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WELFARE IMPACTS OF SPECTRUM GOVERNANCE
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WELFARE IMPACTS OF SPECTRUM GOVERNANCE REGIMES: AN ECONOMIC-ENGINEERING STUDY

By

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ABSTRACT

WELFARE IMPACTS OF SPECTRUM GOVERNANCE REGIMES: AN ECONOMIC-ENGINEERING STUDY

By

Yi-Feng Carol Ting

In spite of the overwhelming victory of the market system around the world, the administrative licensing regime has been the dominant paradigm for spectrum governance until now. Behind this seeming anachronism is the belief that mutual interference can only be mitigated by means of administrative licensing and tight control. However, this once dominant perspective has faced increasing challenges recently. Mounting evidence of the inefficiencies under the administrative licensing regime has received much attention and a consensus for reform has formed among industry players, policymakers and scholars.

Notwithstanding the consensus for reform, proponents of spectrum policy reform are divided over two approaches: spectrum property rights and spectrum commons. Property rights proponents advocate the free market approach and call for privatization of spectrum. To the contrary, commons supporters argue against spectrum ownership and private control of the airwaves, championing the idea of open access to spectrum for the public. Although the intense policy debate between proponents for spectrum property rights and spectrum commons has been ongoing since the late 1990's, the arguments from both sides have been highly abstract and speculative. Through economic modeling of the characteristics of different governance regimes and network structures, this study provides a side-by-side comparisons of welfare outcomes under different regulatory and

technological settings. Such comparisons allow us to more systematically evaluate the merits of competing regimes.

This study identifies three key policy instruments for spectrum governance regimes: entry conditions, transmission power and interference robustness stipulations. Based on these key policy instruments, the study builds a general model of demand for wireless services that reflects the engineering properties of wireless communications and the impact of these policy instruments. Since regimes differ in the configuration of policy instruments, the model allows us to analyze the decisions of firms and consequent welfare outcomes under various regimes.

The analysis of welfare outcomes produces the following findings. First, government regulation on robustness is undesirable. Second, the potential benefit of power restrictions increases with the number of firms in the market. Third, when set inadequately, all three policy instruments can cause significant welfare loss. Moreover, comparison of a prototype property rights regime and a prototype commons regime suggests, given the same power restrictions, the property rights regime tends to outperform the commons regime as long as the number of firms is not significantly smaller (in relative terms) than the optimal number of firms, which itself is a small fraction of the open commons equilibrium number of firms. These observations on the effect of fundamental policy instruments and the theoretical framework are the major contribution of this study.

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Chapter 1 Introduction

1.1 Background

Fifty years from now people may have very different ideas about access to the airwaves (spectrum) than today. At present spectrum is viewed as a public asset, and (somewhat ironically) government agencies serve as guardians in determining how and who among the "public" can access the airwaves. Those who are awarded rights to provide services using this public asset receive strong protections but also undergo intensive scrutiny under administrative laws. All this is likely to change due to accelerating momentum toward spectrum reform.

The current spectrum governance regime was established in the 1920's, in the name of preserving the value of spectrum and protecting users from harmful interference.[1] Under this regime, governments play the role of a central planner and set forward detailed rules governing all aspects of spectrum usage. Although tight government controls over spectrum allocation and uses have provided certainty for wireless businesses and services over the decades, increasing wireless applications and contention for spectrum in recent years have made efficiency concerns a frontline issue. Citing mounting evidence of inefficiencies resulting from regulatory delays and distortions introduced by political maneuvering, calls for replacing the administrative licensing regime with market mechanisms have become stronger and louder. Abandoning the approach of tight

[1] Soon after radio became a commercial success in the 1920's, a power fight between broadcasters broke out in major markets, where broadcasters tried to overwhelm each others signals by transmitting at higher power and mutual interference rendered the spectrum resource unusable. This prompted government intervention and the Federal Radio Commission was established in 1927 to oversee spectrum management issues.

government control, which was unthinkable some forty years ago, is now the mainstream opinion.

