The Economics of Spectrum Management: A Review

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The paper presents the author's own views and interpretations of the literature reviewed which do not necessarily represent those of ACMA. The literature discussed in this paper has mainly been sourced from outside Australia. No attempt has been made to independently examine the Australian spectrum regulatory framework and relate the conclusions drawn from the literature to the Australian regime.

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Abstract

Purpose – The objective of the paper is (i) to characterise spectrum as an economic resource and (ii) to use this knowledge to review spectrum management approaches and their economic justification in theory and practice. In particular, it aims at identifying credible alternatives to the three most debated policy options (command and control, property rights and commons).

Design/Methodology/Approach – The article takes stock of numerous contributions made available through peer-reviewed academic research, agency (or agency-commissioned) reports, think-tank and industry-sponsored policy papers, online articles and conference papers. This overview permits us to contrast the main spectrum management regimes used in practice with those currently experimented or formulated at a conceptual level (a past/present/future perspective).

Findings – Spectrum policy reforms have been the subject of a controversy over the respective merits of two modes of spectrum controls liberalisation: property rights and commons. Ambiguities about what constitutes a socially efficient spectrum management regime emerge from the polarisation of the debate and the conceptual approaches taken by the literature. Empirical research would help unlock the stalemate, but is currently difficult to conduct given limited policy experimentation. If deregulation remains debated conceptually, policy making would benefit from a larger array of spectrum management options than the binary policy choices currently examined.

Research Limitations/Implications – The review does not seek to address detailed technical issues, or issues that are specific to particular frequency bands. The emphasis is on the economic interpretation of efficiency and scarcity rather than on technical or functional interpretations.

Research Gap – The spectrum management literature has hitherto only been partially reviewed, with much focus on three existing modes of spectrum management but very little on potential alternative approaches, which are important to resolve policy ambiguities.

Originality/Value – The multidisciplinary aspect of spectrum management research (economic, legal, engineering, and philosophic) has polarised the policy debate in terms of markets vs. commons, social capital vs. property, freedom vs. regulation, etc. The main contribution of this review is to string these approaches together and lay some foundations for a general theory of spectrum management.

Keywords

Spectrum management, radiofrequencies, regulation, market pricing, commons.

Paper Category

Literature review

Introduction

Efficient spectrum management

Spectrum management by regulating agencies refers to the selection of a regime governing: (i) the *allocation* of spectrum frequency bands to specific uses (commercial, scientific, military, emergency services, etc.); (ii) the *assignment* of usage rights to different spectrum users (broadcasters, communication operators, public agencies, etc.); (iii) *clearance* of bands for new applications and users migration; and (iv) *policy responses* to technological and commercial developments (Webb 1998; Bauer 2002). Acute debates on the best ways to manage the spectrum have traditionally tended to focus on the first two aspects of spectrum management (Valletti 2001).

It is generally agreed that current 'control and command' regimes (centralised management by a regulator) in most countries allocate spectrum in suboptimal manner, with generally too much emphasis on the supply side (technical, or production efficiency) and too little on demand considerations (the social valuation of the services supplied). The two alternative regimes currently considered for reform are spectrum markets with private property rights (a solution which addresses spectrum demand and valuation considerations) and a 'commons' model (which also addresses demand problems but relies strongly on the supply side for its implementation).

Increased spectrum scarcity

The economic implications of spectrum misallocation (wrong pricing, scarcity, congestion) were recognised early (Herzel 1951; Coase 1959; 1960; Levin 1966; De Vany et al. 1969) but its manifestation only became obvious with recent shifts from wireline to wireless systems in telecommunications markets. This radical transformation of the spectrum user market considerably increased demand for specific bands, altering, in various countries, the methods commonly used to assign user rights (eg. moving from fixed license leases to market pricing mechanisms such as auctions) and bringing technological issues to unprecedented prominence in deregulatory debates (for example, can technology tackle scarcity? Is a pricing mechanism actually required?).

Assessing whether technological progress can make new approaches to spectrum management feasible is a contentious issue (Faulhaber 2005, 2006), but there is a sense among agencies and academics that reflection and experimentation is needed before sweeping reforms of the old centralised system are implemented (Baumol & Robyn 2006). In particular, there are strong hints that efficient spectrum management should not be engineered with 'one size fits all' approaches, and suggested similarities to the management of other common resources such as open land or water are commonly found in the literature.

Why is it important to manage the spectrum more efficiently?

The radio frequency spectrum is a key strategic asset for the economies of industrialised nations. It is used for a broad range of business and consumer communication, R&D and IT purposes, such as private and public telecommunication operations (eg. mobile phone networks, wireless internet communication, aviation, shipping, defence, public safety), broadcasting, radar, astronomy and various other applications including countless short-range, low-power wireless devices. Sound and socially efficient management of electromagnetic spectrum usage is a key input into the performance of these markets. Flexible regulatory regimes and technologies that make spectrum use more accessible to start-ups and other small innovative operators offer significant potential to reduce lead times from innovation to market for communication products (Berggren et al. 2004; Chapin & Lehr 2007), and lend a competitive edge to domestic producers in new product markets.

By contrast, current control and command arrangements in most countries rest on administrative licensing regimes that allocate blocks of spectrum to specific uses and entities (often large operators) as the need arises. Originally, control and command through licensing presented desirable properties in terms of interference control, international harmonisation of frequency allocation, new products standardisation and international roaming. However, as demand for spectrum rights grew spectacularly over time, the problem of spectrum scarcity became the main drawback of the current approach. Because it does not evaluate spectrum resources based on standard supply and demand economic criteria, this approach provides the wrong incentives to spectrum licensees and leaves much of the radiofrequency bands idle at any point in time, contributing to scarcity, congestion, and reduced economic performance in communication markets.

Limited examination of all policy options

Although the relative merits of the main approach to spectrum management, and its two challengers, have been the subject of extensive reviews, which are briefly presented and developed in this article, their potential alternatives remain little known. Research is broadly aligned with institutional membership (regulators, business, academics, consumers associations), occupational characteristics (engineer - high tech solutions - vs. economists - market solutions) or even ideological beliefs (private property lobby vs. communitarian or open source philosophy, etc.). There is currently no published material that comprehensively connects all these new strands in spectrum management research and policy work. Although, this would be valuable to resolve the numerous ambiguities presented by the standard 'trichotomic'[1] debate, spectrum management theory and debates about policy design are not currently informed by a general framework.

[1] cf. Hazlett (2007)

A review of spectrum management regimes

Policy debates are currently deadlocked in this control / markets / commons perspective. The necessary liberalisation of regulatory command and control provisions offers a source of policy convergence but acute disagreements about which of the two alternatives (or which mix) best serves the public interest and each alternative's technical or policy intricacies have made these choices more complex. One could learn much about efficient and desirable modes of spectrum management by examining a larger distribution of liberalisation regimes than the discrete choices currently on the regulator's table. This review takes stock of a mushrooming agency and academic-based literature on the topic in the last 15 years. Standard economic models, hybrid solutions, respective merits and downsides are examined, and current trends highlighted.

Structure of the paper

The review is organised as follows. The first section briefly summarises the traditional approach to spectrum management, arguments for reform, and progress towards spectrum liberalisation. Before discussing the two most-publicised alternative modes of spectrum management in current debates, markets and commons, economic concepts are introduced to characterise multi-dimensional difficulties encountered in defining spectrum in economic terms, and associated policy ambiguities. The article then discusses intermediate spectrum management approaches, regularly benchmarked on land-use rent theory[2], and concludes with the presentation of generic models of spectrum management based on existing regimes and their extensions.

The traditional approach to spectrum management

In the original regime of spectrum governance, referred to as command and control, a regulator rigidly allocates non-overlapping frequency bands to specific uses and assigns usage rights to licensees. Potential users apply to the regulator for a license covering a specific purpose, with no guarantee of success. In the US, for instance, if there is more than one competitor the regulator holds 'public hearings', which determine - sometimes quite opaquely - the successful applicant. Mostly, though, license rights are granted in *ad hoc* ways (such as a 'first-come first served') and for modest fees (usually just covering administrative costs).

[2] This theory dates back to economist David Ricardo (Ricardo 1951 orig 1817) and examines productivity margins in land cultivation . Spectrum and land management are two natural resources that share many common features. Both are driven by productivity gains at the margin, that are *intensive* (in-band capacity increases / increased crop yields) or *extensive* (broadening useable spectrum / making uncultivable land suitable for crops). Because the cost of basic research that makes spectrum more productive are often borne by society, spectrum license holders derive economic rents from productivity gains (Melody 1980). How and by whom should these rents be recaptured is an important aspect of spectrum management liberalisation.

Obtaining the license provides no property rights to the licensee but confers enforceable rights concerning the respect of fixed usage with regard to purpose, frequency band, transmission power and location (Faulhaber & Farber 2003), thus preventing dynamic uses and adaptations in the face of technological change. Command and control generally does not permit license trading, which provides no incentives to licensees to maximise the value of their spectrum holdings, leading to spectrum hoarding, idle bandwidths, and a legacy of rules, red tape, incumbent privileges and restrictions to adapt to new market conditions. This regime, which is now considered archaic, inefficient[3] and unsustainable by most - if not all - spectrum analysts and many regulators, traces its roots to the start of the twentieth century: times of war and catastrophes in which the operations of markets were distrusted and the necessity to control interference considered paramount. Because this system failed to be regularly re-evaluated over the century, it has now become difficult to reform, because of entrenched licensee positions and confusion about which type of regime should succeed it. In short, command and control can be characterised by:

- allocation of non-overlapping bands to specific uses and users;
- no or little spectrum trading;
- strong control of interference between users;
- slow progress of innovations to market;
- slow spectrum reallocation for new systems; and
- incongruous contrasts between spectrum shortages and spectrum hoarding.

The control and command model has been extensively discussed, analysed and criticised. Its rationales and weaknesses are well-known and not further investigated here. For additional information see Benjamin et al. (2001), Faulhaber (2006) or Cave et al. (2007).

