Various ways to compute the price of anarchy are proposed in the literature (see the discussion in Moulin 2008: 379-82; Chen and Zhang 2010: 1-5); by and large, the price of anarchy can be computed as the ratio of total delay over efficient

[132] This model, however, presents greater implementation difficulties: the server must elicit individual trade-offs between delay and cash compensation. The author makes the usual simplifying assumption that waiting costs are linear in time and known to the server (Moulin 2007: 877). For an analysis with non balanced transfers among users and a residual claimant, see Moulin (2006).

delay, or the ratio of equilibrium surplus over efficient surplus (the latter approach was used to evaluate output-sharing and cost-sharing methods).

Spectrum commons might experience congestion and delays too (if spectrum use gets too intense). Research on the price of anarchy suggests that, however, congestion will not lead to a collapse. In this growing literature, two contributions are of particular relevance for the case of spectrum sharing, as they offer insights about what one could expect when thresholds such as the Shannon limit or sub-channel capacity (cf., e.g., Bellanger 2010) are reached, following increasing demands of access to a spectrum commons.

One very recent contribution is by Moulin (2008), who aims at finding, for a given cost function and number of users, the cost sharing method(s) with the highest guaranteed surplus. The author notes, firstly, that a more recent application of cost sharing methods is to queuing games, where individual demands are the size of a single job, or the rate of a random flow of small jobs, whereas the cost is the resulting delay before completion of these jobs (in those circumstances, the numeraire is time and a crucial assumption is that waiting costs are linear); secondly, that output sharing methods are not conceptually problematic, once cost sharing methods have been investigated – with congestion games on a network, where agents bid

for capacity, being an example (see Johari and Tsitsiklis 2004, and the other references in Moulin 2008).

With regard to spectrum, this research may be useful for the case of mesh networks (using spectrum commons), where a set of users share a one-input, one-output technology with increasing marginal costs. In addition, a variant of Moulin's model, measuring the output commodity can be applied to the case of cognitive radios and software defined radios, if those radios share protocols which manage a kind of queuing game, where a user (or device) requests an amount of spectrum capacity to transfer some data and suffers a delay.

Johari and Tsitsiklis (2004) offer additional insights into the case of spectrum, especially where networks are comprised of cognitive radios. They show that, when users are sharing a single resource or, in a network context, when users submit individual payments for each link they may wish to use,[133] the aggregate utility received by them is at least ¾ of the maximum possible aggregate utility.[134]

These results suggest that spectrum can be shared with limited failures, if any. Selfish behaviour by users need not lead to arbitrarily inefficient outcomes. However, those models are static models of (network)

[133] Users are required to know the prices of the links they wish to use.

[134] See also Roughgarden (2003), who shows that the price of anarchy is independent of the network topology.

behaviour. In practice, users will dynamically interact and use the shared resource. "In general, convergence of such dynamics is not very well understood" yet (Johari and Tsitsiklis 2004: 433). Further analyses along those lines would be beneficial for the case of shared spectrum.

6.3.- Concluding remarks

The qualitative analysis of possible circumstances (scenarios) of shared spectrum resources, combined with research contributions in areas other than spectrum management, suggests that spectrum sharing is a viable option in a number of settings. Different spectrum environments might be managed relying on various mechanisms (coupled with the appropriate engineering solutions) relatively soon. Moreover, if spectrum sharing and allocation is governed by a BMS, a few (additional) management methods can be relied upon, to avoid or reduce inefficiencies. The following table shows succinctly the various arrangements envisaged with respect to research themes which can enhance spectrum sharing or, at a minimum, provide elements for further investigation of spectrum sharing issues (Table 6).

Table 6 - Managing shared spectrum beyond command and control

<table>
<tr><th colspan="3">Type of spectrum management arrangements</th><th>Research theme</th></tr>
<tr><td rowspan="5">(A):
With a band manager (or mechanism performing a similar function)</td><td rowspan="2">(A.1):
Users with equal rights of access</td><td>(A.1.a):
Continuous spectrum access</td><td>Scheduling problems with arbitrary job size and release time;
MIMD strategies</td></tr>
<tr><td>(A.1.b):
Discontinuous spectrum access</td><td>Random priority mechanisms</td></tr>
<tr><td rowspan="2">(A.2):
Users with different rights of access</td><td>(A.2.a):
Continuous spectrum access</td><td>Possible elaborations building on the themes identified for equal rights</td></tr>
<tr><td>(A.2.b):
Discontinuous spectrum access</td><td>Asymmetric rationing methods;
Compensation schemes</td></tr>
<tr><td colspan="3">(B):
Without a band manager (or mechanism performing a similar function)</td><td>Price of anarchy</td></tr>
</table>

Effective management of shared spectrum relies on the appropriate design of protocols, rules and, in general, mechanisms to cope with congestion, because, at least occasionally, spectrum sharing may involve

inefficiencies, as too much capacity is demanded by too many users in a decentralized environment. Congestion management is crucial to avoid a collapse in shared spectrum. Moreover, radio networks - especially in decentralized environments – are much more complex than other networks, because the sensing of other transmissions (awareness of other devices) cannot be taken for granted. A number of technical engineering solutions need to be explored and tested before some of the qualitative scenarios envisaged can be implemented (e.g. in cognitive radio systems a fundamental element is the operation of a cross-technology layer which deals with access to a common spectrum band for different users/ uses). However, this need not be done by regulators. Arguably, a very promising line of research, which could promote efficient management of a spectrum commons, is the one that investigates, in scheduling problems, the worst possible configuration which might occur in particular circumstances. The worst slowdown concept used in cases of arbitrary job size and release time may be appropriate for shared spectrum problems. Therefore, solutions in line with fair sojourn protocols should be considered to improve spectrum management.

Chapter 7. Conclusion and further research

Wireless communications are experiencing an unprecedented expansion. The increasing mobility of the communication society and the pace of technological change are growing pressure for more spectrum to support more users, more uses and more capacity. Thus, spectrum management has become an extremely important part of wireless communications. However, the traditional approach and its management tools are no longer adequate.

Those developments have brought about several issues for spectrum managers and regulators. One crucial issue is artificial spectrum scarcity, which has emerged in decades of `command and control` spectrum management. This work argues that spectrum management reform has not yet significantly departed from the traditional approach, and spectrum is not treated like any other input. Spectrum management can benefit from more liberal spectrum sharing.

This work set out to answer three main research questions: firstly, whether there is a theoretical framework which can be used to analyze and guide spectrum policy reform, when moving spectrum management from a traditional 'command and control' regime to a market-inspired one;

secondly, whether it is possible to design a plausible mechanism which can promote efficient allocation and assignment of (shared) spectrum commons; and, thirdly, what methods can be used to share spectrum with no harmful interference by new spectrum-using technologies, which are challenging the 'command and control' framework.

The literature on transition economics was used to analyze spectrum management reforms which have been carried out in a few liberalizing countries. A number of propositions, suggested by Dewatripont and Roland (1995), with regard to the speed and sequencing of economic reforms were applied to the case of spectrum reforms. Thus, developments in reforming countries could be analyzed systematically, by focussing on two main areas of spectrum management reform, namely reform of assignment and allocation methods. This contributes to the discussion on modernizing spectrum management in a number of ways: firstly, it provides a unifying framework for the various ingredients (and tools) of spectrum reform towards market-inspired methods already analyzed in the literature; secondly, it offers a structure to carry on research about reforming countries as well as to collect and analyze data on their experiences; thirdly, it enables a more comprehensive discussion of the conditions which might help to successfully move away from `command and control`; finally, and more generally, it presents some empirical work informing the debate on the

sequencing of (telecommunications) reforms, which has been a subject of theoretical analyses, but little empirical work (Wallsten 2002).

Work on the first research question thus benefitted from the use of that theoretical framework, which, however, was not conceived to analyze spectrum policy. Furthermore, spectrum management reform has not been brought forward by policymakers in accordance with theories of transition economics; thus, data to cover all elements considered in that framework was not available.[135] Therefore, avenues for further research include at least two related topics: firstly, the development of a theoretical framework which is specifically conceived to analyze spectrum management reform; secondly, empirical research carried out using that specific theoretical framework.