However, in spite of the consensus on reform, the action plan for reform is a subject of much debate. In essence, the market is the agreed upon mechanism to replace regulatory fiat, but there is strong disagreement over whether technology protocols and etiquettes alone are enough to prevent mutual interference or whether exclusive property rights assignments are necessary. The division between technology-focused and property-rights-focused approaches to spectrum management is commonly referred to as the commons versus property rights debate because those with faith in technological solutions would make spectrum a common resource. Given that there are almost no real-world examples of these alternative regimes, anticipating issues and coming up with solutions is a challenging task. As a result, the proposals are still sketchy and the debate has been mostly philosophical and abstract.

As an attempt to more objectively evaluate alternative spectrum governance regimes, this study models the demand for wireless services, taking the engineering properties of wireless services into account, and incorporates the demand model in models of markets for wireless services. The models tie three key policy instruments (entry restrictions, transmission power and receiver quality regulations) together, providing a framework for systematic examination of the effects of the policy instruments and comparison of regimes in terms of welfare performance.

1.2 Research Questions

Given the complex interplay between regulations, technology and market forces, any attempt to answer the question "should we choose spectrum property rights or spectrum commons?" will inevitably entail a great number of assumptions, whether made explicit or not. One's answer to this question necessarily depends on such assumptions, which often are debatable. To meaningfully compare governance proposals while allowing objective examination of the assumptions used in the analysis, this study focuses on fundamental building blocks and asks the following more narrowly defined research questions:

- What are the most important policy instruments affecting welfare under different governance regimes?
- What are the welfare effects of variation in the policy instruments for different governance regimes?
- Based on the answers to these questions, what can we say about the relative merits of the proposed regimes?

A careful examination of these questions helps identify factors critical to spectrum management and provides more analytical rigor to the debate. This is the major contribution of this study.

1.3 Research Method

This study seeks to evaluate alternative spectrum governance regimes by comparing the predicted outcomes of economic models built to reflect the nature of wireless services and the characteristics of different governance regimes. In principle, this study employs the standard economic approach for welfare analysis, but due to the complicated functional forms required, the results are derived computationally instead of solving systems of equations algebraically.

As a starting point, this study focuses on a one-period economic model. Demand for wireless service in a homogeneous service market with identical service providers is modeled. This modeling effort factors in technical issues affecting demand: transmission power, robustness and network structure. Two types of services based on different network structures are modeled. For the first type users communicate directly with each other via terminal devices without a backbone relay; for the second users are connected via base stations and backbone relay. Given the models, the three key policy instruments are varied and the corresponding equilibrium welfare outcomes are computed and analyzed.

1.4 Research Scope

The models used to study welfare under different regimes are one-period models, which to some extent limit our ability to examine dynamic aspects of efficiency, such as the welfare impact of consolidation of spectrum ownership under a property rights regime and whether a commons regime leads to more innovation versus an ownership regime. In addition, since the study focuses on a homogeneous product market, the efficiency properties of permitting a given block to be allocated among different services are beyond the scope of the study.

This study focuses on the effects of interference and related technological factors (transmission power and receiver quality) on welfare created in a wireless market. Other factors, most importantly network effects and scale economies, are not addressed in the present study.

1.5 Outline

The manuscript is organized as follows. Chapter 2 reviews the scholarly debate over spectrum reform and spectrum governance regimes. Chapter 3 identifies key policy instruments for spectrum management and defines the governance regimes of primary interest in terms of the configuration of the policy instruments. Chapter 4 provides background information on relevant engineering properties of wireless services. Chapter 5 discusses how interference affects demand for wireless services. Chapters 4 and 5 provide foundation for the models of spectrum markets presented in Chapter 6. Findings of a welfare analysis based on these models are presented in Chapter 7. Chapter 8 summarizes and concludes the study.

Chapter 2 A Review of the Spectrum Policy Debate

At the center of the debate over spectrum policy is the issue of choosing the best spectrum governance regime. A spectrum governance regime establishes a configuration of rights to spectrum; it coordinates all activities involved in the appropriation of spectrum through assigning these rights to various stakeholders. Currently spectrum is governed by the principle of administrative licensing, with which the government serves as a central planner and is heavily involved in the coordination between spectrum users and uses. As central planning has been proven unproductive in most industries, the administrative licensing regime governing spectrum usage for the past 80 years has been the subject of increasing scrutiny and criticism. Two regimes have been proposed to replace the administrative licensing approach: a property rights regime and a spectrum commons regime. Currently these proposals do not offer much detail about how exactly rights should be defined and implemented; however, the fundamental principles behind them are in stark contrast: while a property rights regime creates ownership of spectrum and uses the market to coordinate the spectrum owners and potential users, most proposed commons regimes would rely on technical protocols to coordinate spectrum uses.