Trends and reforms

Command and control failure

There is near-unanimous agreement that sole reliance on command and control does not result in efficient outcomes. Regimes in which regulators carve out blocks of spectrum that are then arbitrarily

[3] Economic efficiency in this domain arises from the speed at which new applications reach consumers (households and firms alike), contributing to enhanced production and consumption possibilities and economic growth. However, other efficiency concepts are also commonly associated with spectrum management (Burns 2002). For instance, the manner in which band allocation manages interferences calls upon functional efficiency and productive usage of a given band (high data processing per band) is a density or technical efficiency concept. From a purely regulatory perspective though, spectrum efficiency is maximised when the spectrum management regime is endowed with the flexibility to timely adapt spectrum access and usage to both market requirements and technological advances.

allocated to uses that do not necessarily maximise social welfare lack the flexibility to respond to new spectrum-using product developments and their associated technology (Baumol & Robyn 2006). Also, the distinction between spectrum allocation (specific quantities for specific uses) and assignment (specific users in specific numbers) is artificial and inefficient as it creates a wedge between the expertise and its application (Valletti 2001). Segregation between large but often complacent 'have access' and small but innovative 'have not' operators created market frustration characterised by long lead times from innovation to the market and the dominance of large incumbents with little dynamism. With the increased demand for wireless products in recent years, the consequences are congestion and huge welfare costs in terms of public revenue lost, delayed productivity improvements and missed opportunities in international markets (Hazlett 2006), which eventually led to calls for more efficient ways to allocate and manage spectrum.

Reforms

Limited reforms started in the early and late 1990s and remain restricted to a small group of mainly Anglo-Saxon countries[4]. Auctioning of spectrum property rights was pioneered in New Zealand from 1989 (Mueller 1993; Crandall 1998), then from 1994 in the US and Australia (McMillan 1998). In 1995, Australia, later followed by the United Kingdom and the United States, also initiated administrative spectrum pricing[5] (ie. regulatory pricing based on market information) and legislated spectrum property rights[6], which were implemented in 1997, opening the way for secondary markets trading (Hayne 1997; Webb 1998). Spectrum trading has occurred in low volumes in Australia and New Zealand, apparently because spectrum purchases in these countries are mainly carried out by a few operators intending to build long-term networks (Lie 2004). Although secondary spectrum trading is much more popular in the US, it is also much less flexible, with most of the licenses for commercially viable spectrum allowing fixed use only (Kwerel & Williams 2002, Speta 2004).

Additional steps towards wide-ranging liberalisation included auctioning 3G mobile licenses throughout Europe in 2000 and more recently opening unlicensed bands for ultra wide band (UWB) applications in the United States. In the US, the Federal Communication Commission's (FCC) Spectrum Policy Task Force (SPTF) formalised these new approaches in an important report in 2002 that recommended the agency migrate toward a 'policy-based' solution where spectrum could be used on an opportunistic basis (FCC 2002). In particular, the FCC was looking at means by which licensed spectrum currently assigned to TV broadcasters (and higher frequencies) could be reused in secondary

[4] Countries that party departed from command and control in the early 1990s in recent years include the United States, the United Kingdom, Australia, New Zealand, Canada, El Salvador and Guatemala. For a comprehensive review of these developments see Marcus et al. (2005).
[5] Arguably, Australia already had a system of administrative pricing (on a more ad hoc basis) in the early 1980s.
[6] Spectrum licenses grant rights to flexible band use with respect to area and power, with only general technical requirements on license use.

markets, promoting mainly licensed trading mechanisms (the property right approach) but also some unlicensed solutions such as WiFi.

In the United Kingdom, little happened prior to 2000, at which time the Cave review (Cave 2002) and subsequent enquiries (OFCOM 2005) set out the case for a dramatic extension of market mechanisms with OFCOM, the British communications regulator, setting a target of 71 percent of the spectrum to be devolved to market and license trading by 2010. The European Parliament/Council Decision 676/2002/EC of 7 March 2002 on a regulatory framework for radio spectrum policy in the European Community also recognises that 'the lack of flexibility in spectrum management … has led to a spectrum bottleneck for new radio technologies' (European Commission 2005) and proposes to introduce spectrum markets by 2010 in EU countries, with strong recommendations that 'license-doling' should be the exception, rather than the rule. There is however a feeling that these recommendations, being non-binding, rest too much on the goodwill of the member states and progress is slow (Cave et al. 2007).

Before examining the merits of alternative management regimes suggested in spectrum liberalisation reforms, the next section recapitulates the economic attributes of spectrum and introduces the market and commons models through their advocates' interpretation of spectrum scarcity.

Basic economics of spectrum management

A taxonomy of scarce resources

For business users, the radio spectrum is a fixed factor of production, with unique, infinitely reusable and limited substitutability[7] features. However, the potential for interdependency among users is huge (Melody 1980) and for this reason it is not infinitely available at any given point in time - if it was, the matter of pricing and social evaluation would present few difficulties. Although the number of frequency bands was once thought large enough (compared to demand for their use) to dismiss any thought of economic appraisal, this is no longer the case. Competing uses for available radiofrequencies make spectrum a scarce commodity that now lends itself quite naturally to economic investigation.

Basic microeconomic theory ranks all publicly and commercially available resources in a given society along two criteria: (i) excludability (or exclusiveness), which defines property rights and

[7] Spectrum is substitutable for some uses. For instance, fixed equipments can use wireline rather then wireless. Also, there is always the possibility for mobile phone equipments to trade spectrum for smaller cell size at higher equipment cost.

access; and (ii) rivalry, which examines simultaneous use and depletion. A private good, such as a personal car or dwelling, is both exclusive and rival, which means its owner has rights that exclude others from its consumption and the owner's consumption of the good makes the good unavailable to others. A public good or service, eg. a lighthouse or national defence, is non-exclusive and non-rival. Club goods, eg. a golf club with limited membership, are exclusive but non-rival, whereas common goods, eg. common land and forests, fish stocks, etc. are non-exclusive but rival[8]. Table 1 summarises the economic way of classifying a nation's resources, services and production (this presentation and further discussion are available in most introductory microeconomics textbooks):

Table 1. The standard approach to defining economic goods and services

Characteristics in consumption:	Excludable	Non-excludable
Rival	Private good *cars, ice cream*	Commons *fish stocks, open land*
Non-rival	Club *golf club, private park*	Public good *lighthouse, defence*

Given this taxonomy, which class of economic resource best characterises the radiofrequency spectrum? and what are the implications for its regulation?

Economic attributes

In the command and control regime - and from the perspective of its business users (mobile phone operators, broadcasters, civil and military aviation, etc.) the radio magnetic spectrum is rival - more users means fewer spectrum bands available and more potential interference. The spectrum is also excludable because licensees are guaranteed exclusive access by the regulator.

However, both questions have become vexed issues in the spectrum management reform literature. The exclusivity granted to licensees by regulators was originally meant to protect band users against signal interferences, although in many cases it also shielded license holders from competitors (Goggin 2007). Of the two alternatives to bureaucratic rule discussed in the next section, the market and property rights solution does not challenge the validity of exclusiveness. On the contrary, clearly-defined exclusive ownership rights (and obligations that keep transaction costs low) are critical to successfully implementing spectrum market trading mechanisms such as buying, selling, leasing,

[8] It can be argued that 'commons' are a disappearing species. Fish stocks, drink water, open land and forests have also seen increases in scarcity in recent years. However these are caused by demand-driven depletion rather than congestion of a renewable resource. For a comprehensive review of these concepts applied to spectrum management, see a recent survey by Flaegel et al. (2006).

transferring, auctioning, subdividing and merging blocks of spectrum in exactly the same manner one would trade parcels of land. If exclusivity is a necessary feature of rival spectrum usage, then spectrum is a private good and the way ahead consists of spectrum trading in private commodity markets.

The commons model challenges this vision by suggesting that frequency bands be shared by unlicensed users adhering to codes of conduct and technical standards. Contrary to what the name suggests, this model mainly rests its case for efficient spectrum management on technological rather than economic arguments, which we comment on in later sections. If non-excludability is the desired feature characterising spectrum usage, then rival usage makes spectrum a commons good, just as open land, water, fish stocks and most natural resources. Spectrum is then exposed to the critique known as the 'tragedy of the commons' - inefficient overuse of the spectrum with costly interference spillovers (which are further discussed in subsequent sections). However, various advocates of the commons model go further to suggest spectrum bands could potentially be turned into public goods, which are not exposed to the 'tragedy' argument.

Can dynamic spectrum access (DSA) technology reduce or eliminate the issue of spectrum scarcity? Some scientists and engineers think so. Research in experimental network architectures and agile radio technology such as cognitive radio (CR) suggests that the spectrum could potentially be made non-rival to its users (Shepard 1996; Gupta & Kumar 1999; Mitola 1999; 2000; Reed 2001; Reed 2002). *Spread spectrum technology* that allows simultaneous (underlay[9]) band use and *cognitive* radio technology that potentially allows near-simultaneous (overlay[10]) band sharing, permit one spectrum user to 'consume' the resource without making the resource unavailable to other users. Some short-range adaptations such as the development of ultra wide band technologies (UWB) - an extreme example of spread spectrum technology - have already been given unlicensed spectrum access in the US, subject to a frequency mask (Cave et al. 2007). In principle, removing rivalry in the use of spectrum would lend the radio spectrum the characteristics of a nature-provided public good rather than a 'commons'.

An intermediate regime of spectrum management arises from imposing excludability (licenses, property rights or other access restrictions) on the non-rival mode of spectrum usage just discussed, in

[9] Spread technologies diffuse a weaker signal over larger bandwidth, transmitting bits streams rather than single bits, in effect substituting power for band span. UWB technology spreads signals over such a large portion of the spectrum and at such low power that the interference produced on these bands disappears *under* standard noise floors, hence its characterisation as band *underlay* (Cave et al. 2007).

[10] 'Cognitive radio technology' refers to high power signals transmitted with band-hopping technology, also known as opportunistic spectrum access (OSA). The technology targets whites space on existing bands for secondary users, occupies it and vacates it instantaneously upon primary user usage, hence its characterization as band *overlay* or *spectrum pooling* technology (Faulhaber & Farber 2003). Cognitive radio is sometimes used to mean software defined radios (SDR), wrongly as it happens, for the latter merely enables an easier development of the former (Cave et al. 2007).

which case, spectrum becomes a club good (a private park). As is discussed later in this review, excludability with non-rivalry is not a very interesting arrangement as the essence of new radio technologies is to make interference-free sharing of already occupied spectrum a reality. For this reason, interest in the club good variant relies on various types of easements to the orthodox property rights model, which are discussed in further sections.