Spectrum management reforms have focussed on liberalization of spectrum assignment and allocation. However, spectrum regulators have not changed substantially their approach to making spectrum for collective use available. Therefore, one of the aims of this work was to study a plausible mechanism which could be used in a market-inspired spectrum management context to assign and allocate the resource for collective use. The approach proposed here envisages auctions where bidders demanding spectrum for sole use (such as wireless network operators) compete simultaneously

[135] The data does not show anywhere that a comprehensive framework for reform, similar to that proposed by Dewatripont and Roland (1995) for transition economics, was used to guide the transition from 'command and control' to more market-inspired mechanisms for spectrum management.

against groups of players who demand spectrum for collective use. These players agree to contribute at least a minimum fraction of their wealth and this fraction is set by majority vote. It is shown that a translation of the median-index theorem – originally proposed by Cave and Salant 1995 in the analysis of cartels to restrict output - applies to our circumstances. Thus, in the first stage, potential collective spectrum users vote on a common minimum percentage of wealth to pay during the auction; in the second stage, those users bid at least the common minimum percentage; then the auctioneer compares the total of these bids with the other bids (if any). Therefore, a market-based mechanism might be used to decide whether, and how much, spectrum should be allocated to collective use, thus taking decisions on allocation and assignment of spectrum for collective use away from regulatory fiat.

Research carried out in this part of the work focussed on the translation of Cave and Salant`s results to the problem of collective use of spectrum, which has (severe) specific difficulties compared to cartels. For instance, the incentives to actually reach an agreement to submit a collective bid were not investigated (cf. Gerber and Wichardt 2009, esp. 429-30). The procedure proposed here seems plausible in circumstances where only a few players agree to bid together to get spectrum for collective use. A line for future research might be a test of our envisaged mechanism by means of

simulations. In addition, the design of a plausible mechanism which can be used with a high number of players is an interesting issue which deserves further research (cf. Nitzan and Ueda 2009).

Finally, part of this work took a closer look at plausible arrangements for allocating shared spectral resources among users/ uses, and handling possible congestion or prioritizations of access. It considered, among available arrangements designed to share scarce resources, those rules which can be useful for the case of spectrum management if pieces of spectrum (e.g. spectrum commons) are used to deliver a number of services to many users, in particular deploying new spectrum-using technologies and networks. It also figured out, being as specific as possible at this stage, some conceptual circumstances marked by access to shared spectrum. Among the research themes which were considered for the case of shared spectrum, recent developments in the literature on scheduling problems were identified as the most relevant ones, especially with regard to analyses of the worst slowdown.

The qualitative arguments presented have not considered the technical engineering requirements for effective spectrum sharing. Those requirements have been either taken for granted, by borrowing from areas other than spectrum management, or skipped (and left for engineering research). In addition, the elaboration of dynamic mechanisms, to deal with continuous

demands for spectrum access by users, is of key importance for shared spectrum in a device centric environment with composite and opportunistic networks, but research on dynamic settings is at a relatively early stage (being more complex than static settings). Those complexities, however, do not seem insurmountable and spectrum sharing in flexible and dynamic environments does not seem to be condemned to failures. The qualitative analysis suggests some conceptual settings which might be taken as starting points for further investigation into more specific environments. Some of those settings may turn out to be technically or economically unviable. Further investigation of specific solutions, with quantitative analysis involving the technical elaboration of algorithms, formulas and calculations (linked to appropriate quantitative assumptions),[136] are left for future research.

Nevertheless, policy makers and businesses managing spectrum access may be less worried about spectrum tragedies and more prone to exploiting spectrum sharing opportunities in the near future.

[136] For example, what maximum delay would not be yet considered collapse.

Appendix

Part A: Existence and uniqueness of a pure-strategy Nash equilibrium

Existence

Let $W_N = \sum_1^N w_i$ denote the sum of exogenous wealth of the N players, whose maximization problem is:

$$\max \quad b_i\,[f(B) - c_i]$$

s.t.

$$b_i \geq Fw_i \ .$$

If the constraint is not binding, the F.O.C. requires $f(B) - c_i + b_i\, f'(B) = 0$; therefore, we get $b_i = -\dfrac{f(B) - c_i}{f'(B)}$.

Since $f'(B) < 0$, $b_i > 0$ if $f(B) - c_i > 0$ or, equivalently, $f(B) > c_i$.

If the constraint is binding, firm *i* contributes Fw_i.

Let $\beta_i(B)$ denote firm *i*'s best reply:

$$\beta_i(B) = \max\left\{Fw_i, -\frac{f(B) - c_i}{f'(B)}\right\}$$

for $B \in [FW_N , W_N]$.

Define $\beta(B) = \sum_1^N \beta_i(B)$. Hence $\beta(B)$ is the "aggregate best reply". Since f(B) and f′(B) are continuous and f′(B) < 0, $\beta(B)$ is a continuous function. Moreover, if the firm with the lowest cost of capital has positive average net benefit when firms contribute the minimum fraction of their wealth (i.e. $f(FW_N) > c_i$), then the aggregate best-reply contribution is greater than FW_N:

$\beta(FW_N) > FW_N$ as long as $f(FW_N) > c_i$.

Finally $\beta(W_N) \leq W_N$ (the maximum amount of funds that the N firms can contribute is their entire wealth).

It follows that there exists at least one fixed point $B^* \in [FW_N, W_N]$ such that $\beta(B^*) = B^*$.

Assume that total benefit is strictly concave:

$2f'(B) + B f''(B) < 0$ for all $B \in [FW_N, W_N]$; then $2f'(B) + \beta_i(B) f''(B) < 0$ for all $B \in [FW_N, W_N]$ and each firm's second-order condition will be satisfied whenever its first-order conditions hold. Hence, every fixed point of the mapping $\beta(.)$ is a pure-strategy Nash equilibrium.

Uniqueness

We now verify that the left-hand derivative of $\beta(.)$, evaluated at any fixed point B*, is strictly less than 1 – which implies that there exists a unique fixed point.

If firm i is unconstrained,

$$\beta_i(B) = -\frac{f(B) - c_i}{f'(B)}.$$

Hence $\beta'_i(B) = -\left\{1 + \frac{f''(B)}{f'(B)}\beta_i(B)\right\}$.

Assume that, as $B \to B^*$ from the left, u firms are unconstrained; summing over the unconstrained firms we obtain:

$$\beta'(B^*)^- = -\left\{u + \frac{f''(B^*)}{f'(B^*)}[\beta(B^*) - FW_{co}]\right\}$$

where FW_{co} is the aggregate contribution of the constrained firms (they must contribute the minimum fraction of their wealth according to F, i.e. Fw_i, which is their best reply).

Since $f'(B^*) < 0$ and $\beta(B) \geq FW_{co}$, $\beta'(B^*)^- \leq 0 < 1$ *provided* $f''(B) \leq 0$.

It remains to show that $\beta'(B^*)^- < 1$ if $f''(B) > 0$.

At any fixed point, $2f'(B^*) + \beta_i(B^*)f''(B^*) < 0$ (since total revenue is strictly concave). Hence, summing over the u unconstrained firms

$2uf'(B^*) + [\beta(B^*) - FW_{co}]\, f''(B^*) < 0$.

Adding the negative quantity[137] $2f'(B^*) + \beta(B^*)f''(B^*)$ to the previous inequality (which is negative), we obtain:

$2uf'(B^*) + [\beta(B^*) - FW_{co}]\, f''(B^*) + 2f'(B^*) + \beta(B^*)f''(B^*) < 0$

or, equivalently,

[137] Recall total revenue is strictly concave and $\beta(B^*) = B^*$.

$$2f'(B^*)\,[u+1] + 2\left\{\beta(B^*) - \frac{FW_{co}}{2}\right\} f''(B^*) < 0\,.$$

Dividing by $-2f'(B^*) > 0$ we get

$$-[u+1] - \frac{f''(B^*)}{f'(B^*)}\left\{\beta(B^*) - \frac{FW_{co}}{2}\right\} < 0$$

or, equivalently,

$$-\left\{u + \frac{f''(B^*)}{f'(B^*)}[\beta(B^*) - \frac{FW_{co}}{2}]\right\} < 1.$$

Since $\frac{FW_{co}\ f''(B^*)}{2f'(B^*)} < 0$ we obtain

$$-\left\{u + \frac{f''(B^*)}{f'(B^*)}[\beta(B^*) - \frac{FW_{co}}{2}]\right\} + \frac{FW_{co}\ f''(B^*)}{2f'(B^*)} < 1$$

or, equivalently,

$$-\left\{u + \frac{f''(B^*)}{f'(B^*)}[\beta(B^*) - FW_{co}]\right\} < 1;\ \text{hence } \beta'(B^*)^- < 1.$$

Part B: Unconstrained monotonicity and convexity of the set of fractions binding on firm i

Let B(F) denote the aggregate contribution offered by firms bidding for unlicensed spectrum in the unique Nash equilibrium induced by fraction F

(set by majority-rule vote)[138] and let *i* be an unconstrained bidder at F. Firm *i*'s profits are:

$\pi_i = \{f(B(F)) - c_i\} \cdot b_i(B(F))$.

A change in F will affect *i*'s profits:

$$\frac{d\pi_i}{dF} = \frac{dB}{dF}\left\{[f(B(F)) - c_i]\frac{db_i}{dB} + b_i f'(B(F))\right\}.$$

For firm *i*, marginal benefit and cost are equal:

$f(B(F)) + b_i f'(B(F)) - c_i = 0$;

hence $f(B(F)) - c_i = - b_i f'(B(F))$ and we obtain

$$\frac{d\pi_i}{dF} = \frac{dB}{dF}\left\{[- b_i f'(B(F)]\frac{db_i}{dB} + b_i f'(B(F))\right\} = \frac{dB}{dF}\left\{1 - \frac{db_i}{dB}\right\} b_i f'(B(F))$$

where $f'(B(F))$ is strictly negative.

Since $b_i(B)$ implicitly solves $f(B) + b_i f'(B) - c_i = 0$, we can use the implicit function theorem to get that

$$\frac{db_i}{dB} = -\frac{f'(B) + b_i f''(B)}{f'(B)}$$

and, since total benefit is strictly concave, we obtain

$$1 - \frac{db_i}{dB} = \frac{2f'(B) + b_i f''(B)}{f'(B)} > 0 .$$

Hence $\left\{1 - \frac{db_i}{dB}\right\} b_i f'(B(F)) < 0$ and

[138] Henceforth, to simplify our notation, we will write B(F) without an asterisk.

$$\text{sgn}\ \frac{d\pi_i}{dF} = -\ \text{sgn}\ \frac{dB}{dF}.$$

To show that $\frac{d\pi_i}{dF} \leq 0$ as long as some firm is constrained (clearly $\frac{d\pi_i}{dF} = 0$ if no firm is constrained), we verify that $\frac{dB}{dF} > 0$.

Let Ω be the set of unconstrained firms and u the number of elements in this set. For each unconstrained firm $i \in \Omega$ we have $f(B) + b_i f'(B) - c_i = 0$. Also, let X be the set of constrained firms and v be the number of its elements ($v = N - u$ and FW_{co} is their aggregate contribution, i.e. $FW_{co} = \sum_1^v Fw_j$, where j is a firm in X). The aggregate contribution collected by the unconstrained bidders is $\sum_1^u b_i = B - FW_{co}$.

Summing over the set of unconstrained firms, we obtain

$$uf(B) + [B - FW_{co}]\, f'(B) - \sum_1^u c_i = 0.$$

Total differentiation gives:

$$\frac{dB}{dF} = \frac{W_{co} f'(B)}{(u+1) f'(B) + (B - FW_{co}) f''(B)}$$

which is zero if no firm is constrained ($W_{co} = \sum_1^v w_j = 0$).

Suppose $W_{co} = \sum_1^v w_j > 0$. Since $f'(B) < 0$ and $\left\{u + \frac{f''(B)}{f'(B)}[B - FW_{co}]\right\} > -1$, we get

$(u + 1)f'(B) + [B - FW_{co}]\, f''(B) < 0$. Hence $\frac{dB}{dF} > 0$.

Following the reasoning in Cave and Salant (1995), we now use these results to verify that a firm unconstrained at F will remain unconstrained at any looser fraction F_l (where $F_l < F$). For this it is sufficient that the optimal bid of any unconstrained firm *i* decrease no faster than the minimum contribution required by the voting committee Fw_i, as F decreases:

$db_i \geq dFw_i$ (note that there are both negative); hence

$$\frac{db_i}{dF} = \frac{db_i}{dB}\left(\frac{dB}{dF}\right) \leq w_i .$$

Since $\frac{db_i}{dB} = -\frac{f'(B) + b_i f''(B)}{f'(B)}$ and $\frac{dB}{dF} = \frac{W_{co} f'(B)}{(u+1)f'(B) + (B - FW_{co})f''(B)}$, we get that

$$\frac{db_i}{dF} = -\frac{W_{co}[b_i f''(B) + f'(B)]}{(u+1)f'(B) + (B - FW_{co})f''(B)} \leq w_i$$

where $u \geq 1$ and $(u + 1)f'(B) + [B - FW_{co}]\, f''(B) < 0$.

If $f''(B) \leq 0$ then $W_{co}[b_i f''(B) + f'(B)] < 0$ and $-\frac{W_{co}[b_i f''(B) + f'(B)]}{(u+1)f'(B) + (B - FW_{co})f''(B)} \leq$ w_i clearly holds in this case ($w_i \geq 0$).

Suppose instead that $f''(B) > 0$. Since total benefit is concave, the following inequality holds:

$$B f''(B) + 2f'(B) + \left\{\frac{W_{co}}{w_i} + (u-1)\right\} f'(B) < 0.$$

This is equivalent to

$$B\, f''(B) + \left\{\frac{W_{co}}{w_i} + (u+1)\right\} f'(B) < 0$$

which can be manipulated to get

$$f''(B) + \left\{F w_i W_{co} + w_i (B - F W_{co})\right\} + f'(B)\left\{W_{co} + (u+1) w_i\right\} < 0$$

(note that $w_i B = F w_i W_{co} + w_i\,[B - F W_{co}]$).

Re-arranging we obtain:

$$f''(B)\, F w_i W_{co} + f''(B)\, w_i\,[B - F W_{co}] + f'(B)\, W_{co} + f'(B)\,(u+1)\, w_i < 0$$

or, equivalently,

$$W_{co}\,[f''(B)\, F w_i + f'(B)] + w_i\,\{f''(B)\,[B - F W_{co}] + f'(B)\,(u+1)\} < 0.$$

Therefore, $-W_{co}\,[f''(B)\, F w_i + f'(B)] > w_i\,\{f''(B)\,[B - F W_{co}] + f'(B)\,(u+1)\}$.

Since $\{f''(B)\,[B - F W_{co}] + f'(B)\,(u+1)\} < 0$ we get

$$-\frac{W_{co}\,[f''(B)\, F w_i + f'(B)]}{(u+1) f'(B) + (B - F W_{co}) f''(B)} < w_i$$

where $F w_i \leq b_i$. Hence the following inequality holds:

$$-\frac{W_{co}\,[b_i f''(B) + f'(B)]}{(u+1) f'(B) + (B - F W_{co}) f''(B)} \leq w_i\,.$$

This confirms that a firm unconstrained at F will remain unconstrained at any looser quota.

References

Abbott, A. (1992), What Do Cases Do? Some Notes on Activity in Sociological Analysis, in C.C. Ragin and H.S. Becker (eds.), *What Is a Case? Exploring the Foundations of Social Inquiry*, 53-82, Cambridge, Cambridge U.P.

ACMA – Australian Communications and Media Authority (2008), *Spectrum Trading: Consultation on Trading and Third Party Authorisations of Spectrum and Apparatus Licences*, Canberra.

ACMA – Australian Communications and Media Authority (2009a), *Five-year Spectrum Outlook 2009-2013*, Canberra.

ACMA – Australian Communications and Media Authority (2009b), *Response to Submissions on Spectrum Trading*, Canberra.

Adda, J. and M. Ottaviani (2005), The Transition to Digital Television, *Economic Policy,* 20(41), 160-209.

Aegis and Connogue (2001), *Study on Administrative and Frequency Fees Related to the Licensing of Networks Involving the Use of Frequencies,* Report to the European Commission, Directorate General Information Society, Brussels.

Akyildiz, I.F., W.-Y. Lee, M.C. Vuran and S. Mohanty (2008), A Survey on Spectrum Management in Cognitive Radio Networks, *IEEE Communications Magazine*, 46(4), 40-8.

Analysys, Dotecon and Hogan & Hartson (2004), *Study on Conditions and Options in Introducing Secondary Trading of Radio Spectrum in the European Community. Final Report for the European Commission*, Cambridge.

Arora, S. and B. Brinkman (2004), A Randomized Online Algorithm for Bandwidth Utilization, *Journal of Scheduling*, 7(3), 187-94.

Baumol, W.J. and D. Robyn (2006), *Toward an Evolutionary Regime for Spectrum Governance: Licensing or Unrestricted Entry?*, Washington, D.C., Brookings Press.

Bazelon, C. (2003), Next Generation Frequency Coordinator, *Telecommunications Policy,* 27(7), 517-25.

Bellanger, M. (2010), *Opportunistic Unsynchronized Cognitive Radio Networks*, paper presented at the COST-TERRA meeting no. 1, COST Action IC0905, Bruxelles, 30-31 August 2010.