Table 2 applies the typology introduced in table 1 to this discussion of the desirable economic attributes of spectrum as a renewable natural resource: if smart radio technology is not available, the policy options lie in the first column and spectrum needs to be privatised (as its status as a common good, or commons, is the worst option of all). On the other hand, if the technology is available and can be deployed to different uses, spectrum can take various types of economic definitions depending on the regime considered for usage rights. A rigid license regime can only lead to the use of spectrum as a private good, but more flexible arrangements can lead to other characterisations. All have their costs and benefits, which are the central theme of this review.

Table 2. Spectrum as economic commodity under different regimes

Available technology: Exclusivity rights: (*decreasing*)	Original technology	Dynamic spectrum access
Licensed spectrum – full rights	Private good	Private good
Licensed spectrum - easements	Private good	Club good / Public good
Unlicensed spectrum	Common / Open access good	Public good

Non-rivalry is however far from being a reality today, and there remains numerous technical hurdles to overcome, such as the specification of interference temperature in underlay signals (Mannion 2004; Entman 2004), the hidden terminal problem for overlays (Cave & Webb 2003), protocol definition (Cabric et al. 2004), dynamic regulatory responses (Santivanez et al. 2006) and various other technical problems. Claims of future (at least short-term) non-rivalry in spectrum usage by advocates of the commons model are therefore regularly refuted by prominent economists, as in Faulhaber (2005) or AEI (2006), who stress that it is very difficult to predict with any accuracy what new technological developments can bring, whereas market pricing offers immediate responses.

Spectrum scarcity

Spectrum is often compared to land. Both are natural resources and there is a degree of fixity in usage in both (Noam 1995). To pursue this analogy, the discussion of the economic (private, club, common, public) and technological nature of spectrum also provides an introduction to the divergent views of the spectrum's corporate analysts (economists concerned with efficiency and welfare or profit-maximisation), solicitors (lawyers concerned with usage rights), landowners and tenants (licensees concerned with spectrum rents), real-estate agents (spectrum clearinghouses concerned with pricing and value maximisation) and builders (engineers concerned by technology-based solutions). At the heart of the debate is a wholly different approach to the concept of spectrum scarcity among the disciplines involved with spectrum management.

For economists, scarcity is created by excess demand and inelastic supply[11] (excessively rigid supply management). In such a context, regimes that treat spectrum as a commons worsen the excess demand problem by undervaluing an already scarce resource, yielding overuse and interferences (the notorious 'tragedy' problem), eventually shifting demand downwards (decreasing the benefits derived from spectrum by its users) and reducing social welfare to sub-optimal levels. According to this view, the commons model is only suitable for situations of excess supply, such as the conditions experienced in the first half of the century[12], but not currently. A free-market pricing mechanism would not, on its own, remove demand pressures, but would ensure that, in the absence of market imperfections, spectrum is valued according to its degree of economic scarcity and social welfare maximised.

For 'technologists', scarcity is both a regulatory *and* a technical issue. Although, along with economists, they criticise the scarcity created by command and controls, it tends to be for different reasons. In their view, it is as much the use of licenses and exclusivity rights as their mishandling by regulators that generates market power, forces prices up and imposes suboptimal spectrum usage. The technical rationale for the model comes from considerable evidence that much of the spectrum lies idle at any given time and location (FCC 2002). So the problem is as much an issue of adequate pricing, as market proponents advocate, as a matter of designing the right technological instruments to provide instant, interference-free access to any idle bandwidth. Historically, spectrum scarcity has essentially been managed with technical responses such as using higher and higher frequency bands, increasing technical efficiency (eg. data compression, smaller bandwidths, spectrum re-use) and developing spectrum sharing technology (Hatfield 2005).

There is no doubt that important progress is being made in that area, particularly in the United States[13], and there is increasing research involvement both of the US Government and the military, as these techniques provide applications that go well beyond mere spectrum management improvement. However, the critical question is whether technological development will be able to keep up with the

[11] See eg. spectrum market diagrams 3 and 4 in Cave and Webb (2004 : 8).
[12] Ironically, the reasons invoked by spectrum regulators to justify its command and control approach up that point was that spectrum was too scarce a resource to be trusted to the market, ie. alleged excess demand would inevitably create 'chaos' (Brito 2006a).
[13] For a review of civilian and military cognitive radio research in the US and Europe, see Dimitrakopoulos et al. (2004).

pace of demand increase (Weiss 2006). If it does not, economic scarcity will increase and market pricing and trading would emerge as the only valuable and socially responsible alternative. The two concrete policy propositions for full spectrum liberalisation currently on the table, property rights and commons, are well established in the literature and, together with their merits and weaknesses, briefly summarised below.

Standard Alternatives to Command and Control

According to Baumol and Robyn (2006), a rational spectrum regime must strive to address six constraints to achieve efficient market allocation and other issues of public interest:

- interference control or minimisation;
- encourage innovation;
- prevent market power or its exercise;
- adaptability to technological and demand changes;
- preserve communication diversity;
- encourage provision of services to rural areas;

Of these objectives, the first four have stronger relevance for economic analysis and are also more widely debated in spectrum management research, and this review focuses mainly on these issues[14].

The two main alternatives to the command and control regime considered by competent authorities are (i) market-based spectrum trading and license pricing through the introduction of property rights; and (ii) 'unpriced' and 'unlicensed' arrangements known as the 'commons' model.

Property rights and markets

Marked-based alternatives originate in the work of Nobel Prize winner Ronald Coase (Coase 1959; 1960). This model keeps the idea of licensing the spectrum to users but differs from the command and control model in the following ways, summarised by Levin (1970): (i) property rights are assigned to specific frequencies and areas (*exclusivity*); (ii) a market pricing mechanism is designed for acquisition of frequency bands by primary spectrum users (the license holders), including trading, auctions, tenders, but also 'pseudo-market' mechanisms such as administrative pricing and cost-benefit analysis;

[14] This is not to say that the other two issues are entirely ignored. In fact one of the major arguments for the establishment of a commons model of spectrum management is the development and preservation of diversity and freedom of speech in the communications market. In the US, these issues are regularly connected to the 1st constitutional amendment, particularly as a criticism of command and control (Benjamin 2002).

(iii) freedom is granted to trade licenses in secondary markets (license holders sell, lease, subdivide or give away idle spectrum rights to secondary users); (iv) spectrum allocation is decided by license holders; (v) owners have the right to exclude others who cause interferences (*excludability*); and (vi) interference is controlled by technical rules that govern transmitters specifications and power limits.

This model resolves the arbitrary separation of allocation and assignment mentioned earlier for the command and control model. Spectrum is assigned to an exclusive owner (say by auction) who decides on its allocation and eventual re-allocation through trading. The central motivation driving this alternative regime is that markets would be far more efficient in allocating spectrum to its social-value maximising uses than regulators could possibly be, because markets deal much better with the intrinsic information (demand/supply and allocation/assignment mismatches) and incentive (idle bands) problems encountered by spectrum management. Further details about the important benefits of this approach can be found in the papers commissioned by communications regulators, such as the FCC or OFCOM, and in the large academic literature developed by its most prominent advocates, who are usually economists[15].

However, this is not to say that market outcomes are always efficient or even more efficient than other alternatives, nor that economists always stand by the property rights and markets solution due to pre-established professional inclinations (Baumol & Robyn 2006). Although the market / property rights model offers unparalleled prospects for efficient management, it also entails a long list of potential difficulties, of which market proponents are well aware, which has made reform-driven regulators cautious in their endeavours to free the spectrum and deterred much progress in that area. These potential issues are either caused by malfunctioning markets (market failures) or by excesses in the use of property rights.

Market failures

Seminal contributions by Nobel Prize winner Paul Samuelson (among others) established long ago that markets can 'fail' to produce outputs that maximize social welfare. The most notorious economic arguments describing market failure are: (i) the presence of externalities, also known as spillovers (in which market operations generate costs not 'internalised' by the parties); (ii) the public good nature of some markets (in which markets undersupply or fail to materialise); and (iii) the presence of non-natural monopolies and other sources of market power (which overprice, undersupply and reduce

[15] See an exponential list of contribution, starting with Coase (1959; 1960); Levin (1966); De Vany et al. (1969); Levin (1970; 1971); Minasian (1975); Hazlett (1990); Rosston & Steinberg (1997); Cramton (1998); Hazlett (1998); Spiller & Cardilli (1999); White (2000); Valletti (2001); Cave (2002); Kwerel & Williams (2002); Benjamin (2002; 2003); Faulhaber & Farber (2003); Hazlett (2003a; 2003b; 2003c); Cave & Webb (2004); Doyle (2004); Faulhaber (2005; 2006); Baumol & Robyn (2006); AEI (2006); Cave (2006); Hazlett (2007); Cave et al. (2007).

consumer surplus). Other 'undesirables' in market theory are: (iv) large transaction costs in exchange and disputes, which prevent economic agents to reach mutually beneficial solutions through markets alone; (v) asymmetric information about the quality of the good or service being exchanged, which distorts the true economic valuation of the good or service through market mechanisms; and (vi) uncertainty and risk aversion, which hamper the design and provision of some goods and services. Undesirable redistributive outcomes (such as 'unfair' or 'unbalanced' outcomes) are not a source of market failure *per se* but are also frequently mentioned in conventional critiques of market operations.

Unsurprisingly, given the various economic facets of the spectrum as an economic input, the development of private spectrum markets is potentially exposed to all these sources of market failure. There is little in spectrum ownership and license trading, nor for that matter in any feature of the command and control model, that guarantees against dominant positions in downstream spectrum markets. In fact, Cave et al. (2007) note that market power in spectrum markets is an intrinsic consequence of the type of technologies that require spectrum as input, the nature of their respective product market, and the intricacies of spectrum scarcity (see next section). For instance, studies of spectrum license auctions and their outcomes suggest a confusion between competition *for* spectrum and competition *in* spectrum markets (Gruber 2001; 2002). Levin (1970 : 211) also cautions that, due to transaction costs, '[spectrum] markets will be far less efficient where the number of transacting parties is very large', which is a point also originally made by Coase. Hence, although market power is usually unattractive from an economic perspective, it may have some benefits in this context, and may be unavoidable anyway.