Benjamin, S.M. (2003), Spectrum Abundance and the Choice Between Private

and Public Control, *New York University Law Review*, 78(6), 2007-102.

Benkler, Y. (1998), Overcoming Agoraphobia: Building the Commons of the Digitally Networked Environment, *Harvard Journal of Law and Technology*, 11(2), 287-399.

Benkler, Y. (2002), Some Economics of Wireless Communications, *Harvard Journal of Law and Technology*, 16(1), 25-83.

Berlemann, L. and S. Mangold (2009), *Cognitive Radio and Dynamic Spectrum Access*, Chichester, UK, Wiley.

Best, M.L. (2006), *A Global Survey of Spectrum License Exemptions*, available at http://www.cc.gatech.edu/.

Binmore, K. and P. Kemplerer (2002), The Biggest Auction Ever: The Sale of the British 3G Telecom Licences, *Economic Journal*, vol. 112(478), C74-96.

Blaxter, L., C. Hughes and M. Tight (2001), *How to Research* (2nd edn), Buckingham, Open U. P.

Bracht, J., C. Figuières and M. Ratto (2008), Relative Performance of Two Simple Incentive Mechanisms in a Public Goods Experiment, *Journal of Public Economics*, 92(1), 54-90.

Brito, J. (2007), The Spectrum Commons in Theory and Practice, *Stanford Technology Law Review*, 1, available at http://stlr.stanford.edu/pdf/brito-commons.pdf.

Bryman, A. and R.G. Burgess (1994), Reflections on Qualitative Data Analysis, in A. Bryman and R.G. Burgess (eds), *Analyzing Qualitative Data*, 216-26, London, Routledge.

BTCE - Bureau of Transport and Communications Economics (1990), *Management of the Radio Frequency Spectrum: An Economic Analysis*, occasional paper no. 102, Canberra.

Buchanan, J.M. and Y.J. Yoon (2000), Symmetric Tragedies: Commons and Anticommons, *Journal of Law and Economics*, 43(1), 1-13.

Buck, S. (2002), *Replacing Spectrum Auctions with a Spectrum Commons*, available at http://stlr.stanford.edu/STLR/Articles/02_STLR_2/.

Burgess, R.G., C.J. Pole, K. Evans and C. Priestley (1994), Four Studies from One or One Study from Four?, in A. Bryman and R.G. Burgess (eds), *Analyzing Qualitative Data*, 129-45, London, Routledge.

Bykowsky, M. (2003), A Secondary Market for the Trading of Spectrum: Promoting Market Liquidity, *Telecommunications Policy*, 27(7), 533-41.

Bykowsky, M., M. Olson and W. Sharkey (2008a), Modelling the Efficiency of Spectrum Designated to Licensed Service and Unlicensed Operations, *OSP Working Paper Series*, no. 42, FCC, Office of Strategic Planning and

Policy Analysis, Washington, D.C.

Bykowsky, M., M. Olson and W. Sharkey (2008b), A Market-Based Approach to Establishing Licensing Rules: Licensed versus Unlicensed Use of Spectrum, *OSP Working Paper Series*, no. 43, FCC, Office of Strategic Planning and Policy Analysis, Washington, D.C.

Cable, J., A. Henley and K. Holland (2002), Pot of Gold or Winner`s Curse? An Event Study of the Auctions of 3G Mobile Telephone Licences in the UK, *Fiscal Studies*, vol. 23(4), 447-62.

Campbell, D.E. (1995) *Incentives: Motivation and the Economics of Information*, Cambridge, Cambridge U.P.

Cannon, P.S. and C.R. Harding (2007), Future Military Wireless Solutions, in W. Webb (ed), *Wireless Communications: The Future*, 91-116, Chichester, UK, Wiley.

Casey, T. (2009), Analysis of Radio Spectrum Market Evolution Possibilities, *Communications and Strategies*, 75(3), 109-30.

Cave, J. and S.W. Salant (1987), Cartels That Vote: Agricultural Marketing Boards and Induced Voting Behavior, in E. Bailey (ed), *Public Regulation: New Perspectives on Institutions and Policies*, Cambridge, MA, MIT Press, 255-83.

Cave, J. and S.W. Salant (1995), Cartel Quotas under Majority Rule, *American Economic Review*, 85(1), 82-102.

Cave, M. (2002), *Review of Radio Spectrum Management: An independent review for the department of Trade and Industry and HM Treasury*, available at http://www.ofcom.org.uk/static/archive/ra/spectrum-review/index.htm.

Cave, M. (2006), New Spectrum-Using Technologies and the Future of Spectrum Management: a European Policy Perspective, in E. Richards, R. Foster and T. Kiedrowski (eds), *Communications: The Next Decade*, 220-34, London, Ofcom.

Cave, M., C. Doyle and W. Webb (2007a), *Essentials of Modern Spectrum Management*, Cambridge, Cambridge U.P.

Cave, M., W. Mfuh and L.F. Minervini (2007b), *Review of the Literature on Market-based Methods for Spectrum Management*, paper proposed as part of ITU project on the future of spectrum usage rights and wireless licensing in an increasingly competitive environment, Coventry, University of Warwick, WBS, mimeo.

Cave, M. and L.F. Minervini (2009), Monitoring EU Policy: Spectrum Policy, in M. Cave, J. Haucap, J. Padilla, A. Renda and B. Williamson, *Monitoring EU Telecoms Policy*, Madrid, Mic-Nerec, 19-26.

Cave, M. and T. Valletti (2000), Are Spectrum Auctions Ruining our Grandchildren's Future?, *Info*, 2 (4), 347-50.

Cave, M. and W. Webb (2003a), Band Managers: The Policies and Incentives Needed to Make Them Succeed, *Papers in Spectrum Trading*, no. 3, Coventry, University of Warwick, WBS, mimeo.

Cave, M. and W. Webb (2003b), Designing Property Rights for the Operation of Spectrum Markets, *Papers in Spectrum Trading*, no. 1, Coventry, University of Warwick, WBS, mimeo.

Cave, M. and W. Webb (2003c), Spectrum Licensing and Spectrum Commons: Where to Draw the Line, *Papers in Spectrum Trading*, no. 2, Coventry, University of Warwick, WBS, mimeo.

Chaduc, J.-M. and G. Pogorel (2008), *The Radio Spectrum: Managing a Strategic Resource*, London, ISTE and Hoboken, NJ, Wiley.

Chapin, J.M. and W.H. Lehr (2007), Cognitive Radio for Dynamic Spectrum Access: The Path to Market Success for Dynamic Spectrum Access Technology, *IEEE Communications Magazine*, 45(5), 96-103.

Chen, Y.-J. and J. Zhang (2010), *Design of Price Mechanisms for Network Resource Allocation via Price of Anarchy*, mimeo, available at http://ssrn.com/abstract=1603447 .

Clemons, R.S. and M.K. McBeth (2009), *Public Policy Praxis: A Case Approach for Understanding Policy and Analysis* (2nd edn), London, Pearson Education.

Clough, P. and C. Nutbrown (2007), *A Student's Guide to Methodology: Justifying Enquiry* (2nd edn), London, Sage.

Coase, R. (1959), The Federal Communications Commission, *Journal of Law and Economics,* 2(1), 1-40.

Cohen, L., L. Mannion and K. Morrison (2000), *Research Methods in Education* (5th edn), London, Routledge Falmer.

Collier, D. and J.E. Mahon, jr. (1993), Conceptual "Stretching" Revisited: Adapting Categories in Comparative Analysis, *American Political Science Review*, 87(4), 845-55.

Cramton, P. (2008), *A Review of the L-Band Auction*, mimeo, available at www.cramton.umd.edu .

Cramton, P. and J.A. Schwartz (2000), Collusive Bidding: Lessons from the FCC Spectrum Auctions, *Journal of Regulatory Economics*, 17(3), 229-52.

Cramton, P., Y. Shoham and R. Steinberg (eds) (2010), *Combinatorial Auctions*, Cambridge, MA, MIT Press.

Crès, H. and H. Moulin (2001), Scheduling with Opting out: Improving upon Random Priority, *Operations Research*, 49(4), 565-77.

Crès, H. and H. Moulin (2003), Commons with Increasing Marginal Costs: Random Priority versus Average Cost, *International Economic Review*, 44(3), 1097-115.

Creswell, J.W. (2003), *Research Design: Qualitative, Quantitative and Mixed Methods Approaches* (2nd edn), London, Sage.

Danziger, L. and A. Schnytzer (1991), Implementing the Lindahl Voluntary-Exchange Mechanism, *European Journal of Political Economy*, 7(1), 55-64.

De Vany, A.S., R.D. Eckert, C.J. Meyers, D.J. O'Hara and R.C. Scott (1969), A Property System for Market Allocation of the Electromagnetic Spectrum: A Legal-Economic-Engineering Study, *Stanford Law Review*, 21(7), 1499-561.

Dewatripont, M. and G. Roland (1995), The Design of Reform Packages under Uncertainty, *American Economic Review*, 85 (5), 1207-23.

EC - European Commission (2002a), *Comparative Assessment of the Licensing Regimes for 3G Mobile Communications in the European Union and their Impact on the Mobile Communications Sector*, Brussels.

EC - European Commission (2002b), *Decision No 676/2002/EC of 7 March 2002 on a Regulatory Framework for Radio Spectrum Policy in the European Community*, Brussels.

EC - European Commission (2005a), *A Market-Based Approach to Spectrum Management in the European Union*, COM(2005) 400 final, Brussels.

EC - European Commission (2005b), *A Forward-Looking Radio Spectrum Policy for the European Union: Second Annual Report*, COM(2005) 411 final, Brussels.

EC – European Commission (2006), *Review of the EU Regulatory Framework for Electronic Communications Networks and Services*, SEC(2006) 816-817 final, Brussels.

EC - European Commission (2007), *Rapid Access to Spectrum for Wireless Electronic Communications Services through More Flexibility*, COM(2007) 50 final, Brussels.

EC – European Commission (2009a), *Request by the European Commission to the Radio Spectrum Policy Group for an Opinion on Best Practices Regarding the Use of Spectrum By Some Public Sectors. Final RSPG Opinion*, RSPG09-258, Brussels.

EC – European Commission (2009b), *Progress Report on the Single European Electronic Communications Market, 14th Report*, COM(2009) 140 final, Brussels.

ECC - European Communications Committee within the European Conference of Postal and Telecommunications Administrations, CEPT (2006), *Enhancing Harmonisation and Introducing Flexibility in the Spectrum Regulatory Framework*, ECC Report 80, Oulu.

ECC – Electronic Communications Committee (2009), *Light Licensing, Licence-Exempt and Commons*, ECC Report 132, Moscow.

Entman, R.M. (2004), *Challenging the Theology of Spectrum: Policy Reformation Ahead*, Washington, D.C., Aspen Institute.

ERG - European Regulators Group (2006), *Spectrum Allocation and Bottlenecks/Competition Problems*, ERG(06) 45b.

ERG and RSPG – European Regulators Group and Radio Spectrum Policy Group (2009), *Report on Transitional Radio Spectrum Issues: Report on Competition Issues Arising from the Transition towards More Flexible Radio Spectrum Management for Electronic Communications Networks and Services*, ERG (08) 60 rev 1, RSPG09-277.

ETSI – European Telecommunications Standard Institute (2009), *Reconfigurable Radio Systems (RRS): Cognitive Pilot Channel (CPC)*, TR 102 683 V1.1.1 (2009-09), Sophia Antipolis, available at http://www.etsi.org .

ETSI – European Telecommunications Standard Institute (2010), Reconfigurable *Radio Systems (RRS): Cognitive Radio System Concept*, TR 102 802 V1.1.1 (2010-02), Sophia Antipolis, available at http://www.etsi.org .

Eurostrategies-LS Telecom (2007), *Study on Radio Interference Regulatory Models in the European Community*, available at http://ec.europa.eu/information_society/policy/ecomm/radio_spectrum/documents/studies/index_en.htm.

Falch, M. and R. Tadayoni (2004), Economic Versus Technical Approaches to Frequency Management, *Telecommunications Policy*, 28(2), 197-211.

Falkinger, J. (1996), Efficient Private Provision of Public Goods by Rewarding Deviations from Average, *Journal of Public Economics*, 62(3), 413-22.

Falkinger, J., E. Fehr, S. Gaechter and R. Winter-Ebmer (2000), A Simple Mechanism for the Efficient Provision of Public Goods: Experimental Evidence, *American Economic Review*, 90(1), 247-64.

Faulhaber, G.R. (2005), The Question of Spectrum: Technology, Management, and Regime Change, *Journal of Telecommunications and High Technology Law*, 5(1), 111-58.

Faulhaber, G.R. and D. Farber (2003), Spectrum Management: Property Rights, Markets, and the Commons, in L. F. Cranor and S. S. Wildman (eds), *Rethinking Rights and Regulations: Institutional Responses to New Communication Technologies*, 193-226, Cambridge, MA, MIT Press.

FCC - Federal Communications Commission (2002a), *Report of the Spectrum Efficiency Working Grou*p, Spectrum Policy Task Force, Washington, D.C., available at http://www.fcc.gov/sptf/reports.html .

FCC - Federal Communications Commission (2002b), *Spectrum Policy Task Force Report*, ET Docket 02-135, Washington, D.C., available at http://www.fcc.gov/sptf/reports.html

FCC - Federal Communications Commission (2003), *Promoting Efficient Use of Spectrum Through Elimination of Barriers to the Development of Secondary Markets: Report and Order and Further Notice of Proposed Rulemaking*, WT Docket No. 00-230, Washington, D.C.

FCC - Federal Communications Commission (2004a), *FCC Adopts Spectrum Leasing Rules and Streamlined Processing for License Transfer and Assignment Applications, and Proposes Further Steps to Increase Access to Spectrum through Secondary Markets*, Washington, D.C., press release, July 8.

FCC - Federal Communications Commission (2004b), *Promoting Efficient Use of Spectrum Through Elimination of Barriers to the Development of Secondary Markets: Second Report and Order, Order on Reconsideration, and Second Further Notice of Proposed Rulemaking*, WT Docket No. 00-230, Washington, D.C.

FCC - Federal Communications Commission (2009), *Statement by FCC Chairman Kevin J. Martin*, FCC news release, January 15.

Fette, B.A. (ed)(2009), *Cognitive Radio Technology (*2nd edn), Oxford, Elsevier-A.P.

Gerber, A. and P.C. Wichardt (2009), Providing Public Goods in the Absence of Strong Institutions, *Journal of Public Economics*, 93(3-4), 429-39.

Gerring, J. (2007), *Case Study Research: Principles and Practices*, Cambridge, Cambridge U.P.

Ghasemi, A. and E.S. Sousa (2008), Spectrum Sensing in Cognitive Radio Networks: Requirements, Challenges and Design Trade-offs, *IEEE Communications Magazine*, 46(4), 32-9.

Gibbert, M., W. Ruigrok and B. Wicki (2008), What Passes as a Rigorous Case Study?, *Strategic Management Journal*, 29(13), 1465-74.

Goodman, E.P. (2004), Spectrum Rights in the Telecosm to Come, *San Diego Law Review*, 41, 269-404.

Green, J. and J.-J. Laffont (1977), Characterization of Satisfactory Mechanisms for the Revelation of Preferences for Public Goods, *Econometrica*, 45(2), 427-38.

Groves, T. (1973), Incentives in Teams, *Econometrica*, 41(4), 617-31.

Groves, T. and J. Ledyard (1987), Incentive Compatibility since 1972, in T. Groves, R. Radner and S. Reiter (eds), *Information, Incentives, and Economic Mechanisms: Essays in Honor of Leonid Hurwicz*, 48-111, Minneapolis, University of Minnesota Press.

Guba, E.G. and Y.S. Lincoln (1994), Competing Paradigms in Qualitative Research, in N.K. Denzin and Y.S. Lincoln (eds), *Handbook of Qualitative Research*, 105-117, London, Sage.

Guttman, J.M. (1978), Understanding Collective Action: Matching Behavior, *American Economic Review*, 68(2), 251-55.

Guttman, J.M (1986), Matching Behavior and Collective Action: Some Experimental Evidence, *Journal of Economic Behavior and Organization*, 7(2), 171-98.

Guttman, J.M. (1987), A Non-Cournot Model of Voluntary Collective Action, *Economica*, 54(1), 1-19.

Hammersley, M. (1992), *What's Wrong with Ethnography?*, London, Routledge.

Hantrais, L. (2009), *International Comparative Research: Theory, Methods and Practice*, Basingstoke, Palgrave Macmillan.

Hassin, R. and M. Haviv (2003), *To Queue or Not to Queue: Equilibrium Behaviour in Queuing Systems*, London, Kluwer A.P.

Hatfield, D.N. (2003), Spectrum Management Reform and the Notion of the 'Spectrum Commons', *Southern African Journal of Information and Communication*, no. 4, 1-12.

Hausman, D.M. (1989), Economic Methodology in a Nutshell, *Journal of Economic Perspectives*, 3(2), 115-27.