The major problem with excessive market power is spectrum hoarding and sub-optimal pricing. As with most imperfectly competitive markets, the solution, if one is required, resides in setting spectrum caps and establishing rules, such as antitrust laws, constraining the accumulation of spectrum by one or few owners, when this is deemed to have reached a threshold threatening public interest. Indeed, some policy work, such as Valletti (2001), views this as the key role for regulators in a spectrum trading framework. In any case the market model is probably less conducive to monopolies and oligopolies than the pure regulation model, since it is more open and relatively less vulnerable to rent-seeking activities. Additionally, it is not clear that switching to a commons model solves this problem. In a commons, there are indeed no barriers to entry for small competitors, but there are also no rules excluding the entry of large organisations with economies of scale (Baumol and Robyn 2006). Hence there is no reason to believe *a priori* that small operators can more successfully compete with larger rivals in non-market based regimes.

Externalities present another major problem in the form of signal interferences, which are minimised under the command and control regime. Interferences are imposed by transmissions in a specific band spilling over onto users of adjacent bands. The extent of the externality in this case depends on transmission power and type of application (Falch & Tadayoni 2004). Deregulating the spectrum market and making spectrum usage flexible is likely to increase the number of licenses granted, which opens up the potential for various types of signal interferences, such as out of band power in neighbouring frequencies (Faulhaber & Farber 2003).

For this reason, market proponents have suggested a Coasian solution, which consists of internalising interferences by incorporating current regulatory restrictions to power/place/frequency into property rights (Goodman 2005; Cave et al. 2007). All licenses are endowed with identical interference limits (or limits based on the status-quo) to out-of band power (tolerance levels about amounts of interference imposed on receivers in neighbouring bands) and in-band power (tolerance levels for in-band transmission interference with other, distant transmitters). Acceptable levels of interference are then codified through property rights and its owners held responsible under civil law. Excessive interference can then also be reduced by increasing these limits, say, by requiring higher specification filters. As a consequence license value may be reduced through market clearing, but in theory at least interference can be controlled.

The public good critique of market efficiency does not apply directly to the spectrum, which is naturally available and does not need to be 'produced'. Even if the spectrum could be characterised as a public good, which is very far from certain, its market provision is not a problem. However, the spectrum is an input into the production of various strategic public goods and services which strongly contribute to the public interest, such as national defence, public safety services and basic research (Rosston & Steinberg 1997). This is one of the reasons why there is little talk of 'across the board' full property rights and market liberalisation in policy debates and the principle that some bands will have to remain under control and command management for strategic reasons is generally well recognised in the literature (Cave et al. 2007).

Asymmetric information, particularly the 'market for lemons'[16] issue, is a potential valuation problem for spectrum trading if the owner of a band has important economic information that cannot be verified by potential buyers (eg. persistent interference patterns). Uncertainty and risk aversion may deter the creation of some spectrum markets. If the testing of uncertain new technologies requires access to privatised spectrum, the cost of acquiring access rights could be a deterrent in some cases

[16] See Akerlof (1970): the owner of a poor-quality good (a lemon) has no incentive to price it as such if potential buyers do not and cannot verify quality *ex ante*. Potential buyers know though that there are high and low quality goods on the market and as a consequence the market price reflects the average value of the good. Hence, owner of high quality goods opt out of the market because the price is lower than the value they expect to obtain for their quality good. The process is iterative, with market price reflecting ever lower quality, until the market vanishes.

and commercialisation may consequently be delayed. On the other hand, this critique also holds for the licensed system currently used for the purposes of regulatory control and uncertainty about future technology is a much stronger problem for other spectrum management modes than for the market alternative.

Observation of unequal redistributive outcomes do not entail an economic critique of market inefficiency as, technically, they do not deal with efficiency issues, and can be tackled in other ways than by restricting the actions of efficient markets. In many ways, though, these issues cannot be ignored in research about spectrum reform. The development of spectrum markets poses a threat to the entrenched position of 'legacy users' (insiders), which have protected spectrum access under the current regulatory regime, and is pure benefit for 'have not' (outsiders), currently crowded out by congestion and inefficient spectrum management. Opposition from incumbents is therefore likely to result from major policy changes, bringing about various sources of economic inefficiencies (conflict resolution, policy backlash, etc.). If the net economic gains from reform are large enough, these issues may only have limited influence on policy. Otherwise, efficient ways need to be found to overcome this opposition and a fine balance must be struck between the interests of these two groups.

The main criterion for achieving economic efficiency, the Pareto principle, requires that as long as the beneficiaries of a policy can potentially compensate the losers and remain at least as well-off, the policy is socially desirable. The criterion itself establishes no rules by which such compensatory transfers should proceed, nor does it identify whether such transfers are desirable; economic welfare necessarily increases whether or not compensatory transfers actually take place. As a consequence, there are concerns that spectrum deregulation by markets with full property rights, if not correctly designed, will lead to resistance (passive or active) to change by 'legacy users', or legal conflicts, which will slow down the pace of reforms, with obvious efficiency costs (Lie 2004; Baumol & Robyn 2006). This critique is however not specific to the property right and market trading approach; instead it applies to all modes of spectrum liberalisation.

Property rights failures

There are additional sources of concern for a spectrum market regime, this time stemming from the assignment of full property rights (the exclusivity issue) and the transaction costs involved with exchange and disputes over these rights.

The first problem is known as the 'anticommons' or 'hold up' critique, an underutilisation problem which arises when there exist multiple rights to exclude access to a resource along with incentives for strategic behaviour (Heller 1998) [17]. If spectrum property rights are held by more than one user, new technologies and applications may be 'held up' (ie. barred from spectrum access) by rent-seeking behaviour (Faulhaber & Farber 2003) or even by non-economic (eg. zealot) behaviour (Buchanan & Yoon 2000). In an economic formalisation of the anticommons critique, Buchanan and Yoon (2000) observe that this issue arises more from bureaucratic power than from the mere granting of property rights, because it is bureaucracy that allows the existence of multiple exclusion rights (often to grant a veto right to a bureaucratic segment in an otherwise free market). Market advocates have responded to the anticommons critique by developing an easement model, which is considered in later sections.

An associated problem lies with the transaction costs generated by having to negotiate spectrum access with a large number of owners. Barring license concentration among a few, transaction costs generated by having to negotiate access with a large number of license holders are likely to be prohibitive (Benkler 1998; Snyder 2006), even in the absence of the hold-up problem.

A third issue is the resolution of disputes related to property rights infringement, which are bound to unfold as spectrum scarcity deepens. In command and control, the regulator deals directly with these disputes by weighing public and licensee interests. If usage rights become private property, then common law, and in particular, complex nuisance and trespass common law, replace the administrative mode of dispute resolution (Goodman 2004). Goodman cautions against this idea, stressing that nuisance law is the messy outcome of two centuries of *ad hoc* rulings, and its application to spectrum disputes would require 'unsummoned technical prowess', 'cost assessment never before made' and difficult juggling of public and private interests by courts. Faulhaber (2006) recognises the difficulties ahead but stresses that regulatory resolution of disputes over license rights in the US has a much more dismal record. In his words:

> Disputes drag on for many years as the FCC attempts to reach consensus; third parties intervene in hopes of disadvantaging competitors, and in the end parties may seek redress in the courts, which if successful results in a remand of the issue to the FCC and the process starts all over again (Faulhaber 2006 : 268-9).

If property rights are strongly and clearly articulated, common law would then be a lesser evil than the regulator-administered system of dispute resolution. Recent law research takes a more agnostic view with respect to this argument, seeing pitfalls in both options, and arguing instead for a mix of regulatory power and private control (Goodman 2004) or for having neither (Benkler 2002).

[17] Heller describes the anticommons by his observation of real estate developments in post-communist Moscow, where many buildings remain unused because potential users must first secure the agreement of several agents, each of whom may exercise a right of exclusion.

The fourth issue relates to public interest and expropriation law. Competing uses for privately-owned land can lead to expropriation when one of the competing parties is an infrastructure provider and the public interest overrides the interest of non-infrastructure-providing land owners. If the spectrum is privatised, the resolution of infrastructure conflicts by expropriation law may have to steer a fine course between the public interest value of different types of infrastructure providers, including essential community services (Falch & Tadayoni 2004). This requires a good grasp of what *is* 'public interest'[18] and what it requires. These issues can be relatively straightforward, as in the issue of 'digital dividend' whereby broadcasters are required to switch from analogue to digital technology, in order to free spectrum for higher-valued wireless services. Other infrastructure conflicts may be more complex.

Finally, markets and private property complicate international and cross-border efforts aimed at harmonising frequency uses and standardising equipment. On the other hand, to the extent that these frequency harmonisation exercises are driven by bureaucratic rather than market mechanisms, the risk of regulatory failure can be substantial for bands allocated to new spectrum-using technologies (Cave 2006) and the efficiency gains from harmonisation become less clear. Examples include cordless telephone standards (CT3), mobile satellite services (MSS), etc.

Commons and Open access

The case for a commons approach has a much shorter history than that of market approaches. In 1980, economist William Melody foresaw the essence of current debates in following terms:

> The spectrum resource is a public commons…Theory that directly considers interdependence, externalities, the need for sharing and compensation rules, and the necessity for total system management for system efficiency must represent more fertile ground for [spectrum] analysis than neoclassical market theory with its assumptions of independence and atomistic private markets (Melody 1980 : 396).

More recently, these ideas have gained momentum with the work of Ostrom (1990), Noam (1995, 1998) and Benkler (1998, 2002). These developments have produced two broad ideologies for managing the spectrum in a non-administered, nor privatised way: the open access and common property regimes.

Noam argues for open spectrum access with a single variable access fee (covering duration of transmission and bandwidth used) determined by a clearinghouse set up by users and based on instantaneous electronic supply and demand information[19].

[18] cf. Hazlett (2001)

[19] The various practical difficulties (transaction costs, market design of the clearinghouse) involved with this alternative have been stressed by various authors (Faulhaber 2005, Lee 2007).