Hazlett, T.W. (1998), Assigning Property Rights to Radio Spectrum Users: Why Did FCC License Auctions Take 67 Years?, *Journal of Law and Economics*, 41(2), 529-76.

Hazlett, T.W. (2001), *The Wireless Craze, the Unlimited Bandwidth Myth, the Spectrum Auction Faux Pas, and the Punchline to Ronald Coase's 'Big Joke'. An Essay on Airwave Allocation Policy*, working paper 01-01, Washington, D.C., AEI-Brookings Joint Center for Regulatory Studies.

Hazlett, T.W. (2003), Liberalizing US Spectrum Allocation, *Telecommunications Policy*, 27(7), 485-99.

Hazlett, T.W. (2005), Spectrum Tragedies, *Yale Journal on Regulation*, 22 (2),

243-74.

Hazlett, T.W. (2006), An Economic Evaluation of Spectrum Allocation Policy, in E. Richards, R. Foster and T. Kiedrowski (eds), *Communications: The Next Decade*, 249-58, London, Ofcom.

Hazlett, T.W. (2008a), Optimal Abolition of FCC Spectrum Allocation, *Journal of Economic Perspectives*, 22(1), 103-28.

Hazlett, T.W. (2008b), A Law and Economics Approach to Spectrum Property Rights: A Response to Weiser and Hatfield, *George Mason Law Review*, 15(4), 975-1023.

Hazlett, T.W. (2008c), Property Rights and Wireless License Values, *Journal of Law and Economics*, 51(3), 563-98.

Hazlett, T.W., G. Ibarguen and W.A. Leighton (2006), *Property Rights to Radio Spectrum in Guatemala and El Salvador*, George Mason Law & Economics Research Paper No. 06-07, available at http://ssrn.com/abstract=889409.

Hazlett, T.W. and R.E. Muñoz (2004), *What Really Matters in Spectrum Allocation Design*, working paper 04-16, Washington, D.C., AEI-Brookings Joint Center for Regulatory Studies.

Hazlett, T.W. and R.E. Muñoz (2009), Spectrum Allocation in Latin America: An Economic Analysis, *Information Economics and Policy*, 21(4), 261-78.

Horvitz, R. (2007), *Spectrum Reform: Too Much Is Not Enough*, available at http://ssrn.com/abstract=1007456 .

Howe, K. (1988), Against the Quantitative-Qualitative Incompatibility Thesis or Dogmas Die Hard, *Educational Researcher*, 17(8), 10-6.

Ibarguen, G. (2005), Liberating the Radio Spectrum in Guatemala, *Telecomunications Policy*, 27(7), 543-54.

Illing, G. and U. Klüh (2003), *Spectrum Auctions and Competition in Telecommunications*, Cambridge, MA, MIT Press.

Indepen, Aegis and Warwick Business School (2004), *An Economic Study to Review Spectrum Pricing*, London.

Indepen, Aegis and Ovum (2006), *The Economic Value of Licence Exempt Spectrum*, London.

ITU - International Telecommunication Union (1995), *Spectrum Utilization of Broadly Defined Services*, Recommendation ITU-R SM.1133, Geneva.

ITU - International Telecommunication Union (1998), *Methods for Determining National Long-Term Strategies for Spectrum Utilization*, Report ITU-R SM.2015, Geneva.

ITU - International Telecommunication Union (2000), *Nomenclature of the*

Frequency and Wavelength Bands Used in Telecommunications, Recommendation V.431-7, Geneva.

ITU - International Telecommunication Union (2001a), *Economic Aspects of Spectrum Management*, Report ITU-R SM.2012-2, Geneva.

ITU - International Telecommunication Union (2001b), *National Spectrum Management*, Recommendation ITU-R SM.1047-1, Geneva.

ITU - International Telecommunication Union (2001c), *Guidance on the Regulatory Framework for National Spectrum Management*, Report ITU-R SM.2093, Geneva.

ITU - International Telecommunication Union (2001d), *National Alternative Allocation Methods*, Recommendation ITU-R SM.1265-1, Geneva.

ITU - International Telecommunication Union (2003), *Spectrum Redeployment as a Method of National Spectrum Management*, Recommendation ITU-R SM.1603, Geneva.

ITU - International Telecommunication Union (2005a), *National Spectrum Management*, Geneva.

ITU - International Telecommunication Union (2005b), *Software-Defined Radio in the Land Mobile Service*, Report ITU-R M.2064, Geneva.

ITU - International Telecommunication Union (2006a), *Definition of Spectrum Use and Efficiency of a Radio System*, Recommendation ITU-R SM.1046-2, Geneva.

ITU - International Telecommunication Union (2006b), *Characteristics of Ultra-Wideband Technology*, Recommendation ITU-R SM.1755, Geneva.

ITU – International Telecommunication Union (2007), *Determination of the Geographical and Frequency Distribution of the Spectrum Utilization Factor for Frequency Planning Purposes*, Recommendation ITU-R SM.1599-1, Geneva.

ITU-R – International Telecommunication Union – Radiocommunication Sector (2010), *Cognitive Radio Systems in the Land Mobile Service*, Annex 19 to document 5A/513, working document towards a preliminary draft new report, May, 31, available at http://www.itu.int/md/R07-WP5A/new/en .

Jackson, M. and H. Moulin (1992), Implementing a Public Project and Distributing Its Costs, *Journal of Economic Theory*, 57(1), 125-40.

Janssen, M.C.W. (ed) (2004), *Auctioning Public Assets: Analysis and Alternatives*, Cambridge, Cambridge U.P.

Jehiel, P. and B. Moldovanu (2001), *The European UMT/IMT-2000 Licence Auctions*, available at www.cramton.umd.edu .

Johari, R. and N. Tsitsiklis (2004), Efficiency Loss in a Network Resource Allocation Game, *Mathematics of Operations Research*, 29(3), 407-35.

Jonhson, R.B. and A. Onwuegbuzie (2004), Mixed Methods Research: A Research Paradigm Whose Time Has Come, *Educational Researcher*, 33(7), 14-26.

Jonhson, R.B., A. Onwuegbuzie and L. Turner (2007), Towards a Definition of Mixed Methods Research, *Journal of Mixed Methods Research*, 1(2), 112-33.

Juarez, R. (2008), The Worst Absolute Surplus Loss in the Problem of Commons: Random Priority versus Average Cost, *Economic Theory*, 34(1), 69-84.

Karp, R.M., E. Koutsoupais, C.H. Papadimitriou and S. Shenker (2000), Algorithmic Problems in Congestion Control, *41st IEEE Symposium on Foundations of Computer Science*, 66-74.

Kayı, Ç. and E. Ramaekers (2010), Characterizations of Pareto-Efficient, Fair, and Strategy-Proof Allocation Rules in Queuing Problems, *Games and Economic Behavior*, 68, 220-32.

Klemperer, P. (2002), How (Not) to Run Auctions: The European 3G Mobile Telecom Auctions, *European Economic Review*, 46 (4-5), 829-45.

Klemperer, P. (2004), *Auctions: Theory and Practice*, Princeton, Princeton U.P.

Klemperer, P. and K. Binmore (2002), The Biggest Auction Ever: The Sale of the British 3G Telecom Licences, *Economic Journal*, 112(478), C74-96.

Kwerel, E. (2000), *Spectrum Auctions Do not Raise the Price of Wireless Services: Theory and Evidence*, FCC white paper, Washington, D.C., available at

http://wireless.fcc.gov/auctions/data/papersAndStudies/SpectrumAuctionsDoNotRaisePrices.pdf.

Kwerel, E. and G. Rosston (2000), An Insider's View of FCC Spectrum Auctions, *Journal of Regulatory Economics*, 17(3), 253-89.

Kwerel, E. and J. Williams (2002), A Proposal for a Rapid Transition to Market Allocation of Spectrum, *OPP Working Paper Series*, no. 38, FCC, Office of Plans and Policy, Washington, D.C.

Laffont, J.J. (1987), Incentives and the Allocation of Public Goods, in A.J. Auerbach and M. Feldstein (eds), *Handbook of Public Economics*, vol. 2, 537-69, Amsterdam, North-Holland.

Lehr, W. (2005), The *Role of Unlicensed in Spectrum Reform*, Cambridge, MA, MIT, mimeo.

Lehr, W. and J. Crowcroft (2005), *Managing Shared Access to a Spectrum Commons*, available at

http://cfp.mit.edu/docs/lehr-crowcroft-sept2005.pdf .

Levin, H.J. (1966), New Technologies and the Old Regulation in Radio Spectrum Management, *American Economic Review*, 56(1-2), 339-49.

Lie E. (2004), *Radio Spectrum Management for a Converging World*, background paper prepared for the ITU New Initiative Workshop on "Radio Spectrum Management for a Converging World", Geneva, available at http://www.volweb.cz/horvitz/os-info/library.html.

Lincoln, Y.S. and E.G. Guba (2000), Paradigmatic Controversies, Contradictions, and Emerging Confluences, in N.K. Denzin and Y.S. Lincoln (eds), *Handbook of Qualitative Researc*h (2nd edn), 163-88, London, Sage.

London Economics (2008), *Economic Impacts of Increased Flexibility and Liberalisation in European Spectrum Management*, London.

Maasland, E. and B. Moldovanu (2004), An Analysis of the European 3G Lincensing Process, in M.C.W. Janssen (ed), *Auctioning Public Assets: Analysis and Alternatives*, 177-196, Cambridge, Cambridge U.P.

Marcus, M.J., P. Kolodzy and A. Lippman (2006), *Why Unlicensed Use of Vacant TV Spectrum Will Not Interfere with Television Reception*, New America Foundation, Issue Brief No. 19, Washington, D.C.

Mason, J. (1994), Linking Qualitative and Quantitative Data Analysis, in A. Bryman and R.G. Burgess (eds) (1994), *Analyzing Qualitative Data*, 89-110, London, Routledge.

May, T. (1993), *Social Research: Issues, Methods and Process*, Buckingham, Open U.P.

Mayer, T. (1996), The Dark Side of Economic Modelling, in S.G. Medema and W.J. Samuels, *Foundations of Research in Economics: How Do Economists Do Economics?*, 191-203, Cheltenham, UK, Elgar.

McKinsey & Co. (2002), *Comparative Assessment of the Licensing Regimes for 3G Mobile Communications in the European Union and Their Impact on the Mobile Communications Sector*, Brussels.

McLean Foster & Co. (2007), *Study of Market-Based Exclusive Spectrum Rights*, Ottawa, available at

http://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/sf09398.html .

McMillan, J. (1998), Selling Spectrum Rights, *Journal of Economic Perspectives*, 8(3), 145-62.

MED - Ministry of Economic Development (2005a), *Spectrum Auction Design in New Zealand*, Radio Spectrum Policy and Planning Resources and Networks Branch, Wellington.

MED - Ministry of Economic Development (2005b), *Review of Radio Spectrum Policy in New Zealand*, Wellington.

MED - Ministry of Economic Development (2009a), *Report of the Ministry of Economic Development for the Year Ended 30 June 2009*, Wellington.

MED - Ministry of Economic Development (2009b), *Spectrum Management in the Radio Licensing Regime. Discussion Document*, Wellington.

Melody, W. (1980), Radio Spectrum Allocation: Role of the Market, *American Economic Review*, 70(2), 393-7.

Minervini, L.F. (2007), Emerging Technologies and Access to Spectrum Resources: The Case of Short-Range Systems, *Communications and Strategies*, 67(3), 107-25.

Minervini, L.F. (2008), *How Much Is Spectrum Really Worth?*, Coventry, University of Warwick, WBS, mimeo.

Mott MacDonald, Aegis, Indepen, IDATE and Wik Consult (2006), *Study on Legal, Economic and Technical Aspects of 'Collective Use' of Spectrum in the European Community*, Croydon.

Moulin, H. (1992), An Application of the Shapley Value to Fair Division with Money, *Econometrica*, 60(6), 1331-49.

Moulin, H. (2000), Priority Rules and Other Asymmetric Rationing Methods, *Econometrica*, 68(3), 643-84.

Moulin, H. (2003), *Fair Division and Collective Welfare*, MIT Press.

Moulin, H. (2006), *Efficient Cost Sharing with a Cheap Residual Claimant*, available at http://med.ces.free.fr/pdf/Moulin.pdf .

Moulin, H. (2007), Minimizing the Worst Slowdown: Offline, Online, *Operations Research*, 55(5), 876-89.

Moulin, H. (2008), The Price of Anarchy of Serial, Average and Incremental Cost Sharing, *Economic Theory*, 36(3), 379-405.

Mueller, M. (1993), New Zealand's Revolution in Spectrum Management, *Information Economics and Policy*, 5(2), 159-77.

Neuman, W.L. (2003), *Social Research Methods: Qualitative and Quantitative Approaches* (5th edn), Boston, MA, Pearson Education.

Newman, I., C. Ridenour, C. Newman and G.M.P. De Marco, jr. (2003), A Typology of Research purposes and Its Relationship to Mixed Methods Research, in A. Tashakkori and C. Teddlie, *Handbook of Mixed Methods in Social and Behavioural Research*, 167-88, London, Sage.

Nitzan, S. and K. Ueda (2009), Collective Contests for Commons and Club Goods, *Journal of Public Economics*, 93(1-2), 48-55.

Noam, E.M. (1995), Taking the Next Step Beyond Spectrum Auctions: Open Spectrum Access, *IEEE Communications Magazine*, 33(12), 66-73.

Nsouli, S.M., M. Rached and N. Funke (2005), The Speed of Adjustment and the Sequencing of Economic Reforms: Issues and Guidelines for Policymakers, *International Journal of Social Economics*, 32(9), 740-66.

OECD – Organisation for Economic Co-operation and Development (1993), *The Economics of Radio Frequency Allocation*, ICCP, No. 33, Paris.

Ofcom – Office of Communications (2004), *Spectrum Framework Review: A Consultation on Ofcom's Views as to How Radio Spectrum Should Be Managed*, London.

Ofcom–Office of Communications (2005), *Spectrum Framework Review Statement*, London.

Ofcom – Office of Communications (2006a), *Spectrum Usage Rights*, London.

Ofcom – Office of Communications (2006b), *Higher Power Limits for Licence Exempt Devices: Understanding the Scope for a Power Increase at 2.4 and 5 GHz*, London.

Ofcom - Office of Communications (2007a), *Discussion Document on the Award of Available Spectrum 1452–1492 MHz: Auction Design*, London.

Ofcom – Office of Communications (2007b), *Licence-Exemption Framework Review*, London.

Ofcom – Office of Communications (2008a), *Progress on Key Spectrum Initiatives: A Review and Update of the SFR and SFR: IP*, London.

Ofcom – Office of Communications (2008b), *Auction of Spectrum: 2500-2690 MHz, 2010-2025 MHz*, London.

Ofcom – Office of Communications (2009a), *Simplifying Spectrum Trading: Regulatory Reform of the Spectrum Trading Process and Introduction of Spectrum Leasing*, London.

Ofcom - Office of Communications (2009b), *Application of Spectrum Liberalisation and Trading to the Mobile Sector,* London.

Ofcom - Office of Communications (2009c), *Digital Dividend: Geolocation for Cognitive Access: A Discussion on Using Geolocation to Enable Licence-Exempt Access to the Interleaved Spectrum*, London.

Ofcom - Office of Communications (2010a), *International Communications Market Report*, London.

Ofcom - Office of Communications (2010b), *Simplifying Spectrum Trading: Regulatory Reform of the Spectrum Trading Process and Introduction of Spectrum Leasing – Interim Statement*, London.

Ofcom - Office of Communications (2010c), *Applying Spectrum Pricing to the Maritime Sector, and New Arrangements for the Management of Spectrum Used with Radar and Aeronautical Navigation Aids – A Statement*, London.

Ofcom - Office of Communications (2010d), *Notice of Proposals to Make the Wireless Telegraphy (Licence Charges) Regulations 2011*, London.

Ofcom - Office of Communications (2010e), *Advice to Government on the Consumer and Competition Issues Relating to Liberalisation of 900 MHz and 1800 MHz Spectrum for UMTS*, London.

Ofcom – Office of Communications (2010f), *Notice of Ofcom's Proposals for Changes to Licence Exemption for Wireless Telegraphy Devices*, London.

Ofcom - Office of Communications (2010g), *Notice of Ofcom's Proposal to Make the Wireless Telegraphy (Ultra-Wideband Equipment) (Exemption) (Amendment) Regulations 2010*, London.

Olafsson, S., B. Glover and M. Nekovee (2007), Future Management of Spectrum, *BT Technology Journal*, 25(2), 52-63.

Olson, M. (1965), *The Logic of Collective Action*, Cambridge, MA, Harvard U.P.

Ostrom, E. and E. Schlager (1992), Property-Rights Regimes and Natural Resources: A Conceptual Analysis, *Land Economics*, 68(3), 249-62.

Patton, C.V. and D.S. Sawicki (1993), *Basic Methods of Policy Analysis and Planning* (2nd edn), Upper Saddle River, NJ, Prentice-Hall.