In his critique of the license model, Noam uses highways as a metaphor for the success of open access to common resources. Licensing the spectrum to different uses and users in a control and command model is similar to dividing up a highway into different uses: tourism driving, business uses, sport driving, bikes use, etc. Users have cheap but exclusive access rights to a specific lane. The inefficiencies in terms of lane idleness are obvious. Reforming highway management with lane auctions does not solve the problem. It would not only keep lanes access exclusive and mainly idle but further exclude many users who cannot afford entry[20]. Instead, unrestricted access with a market clearing fee frees the market of uncompetitive practices (sub-optimal usage) and encourages usage diversity. Interferences (accidents) and other externalities (traffic jams) are minimised by adherence of all users to the 'rules of the road', which can be enforced by civil law. Since this is the way we have decided to manage our highways and networked computers, asks Benkler, what prevents us from applying the same principles to spectrum management?

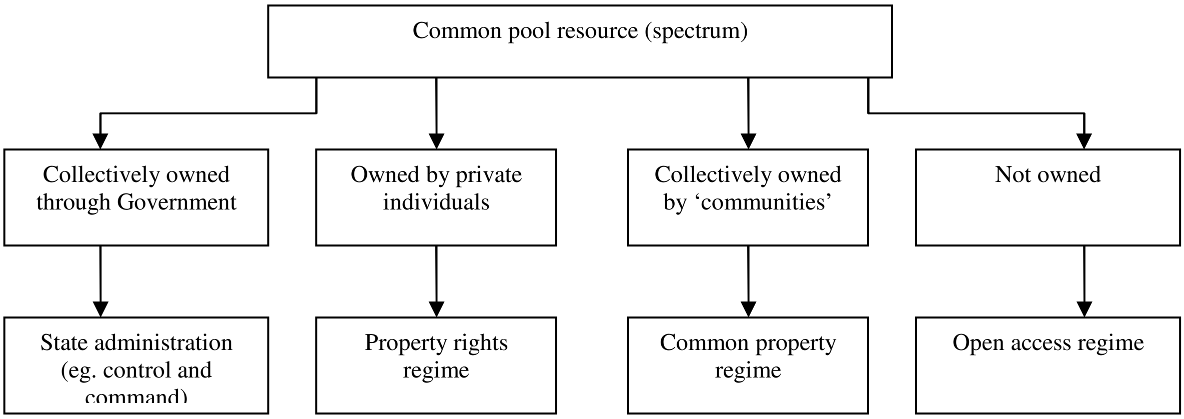
There are various unlicensed approaches to the commons model and a fair amount of confusion as to what the term really describes (Buck 2002; Brito 2006b). The approach suggested by Noam, just described, that permits spectrum access and usage *without* limitation to all potential users, is usually referred to as the *open access* model. Because it is conditional on the payment of a market-clearing, perpetually-auctioned fee and because 'the rules of the road' are potentially determined by a regulator, this model is not what is generally viewed as the 'standard' spectrum commons model[21].

The standard commons model is a co-management regime that draws from the *common pool* literature recently surveyed by Ostrom (1990), then applied to spectrum policy by Benkler (1998, 2002), Lessig (1999) and Buck (2002). The model draws from successful co-management experiences with other types of scarce common resources (particularly fish stocks, irrigation resources and open pastures and forests) and is known as the *common property* regime. In this approach, the government legitimises and protects the boundaries of spectrum usage by a group of users (including criteria for group membership) but takes no part in its intrinsic governance. The spectrum management community so defined, composed only of end-users, has sole authority for spectrum uses, setting standards and dealing with interference. In essence, this model excludes individual property rights *over the core resource exploited* (yet not necessarily over its yield), but tolerates access restrictions, thus conferring some degree of joint-ownership *by membership* to spectrum communal users. Yet, the model stops short of establishing property rights as such. Indeed the main creed of commons advocates is that there is to be no property rights assigned for a common-pool resource held and used by the community. Approaches that confine access to and usage of frequency band by a group of users under private

[20] This critique has been duly considered by various markets / property rights advocates who have responded by developing the intermediary 'easement' approach, which is discussed in later sections.
[21] Confusion between *open access*, *commons* and *unmanaged regimes* are pervasive in the spectrum- and other natural resources literature, eg. Quiggin (1993) and Hess (1998), and is a source of ambiguity in current debates.

property rights are referred to as *privately run commons,* or *commons parks*. Technically, the latter has little to do with the commons model of spectrum management[22], and is discussed in later sections.

As is regularly stressed in the literature (eg. Hess & Ostrom 2001, 2003), there needs be no particular association between common pool resources (as defined in table 1) and common property regimes (as just defined). Figure 1 upgrades the taxonomy introduced in table 2 and summarises the different ownership models suggested so far for the management of a common pool resource such as the radio spectrum.



<u>Figure 1. Ownership and management modes for a common pool resource</u>

The benefits of the commons approach (whether open access or common pool) include low barriers to entry (which is a source of competition), no or little uncertainty about band access, low lead times from innovation to market (eg. development of WiFi technology in unlicensed bands), less pressure on licensed portions of the spectrum, creativity through information sharing and diversity. The model may also be more compatible with international harmonisation and standardisation efforts as it offers a collaborative rather than competitive environment for equipment standards (ie. manufacturers first collaborate on standards, then compete in markets).

Regulators such as the FCC and Ofcom have traditionally permitted, under certain conditions, the unlicensed[23] use of low-power, short-range wireless devices, setting a precedent for an open access[24]

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[22] Bucks (2002 : ¶ 35) notes: "true common property systems - in which distinct groups of individuals hold property rights to a resource - are closer to individual private property rights and hence are far les likely to fall prey to the same problems as an open access system".

[23] For a review of geographical experiments with unlicensed use, see Best (2006) who surveys 75 countries, a third of which currently permit unlicensed spectrum access, and finds strong correlation between license exemptions and internet penetration rates.

[24] The view that unlicensed spectrum use constitutes a foray into commons experimentation is in fact strongly debated due to the regulatory control that still governs band allocation, standards development and interference management in this regime. See Snider (2006) and further discussions in Cave & Webb (2004), Benjamin (2003), Lehr (2005) and Hazlett (2007).

regime of spectrum management. In this context, unlicensed spectrum works as a public good because it is freely available to all users (non excludability) and its confinement to very short-range applications removes interference spillovers (rivalry). This unlicensed wireless experiment has hitherto been both successful at controlling interference, promoting innovation, and bringing products quickly to the market. For precisely these reasons, its advocates have, from the mid 1990s, urged its consideration as a mode of spectrum management liberalisation[25]. In particular, the development of smart technologies enabling signal underlays (eg. UWB) or overlays (eg. cognitive radio) and their potential architectures (mesh networks) offers the prospect of experimenting more broadly with commons management (however this is true for both licensed and unlicensed regimes) and removing, or at least reducing, the scarcity problem.

Commons failure

The main criticism of the commons approach unfolds naturally from the comparison of spectrum with other scarce natural resources. The phenomenon known as *Tragedy of the commons* (congestion and interferences) is in essence another externality issue that takes its root in a game-theoretic problem known as the *Prisonner's Dilemma*[26]. It refers to overuse of a scarce common resource as benefits accrue to private parties and costs are borne by all participants (Gordon 1954; Hardin 1968). Because nobody owns the resource, no-one can be excluded from its use, and since the use of the resource is rival and profitable, scarcity ensures depletion. In the context of spectrum, depletion is fortunately not an issue, but ever increasing spectrum demand generates congestion and the commons model does not really offer guarantees against interferences, especially from new untested systems. For instance, Baumol & Robyn (2006) respond as follow to Noam's open access highway metaphor:

> We all know from bitter experience that overcrowded roads generally continue to be overcrowded and unclog themselves only when significant tolls are adopted or some other rationing device is put into place, and spectrum is not essentially different (Baumol & Robyn 2006 : 27)

The systemic response that consists of imposing etiquette rules regarding transmitter behaviour, power and emission limits may or may not work in situations where incentives are unclear and countless users wish to transmit simultaneously. Stronger and more coercive, enforceable rules may clear the incentive problem, but would effectively move the commons regime much closer to the property rights and command and control regimes. Indeed, there have been proposals among proponents of the

[25] See among others (Noam (1995); Benkler (1998); Noam (1998); Werbach (2002); Benkler (2002); Buck (2002); Ikeda (2002); Lessig (2003a); (2003b); Werbach (2004).

[26] In its simplest expression, this economic theory suggests that, due to an insurance and information problem, two rational agents will always choose to compete ('defect') rather than collaborate even when collaboration is in their join interest. In the commons and open access regime context it indicates that the resource will be depleted by strategies maximising personal interest rather than sustained by collective action.

commons approach to use ‘light handed’ government controls to check interferences (Weiser & Hatfield 2006). Sharing rules in spectrum use, common technical standards and protocols, and resource control would have to remain in the hands of the government, which would allow the commons approach retain the same potential for inefficient allocation as the command and control system (Brito 2006a; 2006b; Hazlett 2007).

For instance bands set aside for unlicensed use are not a commons but are administratively allocated. Sharing rules in these bands are not designed collectively, but by regulators. Hence, there is a feeling that the commons approach (currently a utopia) is often confused with the unlicensed model (currently in use but more an experiment in administrative commons management than a straight application of the commons model). Baumol and Robyn (2006) also caution that the light-handed control approach to the commons regime would: (i) lead to inefficient one-size-fits-all solutions that would not take account of within- and between bands interference heterogeneity, thus regularly under- and overcorrecting; and (ii) re-introduce resource-wasting rent-seeking practices.

These difficulties, argue the model’s detractors, will create strong demand for ownership rights in the future and will make the assignment of property rights ineluctable. As has been discussed earlier, commons proponents have replied with various types of technological arguments, such as signal underlays and overlays, which permit to increase spectrum capacity by dynamic interference management. However, market advocates feel that these technical improvements will not be enough to keep up with demand increases, will not be commercially available in the short to medium term (even existing technologies such as UWB can hardly be described as ‘commercially deployed’) and that even if they do, their utilisation would be just as appropriate in a market as in a commons approach. Moreover, they stress, whereas the case for a commons relies heavily on the performance and availability of these new technologies, the case for markets and property rights is independent of these developments and therefore more adaptable and robust (Hazlett 2001; Faulhaber 2005; Lee 2007).

Note also that the high transaction costs of dispute resolution discussed in the property rights section also apply to the commons model because of expected conflicts on the definition of etiquette rules, technical protocols, enforcement mechanisms and conflict with adjacent private spectrum properties (Goodman 2004; Hatfield 2005).

Another weakness of the commons model is its relative lack of modularity. Whereas a property rights system can be relaxed by various degrees of ownership, property and easement rights to accommodate the specificities of different types of spectrum-using services, the commons approach appears, by contrast, monolithic. Any departure from the model towards more government control of the regime, or rights discrimination among users, quickly invalidates the model.

If its critics are right, the commons model is only suitable and efficient for local, low power use, uses for which etiquette protocols are likely to be respected and high frequency bands for which supply still exceeds demand. Even if this were to be the case, such restrictions would still leave room for some applications of the commons model. The impact and consequences of these two alternatives for social welfare, economic efficiency and scarcity alleviation are examined next.

Regime comparison

The previous sections summarised the pros and cons of spectrum property rights and commons regimes at a purely theoretical level, which is the way the spectrum management literature usually approaches these issues.

Table 3 provides a brief synopsis of the main conceptual points distinguishing the two regimes discussed in the previous sections (treating open access and common pool as one model). There are other problems with conceptual analysis. The discussion in this literature review reveals that both sides of the policy debate not only produced persuasive arguments for the implementation of their preferred model, but also developed very effective critiques of the alternative, competing model. In particular, the argument that model A will achieve the benefits sought by proponents of the model B, which cannot achieve its own objectives for reasons X and Y, recurs in the literature, eg. Benkler (1998) or Faulhaber (2005).

Table 3. Regime comparison

Markets and Property rights	Commons (with open access)
Spectrum as private property	Spectrum as public good (non-rival, open access)
Exclusive and transferable usage rights	Unlicensed users share frequencies
Barriers to entry	Easy entry for all
Responsibility for interference (internalisation)	Rules and etiquette standards manage interference
Model maximises owner profits	Model maximises spectrum access
Market failures (undersupply, interference)	Tragedy of the commons (overuse, interference)
Tragedy of the anticommons (hold up problem)	Commercially undeployed technology
Transaction costs (depending on type of rights)	Low transaction costs in exchange
Modularity (different degrees of ownership)	High transaction costs in dispute
Ownership incentives for innovation	So far only experimented under a regulatory regime
Restricted access to innovation	Positive externality problems in innovation
Lower scope for rent-seeking activities	Access a factor of innovation success (eg. WiFi)
Less suited for low-power local uses	In most cases, still dependent on regulatory power
	Less suited to high-power international uses

Source: amalgamated from arguments in Struzak (2004); Faulhaber (2005); Baumol & Robyn (2006) and Snyder (2006).

That conceptual analysis tends to be influenced by the professional or political background or beliefs of its initiators is not a particular problem - all policy debates are constructed this way, but conceptual analysis is unable *per se* to effectively demonstrate a hierarchy in the costs and benefits generated by each regime. Are marginal increases in interference an acceptable price for marginal decreases in market power? Are expected technological benefits worth waiting for at times of rapidly increasing spectrum demand? Most of the answers provided by top economic experts in the literature are based on experience, intuition and 'gut feelings', not empirical cost-benefit analysis.

Empirical research is virtually non-existent in this field, and for good reasons. The radiospectrum is no scientific laboratory. Practical experiments by which similar portions of spectrum are assigned to different regimes and the economic outcomes regularly evaluated offer very limited options. Moreover since very few of these new regime alternatives have actually been implemented in practice, real-life policy experiments present few observations to the analyst, and it is difficult to conduct empirical assessments of their merits and drawbacks that go beyond case studies, anecdotes and 'visions of the future'[27].

Ting et al. (2005) propose a different way of conducting evaluations of these policies' respective social desirability. They develop an analytical model designed to measure the relative welfare properties of spectrum markets and commons. Standard functional specifications are formulated for market demand and a representative firm's demand curve, which are then submitted to in-band and off-band interfering signals. Robust but costly receivers can help the firm reduce the welfare losses imposed by these interferences, but the degree of robustness may be also determined by the government, as are barriers to entry, which determine property relative to commons solutions. Governments aim at maximising welfare while firms maximise profits.

This set-up characterises four regimes of spectrum management, with robustness and firm entry as main dimensions. In the property regime with government (firm-) -decided level of robustness, the government selects the number of licenses and the degree of receiver robustness subject to the firms' profit-maximising conditions with respect to output (and robustness). In the two commons regime, firms set output (and robustness in the second model) so as to maximise profits, but these are always driven to zero by free entry, which determines the number of players in the market. Comparisons within the property regimes shows the government cannot improve on firm's robustness choices because firms make better informed choices, impose no spillovers on the investment decisions of other firms and increases in regulated robustness are passed on though higher service prices. In the two commons regimes social welfare is similar regardless of government intervention on robustness levels.

[27] Benkler (1998 : 66) analyse the evaluation of earlier commons endeavours, such as public waterways, roadways and railroad, and discusses the difficulties encountered with crude empirical evaluations of licensed and unlicensed uses of the spectrum, in terms of users time spent on both, and expenditures on regime-specific equipments.

Comparing property with commons approaches when firms set robustness levels shows that with both regimes firms set robustness at the social welfare-maximising level of the regime. With government determination, base case simulations yields potential social welfare gains under a property regime of 10 percent compared to the commons regime, but the property regime requires much more information on demand, interference and cost parameters. Getting the parameters wrong consistently yields lower simulated social welfare outcomes for the property regime. Hence, uninformed choices by regulators can only reduce the merits of the property regime with respect to the commons regime. In a companion paper, Wildman et al. (2006) expand the model and confirm the results.

The policy debate would benefit from more multi-regime impact analysis such as these ones. This also provides a fitting introduction to the next section, which presents intermediate approaches to the three polar positions discussed so far and attempts a synthesis.

Intermediary spectrum management approaches

Four modes of spectrum management have been introduced so far: command and control, full property rights, open access and common pools. The literature does not provide other ideologies but there are many intermediary models worth mentioning.

Ownership with easements

In recognition of some drawbacks in the property rights model, Faulhaber & Farber (2003 : 13-20) present a regime of ownership with easement. The rationale starts with the fact that private property may lead to dominant positions in which market incentives against band idleness may not perform as well as in more competitive environments. Also exclusive rights condemn the deployment of new dynamic radio technology, such as underlays and overlays, by creating barriers to their use and experimentation - not quite the flexible, socially efficient regime envisioned by Coase.

To reunite the potential of new sharing technologies with the market model, Faulhaber and Farber suggest a regime characterized as *fee simple ownership with non-interference easement*, in which owner users (license holders) have rights to transmit signals at any time without interference (the 'clear broadcast' right). Unlicensed users are entitled to use the band in as much as they never purposely interfere with the owner's rights to clear signal reception, which can be checked by requiring emission of identification signals and finding compensation schemes for owners' monitoring costs.

Leighton (2004) provides an entertaining analogy of the easement model with real property management. Suppose your neighbours' pets ('high power' elephants and 'low power' fruit flies) regularly invade your backyard searching for food (which always regenerates itself). The elephants are loud and noisy but only occupy the yard when you are away, whereas the neighbours' flies are there permanently but are hardly noticeable and difficult to distinguish from your own and other neighbours'. If you have given your consent to these intrusions, conditional on not ever seeing these animals in your yard, then the situation is a Pareto improvement: your neighbours' welfare increases at no expense of yours, so 'society' (the two neighbours) is better off. If you have not given your consent, your options are limited. Nuisance law is unlikely to be any help, as no nuisance can be detected by yourself, whereas trespass law will require a considerable portion of your time and resources to provide the evidence required to stop the intrusions (setting cameras in the yard, 'bugging' the flies, etc.).

Faulhaber and Farber sum up their model in the following terms:

> In this regime, spectrum would be owned but subject to an easement that any and all users that did not meaningfully interfere with the owner's right to spectrum could not be excluded from using the spectrum. In effect, this easement creates a commons at all frequencies and in all locations of a special type: non-interfering uses only (Faulhaber & Farber 2003 : 14)

This regime is entirely compatible with (and made possible by) the use and development of spread and agile radio technologies (whenever these will be commercially ready) and appears to combine some of the best features of both models. Why, then, is it not more actively promoted?

Baumol & Robyn (2006) stress that this intermediary regime does not need to be an option on the policy maker's table, as it can be derived freely by a property right regime of flexible licenses with secondary markets. Allow spectrum trading and, if the technology is available, owners will share their property whenever it maximizes their profit. There are various caveats to this last point. On the one hand, many owners will plan their mobile network based on maximum noise floor standards. The owner's reputation as a robust network may depend on how these standards are upheld. In these circumstances letting any secondary users in, even for a gain, may be too great a risk to take. Also, if transaction costs, such as interference monitoring and enforcement, are excessive, handling this situation may easily become too complex for the owner. Government may intervene to internalise transaction costs, thereby opening opportunities for policy-protected 'squatting effects' by unlicensed users seeking free access to licensed bands[28].

[28] For further discussion of the easement regime as a compromise between property rights and commons approaches to spectrum management, see Leighton (2004). For a contrasting perspective between the government-imposed non-interfering easement regime (favoured by Faulhaber & Farber 2003) and its secondary market analogue favoured by Baumol & Robyn 2006, see Cave et al. (2007 : chapter 8, section 8.3).

Privately run commons

Another hybrid model is the private commons or 'commons park' (Hazlett 2007), in which a community of private owners manage 'commons enclaves' (with barriers to entry erected not by government regulation but by private usage rights) in the midst of otherwise privately managed spectrum. This alternative differs from a command and control regime by assuming freedom to use licenses for any type of spectrum allocation, and sits uneasily with the commons model because the principles of low transaction costs and collaboration, inherent to the commons model, are mostly inconsistent with incentives of profit maximisation, inherent to the commons park model. Last, it differs from private property and easement regimes by requiring the use of unlicensed technology within the park, hence standards are developed jointly. Incentives for such solutions appear slim, but are better understood from a property rights perspective. If the profit derived by a license holder from operations in the licensed band is inferior to the profit that can be extracted by letting others share the band against the payment of a fee, then the licensee benefits ('economise') by setting the interference threshold to levels that equalise marginal cost and benefit of common use (Baumol & Robyn 2006). Note though, that the term 'commons' is probably misleading for such solutions as there is still exclusive usage[29] (the park is inaccessible without payment of the fee), strong interference control *without* regulatory intervention and allocative efficiency derived from market-based incentives. The clearest analogy with the commons approach is the necessity, as with the easement approach, to equip the park with cognitive and spread spectrum technologies. However, the park's set up is also subject to the anticommons critique if there is more than one band owner.