PC - Productivity Commission (2002), *Radiocommunications Inquiry Report*, Canberra, Ausinfo.

Peha, J.M. (2009), Sharing Spectrum Through Spectrum Policy Reform and Cognitive Radio, *Proceedings of the IEEE*, 97(4), 708-19.

Plextek, Spectrum Trading Associates and UCL Consultants (2006), *Study of Efficient Mobile Mesh Networks*, final report to Ofcom, Great Chesterford.

Pogorel, G. (2007), Regulation and Competition: Nine Regimes of Radio Spectrum Management: A 4-Step Decision Guide, *Communications and Strategies*, 65(1), 167-83.

Prasad, R. and V. Sridhar (2009), Allocative Efficiency of the Mobile Industry in India and Its Implications for Spectrum Policy, *Telecommunications Policy*, 33(9), 521-33.

Punch, K.F. (1998), *Introduction to Social Research: Quantitative and Qualitative Approaches*, London, Sage.

Qinetiq (2006), *Cognitive Radio Technology: A Study for Ofcom*, Farnborough, Qinetiq.

Quotient Associates (2007), *Higher Frequencies for Licence Exempt Applications*, final report to Ofcom, Cambridge.

Ragin, C.C. (1992), Introduction: Cases of "What Is a Case?", in C.C. Ragin and H.S. Becker (eds), *What Is a Case? Exploring the Foundations of Social Inquiry*, Cambridge, Cambridge U.P., 1-17.

Reed, D. (1992), Putting It All Together: The Cost Structure of Personal Communications Services, *OSP Working Paper Series*, no. 28, FCC, Office of Plans and Policy, Washington, D.C.

Richards, E., R. Foster and T. Kiedrowski (eds) (2006), *Communications: The Next Decade*, London, Ofcom.

Ritchie, J. and L. Spencer (1994), Qualitative Data Analysis for Applied Policy Research, in A. Bryman and R.G. Burgess (eds), *Analyzing Qualitative Data*, 173-94, London, Routledge.

Roland, G. (2002), The Political Economy of Transition, *Journal of Economic Perspectives*, 16(1), 29-50.

Rosston, G. and J. Steinberg (1997), Using Market-Based Spectrum Policy to Promote the Public Interest, *Federal Communications Law Journal*, 50(1), 88-116.

Roughgarden, T. (2003), The Price of Anarchy Is Independent of the Network Topology, *Journal of Computer and System Sciences*, 67(2), 341-64.

RSPG – Radio Spectrum Policy Group (2004), *Opinion on Secondary Trading of Rights to Use Radio Spectrum*, RSPG04-54 Rev.(final), Brussels.

RSPG – Radio Spectrum Policy Group (2005), *Opinion on Wireless Access Policy for Electronic Communications Services (WAPECS): A More Flexible Spectrum Management Approach*, Brussels.

RSPG - Radio Spectrum Policy Group (2009), *Opinion on Best Practices Regarding the Use of Spectrum by Some Public Sectors*, RSPG09-258, Brussels.

Salmon, T.C. (2004), Spectrum Auctions by the United States Federal Communications Commission, in M.C.W. Janssen (ed), *Auctioning Public Assets: Analysis and Alternatives*, 147-76, Cambridge, Cambridge U.P.

Santivanez, C., R. Ramanathan, C. Partridge, R. Krishnan, M. Condell and S. Polit (2006), *Opportunistic Spectrum Access: Challenges, Architecture, Protocols*, Proceedings from the 2nd Annual International Wireless Internet Conference (WICON), Boston, MA, August.

Sartori, G. (1970), Concept Misformation in Comparative Politics, *American Political Science Review*, 64(4), 1033-53.

Schotter, A. (1996), 'You're Not Making Sense, You're Just Being Logical, in S.G. Medema and W.J. Samuels, *Foundations of Research in Economics: How Do Economists Do Economics?*, 204-215, Cheltenham, UK, Elgar.

Spiller, P. and C. Cardilli (1999), Towards a Property Rights Approach to Communications Spectrum, *Yale Journal of Regulation*, 16(1), 53-84.

Stern, J. (2010), The Evaluation of Regulatory Agencies, in R. Baldwin, M. Cave and M. Lodge (eds), *The Oxford Handbook of Regulation*, 223-58, Oxford, Oxford U.P.

Stigler, G. J. (1974), Free Riders and Collective Action: An Appendix to Theories of Economic Regulation, *Bell Journal of Economics*, 5(2), 359-65.

Sutherland, E. (2007), *European Spectrum Management: Successes, Failures and Lessons*, ITU workshop on market mechanisms for spectrum management, Geneva, January.

Tashakkori, A. and J.W. Creswell (2007), Exploring the Nature of Research Questions in Mixed Methods Research, *Journal of Mixed Methods Research*, 1(3), 207-11.

Tashakkori, A. and C. Teddlie (1998), *Mixed Methodology: Combining the Qualitative and Quantitative Approaches*, London, Sage.

Teddlie, C. and A. Tashakkori (2009), *Foundations of Mixed Methods Research: Integrating Quantitative and Qualitative Approaches in the Social and Behavioural Sciences*, London, Sage.

TRAI – Telecom Regulatory Authority of India (2006), *Recommendations on Allocation and Pricing of Spectrum for 3G and Broadband Wireless Access Services*, New Delhi.

Trochim, W.M.K. (1989), Outcome Pattern Matching and Program Theory, *Evaluation Program Planning*, 12(4), 355-66.

UMTS Forum (2006), *Thriving in Harmony. Frequency Harmonization: The Better Choice for Europe*, UMTS Forum.

Valletti, T.M. (2001), Spectrum Trading, *Telecommunications Policy*, 25 (10-11), 655-70.

Varian, H.R. (1994a), A Solution to the Problem of Externalities When Agents Are Well-Informed, *American Economic Review*, 84(5), 1278-93.

Varian, H.R. (1994b), Sequential Contributions to Public Goods, *Journal of Public Economics*, 53(2), 165-86.

Vodafone (2006), *Reforming Spectrum Policy*, Vodafone Policy Paper Series, no. 5, available at

http://www.vodafone.com/content/dam/vodafone/about/public_policy/policy_papers/public_policy_series_5.pdf .

Walker, M. (1981), A Simple Incentive Compatible Scheme for Attaining Lindahl Allocations, *Econometrica*, 49(1), 65-71.

Wallsten, S. (2002), *Does Sequencing Matter? Regulation and Privatization in Telecommunications Reforms*, World Bank working paper No. 2817, available at

http://elibrary.worldbank.org/content/workingpaper/10.1596/1813-9450-2817 .

Webb, W. (ed) (2007), *Wireless Communications: The Future*, Chichester, UK, Wiley.

Webbink, D.W. (1980), Frequency Spectrum Deregulation Alternatives, *OSP Working Paper Series*, no. 2, FCC, Office of Plans and Policy, Washington, D.C.

Wei, S.J. (1997), Gradualism versus Big Bang: Speed and Sustainability of Reforms, *Canadian Journal of Economics*, 1234-47.

Weiser, P.J. and Hatfield D. (2006), Policing the Spectrum Commons, *Fordham Law Review*, 74(2), 101-32.

Weiser, P.J. and Hatfield D. (2008), Spectrum Policy Reform and the Next Frontier of Property Rights, *George Mason Law Review*, 15(3), 549-609.

Weiss, M. (2006), Secondary Use of Spectrum: A Survey of the Issues, *Info*, 8(2), 74-82.

Wellenius, B. and I. Neto (2007), *Managing the Radio Spectrum: Framework for Reform in Developing Countries*, mimeo, available at http://econ.worldbank.org .

Werbach, K. (2004), Supercommons: Toward a Unified Theory of Wireless Communication, *Texas Law Review*, 82, 863-973.

Wik Consult (2005), *Towards More Flexible Spectrum Regulation*, Bad Honnef.

Wik Consult (2008), *Optimising the Public Sector's Use of the Radio Spectrum in the European Union – Study for the European Commission*, Bad Honnef.

Xavier, P. and D. Ypsilanti (2006), Policy Issues in Spectrum Trading, *Info*, 8(2), 34-59.

Yan, X. (2001) *3G Mobile Policy: The Case of China and Hong Kong*, case study prepared for ITU New Initiatives Workshop "Licensing Policy for Third Generation Mobile", Geneva, available at

http://www.itu.int/osg/spu/ni/3G/casestudies/china/China_3g_Final.pdf.

Yin, R.K. (1992), The Case Study Method as a Tool for Doing Evaluation, *Current Sociology*, 40(1), 121-37.

Yin, R.K. (2009), *Case Study Research: Design and Methods* (4th edn), London, Sage.