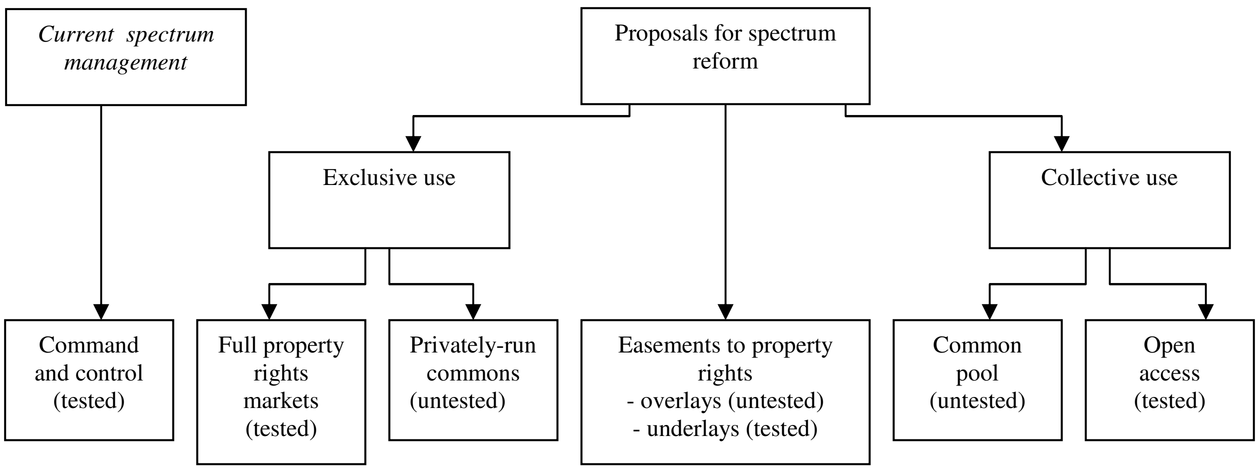

Figure 2. Spectrum management: standard and intermediate models

[29] Noam's (1995, 1998) vision of the commons also include the payment of an access fee. However this access fee is competitive, whereas the commons park fee includes payments for rent privileges.

Figure 2 schematises the mainstream and intermediary ways of thinking about spectrum management introduced so far - command and control, exclusive rights, easements and commons - highlighting which models are currently being used and which remain experimental. Although this diagrammatic presentation is popular (eg. Flaegel et al 2006, Zao & Sandler 2007), it is perhaps excessively articulated around notions of exclusivity and access.

There are other important dimensions defining these management models. For instance, the two intermediate approaches just discussed can be re-framed to yield alternatives regimes: the easement model can be initiated and partly regulated by the government, can be market-delivered, or can be modulated by using different types of property rights (eg. property, ownership, privileged access, rights of usage) and types of easements to these rights derived from land property and torts law (prescriptive easement, adverse possession, eminent domain, etc.)[30].

The commons park alternative can also be run with some degree of government control in the form of interference management (eg. setting receiver robustness as in the Ting et al. model) or other technological standard settings. Hence, beyond these intermediate solutions may lie a continuum (a 'spectrum') of policy options defined by more refined concepts of exclusivity and the degrees of government intervention in technological standard setting.

Spectrum regimes and regimes spectrum

The notion of a continuum of spectrum management options rests uneasily with the literature as most of the dimensions separating potential regimes appear discrete: open or exclusive access, administrative allocation or not, license with or without easement, agile technology ready or not, etc. Although some of these choices do not lend themselves to continuous analysis, others do: the law permits, in principle, to define property rights at ever finer levels and there are different degrees of government intervention in spectrum matters. However, this is an area into which the spectrum literature has not ventured much. This review concentrates instead on attempts to generalise spectrum management options into a discrete framework. Here too, much remains at draft level[31]. A recent model generates nine spectrum regimes with four spectrum policy dimensions[32] (Pogorel 2007): (i) frequency harmonisation, (ii) product standardisation, (iii) degree of rights exclusivity, and (iv) assignment modes.

[30] See Leighton (2004) for details and examples of torts and nuisance law applied to the easement problem.
[31] Leighton (2004) and Bauer (2002) put strong caveats to any use made of their unpublished work at this stage. The succinct presentation of these research papers here is made with these authors' consent.
[32] Pogorel provides 15 distinct regimes, some of which are 'bunched' along the assignment modes dimension.

Frequency harmonisation and products standardisation are of great importance to countries with little manufacturing tradition in the telecommunications sector, such as Australia, New Zealand, Canada and various non-Scandinavian European countries. Because these countries systematically adopt imported technology from various provenance (say US, EU, Japan), lack of frequency harmonisation in manufacturing countries adds to congestion in non-manufacturing countries by forcing the use of different band frequencies for different technologies (eg. CDMA and GSM) when one band could have been sufficient.

Product standardisation, the technical flexibility dimension of the nomenclature, works in the same direction as similar standards would make communications equipment sensitive to similar frequency properties. On the other hand, less harmonisation and technological standardisation means more flexibility for license users. Hence potential for harmonisation and product standardisation is a valuable input into a nomenclature of spectrum management regimes - if it is defined correctly by relevant authorities (see eg. caveats by Cave 2006).

The degree of user rights exclusivity has been sufficiently commented upon in this research and is a key input into any generic spectrum management model. In Pogorel's framework, user rights takes three positions: exclusive property rights (FPR), eased property rights (EPR) and collective use (CU). However, the standard mode of command and control often does not grant 'property' rights to the licensee but merely rights of usage. These dimensions are probably better re-interpreted as exclusive, semi-exclusive and non exclusive which, combined with rights assignment mode, (auction or other) permits to deduct whether the regime grants full property rights or 'controlled' rights.

The fourth dimension, assignment modes, refers mainly to the type of licensing regime, which can be administrative (AL), auctioned and flexibly tradeable (AT), or license-exempt (unlicensed bands - UB). The administrative licensing regime is the most ambiguous as it varies from very rigid licenses to more hybrid forms of controls on the license. License-exempt UB refers to bands originally unallocated by administrative decision, in which end-users make allocation decisions. Auctioned licenses are equated to pure property rights on the spectrum in the auctioned band.

Table 4 provides an abridged version of this generic approach to spectrum management. The standard control and command, full property rights and commons regimes are identified as regimes 1, 12, and 10 respectively. The table has some quite intuitive features. For instance, it shows that unlicensed band experiments with UWB technology are not quite a 'commons', as is regularly claimed (and corrected) in the literature, because the spectrum in each band is allocated by administrative rule (AL), rather than by end-users (UB). Also, the current mode of auctioning and trading the spectrum in reform countries comprises both the quasi-property rights in regime 2 (with flexible *and* specific use licenses) and the full property right regime 12, which is free of any regulatory constraints[33]. This table also vindicates the proposition put by Leighton (2004) that the easement model entails more complexity than the other models and can arise from government intervention as in regimes 3, 8 and 13 or independently through market trading as in regimes 4, 9 and 14.

Table 4. A general framework for spectrum management

Regime	Harmonisation (service flexibility)	Standardisation (technical flexibility)	Usage Exclusivity	Rights Assignment
1. Standard C&C	Yes	Yes	FPR	AL
2. Property rights and Market	Yes	Yes	FPR	AT
3. Eased C&C	Yes	Yes	EPR	AL
4. Technical C&C + Market	Yes	Yes	EPR	AT
5. Collective C&C	Yes	Yes	CU	UB
6. Flexible C&C	Yes	No	FPR	AL
7. Harmonised flexibility	Yes	No	FPR	AT
8. Controlled flexibility	Yes	No	EPR	AL
9. Enhanced harmonised flexibility	Yes	No	EPR	AT
10. Standard Commons regime	Yes	No	CU	UB
11. Administered flexibility	No	No	FPR	AL
12. Libertarian regime	No	No	FPR	AT
13. Flexible semi property rights	No	No	EPR	AL
14. Semi libertarian regime	No	No	EPR	AT
15. Autonomous commons[34]	No	No	CU	UB

Source: adapted from Pogorel (2007), C&C = Command and Control; FPR = Full property rights; EPR = Eased property rights, CU = collective use, AL = Administrative licensing; AT = Auctioned licenses and market trading; UB = Unlicensed band. The term 'flexible' refers to technological flexibility (no product standardisation).

Pogorel (2007) views regime 9 as one of the most desirable spectrum management regimes, offering both technological and market flexibility together with interference-free technologies and incentives against spectrum hoarding. Note that the alternative, known as the 'commons park' (privately-run commons), does not differ much here from the libertarian regime since it tolerates neither the freely accessible commons nor the command and control regimes and harmonisation would constrain freedom of usage in the commons park. Note also that 'property rights and market' (regime 2) is constrained by non-market driven harmonisation and technology standardisation procedures and, therefore, does not equate to the 'full' property rights model.

The original article provides the EU's Universal Mobile Telecommunications System (UMTS, also called 3GSM), a 3G mobile internet technology, as example for regime 2. Regime 6 'technologically flexible command and control' is equated to the high control regime that governs, in France, the licensing of Worldwide Interoperability for Microwave Access technology (WiMax), a mobile internet rival to UMTS technology.

[33] Shelanski & Huber (1998) argue though that the *de facto* rights enjoyed by license owners in quasi-property rights regimes can under certain conditions be interpreted as full property rights.
[34] In the original paper, this regime is referred to as a utopian 'California Dream'. It seems to refer to an open access model with neither external management nor obligations, and no access fee.

There are limitations to this framework. First, although technological flexibility is discussed, the existence and functionality of overlay and underlay technologies is taken implicitly. If band-sharing technology does not work, easement and commons solutions disappear but property rights regimes are mainly unaffected (although some market outcomes such as market-driven easements or privately-run commons would also become difficult or impossible). Hence, table 4 assumes that the technology works[35] (or will work) for the options that rely on it. This is difficult to avoid, though, as most of the options discussed in this review rely on the success of underlay and overlay technologies. Negating this condition annihilates the policy debate.

Second, although frequency harmonisation and technology standardisation are important issues for some countries, economic arguments rationalising their social value are few. Is constrained standardisation better for society than technological flexibility? The question, which depends on uncertainty, lock-in effects, economies of scale in production, etc. is deserving of a literature review in its own right and cannot be answered here. In the absence of an answer, it is difficult to generalise about the desirability of various specific regimes in table 4 (is regime 9 indeed better than regime 4 or 14?).

Third, some important dimensions are missing. The user rights dimension should also distinguish between property rights with flexible use or with specific use, which defines a finer grain of property rights regimes and, similarly, for the easement dimension. For instance, the *interference internalisation* regime discussed in the market failure section (licenses specifying interference limits along with power/area/frequency) is likely to work better with specific use license than with flexible use licenses.

Bauer provides another attempt at a general framework (Bauer 2002), partly based on the work of Benkler (1998)[36], dissociating spectrum regimes along allocation, assignment and adjustment lines and examining decision-making locus (government, licensees, manufacturers, owners, end-users). He dissects the commons model into three distinct regimes (unlicensed, open access, autonomous) based on three management dimensions (access, congestion rules and development standards) and suggests a general framework of spectrum management and industry evolution (entry costs, market structure and appropriability). Bauer's work is, however, still experimental and not currently available for further research.

In answer to the limitations of the generic discrete model presented in table 4, table 5 suggests an amended version in which harmonised frequency use and equipment standards issues are merged as 'government constraints on technological standards'. In accordance with Bauer (2002), the model

[35] Pogorel also briefly discusses game-theoretic implications if band-sharing technologies do not work.
[36] Other reviews of the property/easement/commons literature can also been found in Xavier & Ypsilanti (2006) and Cave et al. (2007 : chapter 8), which stop short though of formulating a generic framework.

incorporates a finer grain for the commons model, which can have limited or unlimited membership, capturing the distinction that 'collective use' does not necessarily mean 'open access'. Table 5 also introduces the possibility of government intervention and self-regulated ways to deal with interference and whether licenses in licensed models allow flexibility in spectrum allocation.

Table 5. An alternative general framework for spectrum management

Regime	Technology flexibility	Club membership	Rights Exclusivity	Rights flexibility	Interference control	Rights Assignment
1. Standard C&C	No	:	FPR	R	GM	AL
2. Property rights & market	Yes	:	FPR	F	SC	AT
3. Privately-run commons	Yes	Yes	FPR/CU	F	SC	AT/UB
4. Monitored easement	Yes	:	EPR	F	GM	AT
5. Common pool (Benkler)	Yes	Yes	CU	F	SC	UB
6. Open access I	Yes	No	CU	F	SC	UB
7. Open access II	Yes	No	CU	#	GM	UB
8. Quasi property rights	Yes	:	FPR	R	SC	AT
9. Market-run easement	Yes	:	EPR	F	SC	AT
10. Managed commons	Yes	Yes	CU	#	GM	UB
11. Open access III (Noam)	#	No	CU	F	SC	UB
12. Collective C&C	No	:	CU	R	GM	AL
13. Open access C&C	No	No	CU	R	GM	UB
14. Controlled easement	No	:	EPR	R	GM	AT
15. Eased C&C	No	:	EPR	R	GM	AL
+various other combinations						

C&C = Command and Control; FPR = Full property rights; EPR = Eased property rights, CU = Collective use, AL = Administrative licensing; AT = Auctioned licenses and market trading; UB = Unlicensed band; SC = Self-controlled, GM = Government managed; F = Flexible; R = rigid; : = Not Applicable, # = Undetermined or Variable.

This model permits the classification of the various regimes discussed in this paper: the first group of six regimes correspond to the standard and intermediate models appearing on the last line of figure 1. Command and control provides exclusive license rights, assigned in administrative fashion, with rigid rules about transmission standards (use, power, area, etc.) and regulatory constraints on equipment standards, frequency use and interference management. The full property rights approach differs by higher degree of flexibility with regard to technological standards and license use, and is assigned by auctions or similar competitive mechanisms rather than administrative rule.

Privately-run commons turn the spectrum into a club secluded from outside constraints by licensed property rights but with collective unlicensed use within the club. Because the bands within the club are assigned to a private owner, this model is essentially an offshoot of the full property rights regime. 'Monitored easement' refer to the model by which the government curtails primary users' rights by allowing interference-free underlay and overlay transmissions by secondary users and monitors compliance. The common pool is the historical commons model in which a community (a club) receives rights to collectively manage a resource from the government. Open access I is essentially the same model with unlimited, unrestricted access to the resource (at this stage, an utopia). Open access

II, which is the unlicensed model in the US - also called ‘class licensing’ in Australia, is a slight variant on the open access I model in which bands are unlicensed, collectively used, interferences self-managed and usage rights fully flexible except for power limits, which are imposed by regulation (eg. the WiFi model).

There follows a large number of combinations among the six dimensions considered by the table, of which only a few prominent ones are presented as options 7 to 14. Possible extensions include regime 8, quasi-property rights in which auctioned property rights are still subject to restrictions on area, power and type of usage, regime 9, free easement, by which the market develops simultaneous band-sharing arrangements between primary and secondary users without regulatory intervention and regime 12, collective C&C, which retains all the characteristics of command and control except that the licenses granted do not offer exclusive rights.

Table 5 also reveals that the generic ‘commons’ regime (which is better described as ‘unlicensed’ than commons) is not as monolithic as usually surmised: regime 7, open access II, lets users free to use the spectrum as they please but government manages and monitors interference, regime 10, managed commons, is similar with additional restrictions in that the government rules club entry. This regime could for instance describe the manner in which two-way radio and aircraft communications are managed: anyone who meets the criteria for entry can operate and the criteria for entry are transparent and achievable for most people (eg. get a pilots license and hire a plane). Regime 11 is the Noam model in which there is open yet not free access, and technological standards could be determined by the government in conjunction with other players. For various practical reasons, this regime is also currently a utopia.

Regime 13, open access C&C, is an extension of the collective C&C model in which there are no licenses (or, as for class licensing, ‘licenses for unlicensed use’). Here, the use of unlicensed bands coexists with rather strict government controls (equipment standards, interference tolerance, specific use). This model could for instance describe the way the space objects class license work in Australia. This class license only authorises operation of devices to communicate with satellites when those satellites are internationally coordinated through ITU processes - which is probably the most prescriptive command and control spectrum management regime in the world (literally). And, of course, operation is only authorised if there is an apparatus licence for the satellite transponders that has been issued by the control and command authority.` Yet, once the satellite is coordinated and the apparatus licence is in place, entry into the 'space objects commons' is open to pretty much any user prepared to have a satellite receiver installed.

The preliminary work of Bauer (2002) and Leighton (2004) strongly suggests that various further refinements, which are not considered here for simplicity, could still be introduced in table 5. For instance, the degree of interference control, which is assumed discrete in table 5 (government intervention or none) is more realistically modelled in a continuous manner (government is more or less restrictive on maximum acceptable power, the class of transmitter used, the length of the signal transmitted, the vicinity of other stations nearby, etc.). It is reasonable to assume that there are potentially as many modes of managing the spectrum as there are ways for regulators to intervene, for property rights to be defined and for radiofrequency spectrum to be used.

Conclusions

Many natural resources characterised by unrestricted access are considered ‘commons’ and subject to the tragedy of the commons critique: without property rights or government intervention, the resource is over-consumed and eventually depleted. Increased demand and inefficient supply have recently made spectrum vulnerable to this critique (through congestion rather than depletion) and various policy propositions currently debated among communications regulators urge reform of spectrum management practice by considering alternative visions of the spectrum as an economic resource. In particular, there are suggestions to solve the scarcity and interference problems inherent to the common good nature of the spectrum by using it as a private good (the property rights approach), a public good (the ‘open access’ approach) or multi-faceted variants of a club good (easement regimes, commons parks, common pools, etc.). The central question for the policy-maker is to determine under which category (or mix of categories) does the spectrum best serve society and what policies achieve the desired outcome.

This review examined these proposals, which consist of either assigning spectrum property rights in primary markets and develop spectrum trading in secondary markets, or managing the spectrum in less or non-exclusive ways. Barring ‘natural reasons’ for market power, or ‘market failures’ prompting government intervention, it is standard in neo-classic economic theory to expect competitive market interactions to bring about efficient outcomes, ie. outcomes that maximise social welfare. Whereas this favours the market option, the renewable nature of the spectrum lends it economic attributes that vary with (i) the degree of government intervention in spectrum allocation, assignment and interference management; (ii) the commercialisation of technological research on simultaneous multi-user access; and (iii) the types of spectrum uses considered. These ambiguities introduce a high degree of complexity into policy debates over spectrum liberalisation.

Each of the policy propositions discussed in the review entails drawbacks of different nature. The property right alternative is subject to a large variety of potentially undesirable market outcomes, whereas the commons and easements alternative presents serious management and interference problems, which currently narrow their application to a specific subset of technologies. The literature is highly divided in its policy recommendations. Ambiguities result in part from the polarisation of the main research contributions, but also from the conceptual framework in which most of the analysis has been conducted.

Spectrum fits uneasily with conceptual reasoning because there is, potentially, a large number of theoretical models (many still waiting to be developed) reliant on different versions of legal, economic and technological arguments. Some of these concepts (such as ‘spectrum commons’) are regularly conflated in the literature. Because of its ‘policy-metamorphic’ economic nature there are few limits to the number of actual or counterfactual arguments that can make spectrum what policy wants it to be.

Alternatives to conceptual research are few. This is not a field in which empirical economic methods have been much tested, partly due to the limited number of countries experimenting with spectrum management reforms, too few reforms having been implemented, and little available economic data on the impact of these reforms. In the meantime, simulations of the welfare and redistributive effects of different policies such as conducted by Ting et al. (2005), with legal, economic and technical parameters would help develop valuable alternative ways of thinking about spectrum management.

It is striking that the spectrum management debate has so far exclusively focused on two relatively extreme policy options, when in reality there is a large array of alternatives. As is frequently recognised in the literature, there is a high degree of heterogeneity in spectrum uses and applications. There is, therefore, no reason to believe a single model (or two) will most efficiently deal with the scarcity and interference problems specific to each spectrum utilisation, or, if a single regime is required, one that can accommodate various models of band ownership would necessarily be more efficient than ‘one size fits all’ regimes. For these reasons, more work is needed towards developing a general theory of spectrum management.

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