Most research on spectrum governance falls into one of the following categories: (1) institutional design of spectrum governance regimes and cost-benefit analysis; (2) empirical and comparative studies on efficiency under different spectrum governance approaches; (3) engineering studies on mechanisms that facilitate coordination among devices, improve spectrum utilization and increase capacity. The following sections briefly summarize research in these areas, with emphasis on the first category, which is the category this dissertation falls into.

2.1 Research on Institutional Design of Spectrum Governance Regimes

Scholarly work on alternatives to administrative licensing as spectrum policy can be traced at least back to 1951, when Leo Herzel first proposed to replace the administrative licensing regime with a spectrum market, which he argues would be much more efficient in determining the best uses for spectrum resource. Herzel's viewpoint was echoed in Nobel laureate Ronald Coase's seminal 1959 article "The Federal Communications Commission," which argues from a property rights and transaction cost perspective that spectrum is no different from other scarce resources. Coase explains how the problem of interference can be dealt with by defining spectrum property rights that can be traded in a market and provided a detailed analysis about how such a market would work similarly to markets for other goods.

The idea of allocating spectrum through a market system slowly gain acceptance among scholars in the three decades after Coase's "The Federal Communications Commission." DeVany et al. (1969) proposed a system in which the government defines initial property rights by dividing spectrum into packages along time, area and frequency dimensions and allows firms to trade these packages and redefine the property rights based on a market mechanism. Their proposal also provides an analysis on the engineering and legal issues that can potentially arise under their proposed system. In similar vein, Minasian (1975), Levin (1971) and Webbink (1987) provided similar analysis of property definitions that would promote efficiency.

As wireless technologies progress and wireless applications became an increasingly important part of people's daily lives, contention for spectrum began to surface. The rising value of spectrum prompted questions about the efficiency and merit of the administrative licensing regime, and the property rights approach emerged as a strong candidate for replacing it. Proposed property rights regimes share the fundamental principle that spectrum ownership should be established with exclusive and full property rights. With exclusive and full property rights to spectrum, owners can alter the use of their spectrum, sell, combine, partition or disaggregate the spectrum they own (Kwerel and Williams, 2002; Faulhaber & Farber, 2003). Such flexibility would guarantee liquidity for a spectrum market where spectrum owners can work with one another to deal with harmful interference. Following the traditional rationale for a market economy, property rights proponents argue that spectrum owners' information (about costs and benefits of wireless services) and incentives to profit-maximize will lead to the most efficient allocation and use of spectrum (Hazlett, 2001; White, 2000; DeVany, 1998; Spiller and Cardilli, 1998).

A premise of a property rights system is that rights are enforceable; therefore, the definition of spectrum property rights and protection against interference is of critical concern. In general, property rights proponents advocate defining spectrum property rights in terms of specified signal strength at property boundaries. For example, Kwerel and Williams propose:

> To provide licenses maximum technical and service flexibility, spectrum emissions rights between licenses should be defined in terms of power limits at the boundaries between spectrum blocks and geographic areas

> together with maximum in-band power limits. Subject to these output limits, each licensee should be free to deploy transmitters within its licensed spectrum block and area without coordination with licensees in adjoining blocks and areas. Conversely, each licensee must design its own receiving system to tolerate permissible levels of interfering power from adjoining licensees.

By allowing an owner to make tradeoffs among inputs (for instance, antenna height and transmission power), this approach promotes efficient use of resources. Moreover, predefined power limits at the boundaries also bestow on property owners more certainty and protection, thereby preserving investment incentives.

The increased appeal of the property rights regime is reflected in FCC policy in many ways. Viewed as the first step towards establishing spectrum ownership, auctions were introduced in 1993 as a mechanism for spectrum assignment and have been widely used in many countries to expedite spectrum assignment and generate revenue for governments. Although in some European countries 3G license auctions have led to financial problems for successful bidders, overall the efficiency of spectrum auctions is widely hailed and considered to be a successful first step towards spectrum privatization. Changes happened on other fronts, too. Shelanski and Huber (1998) provide a detailed analysis on a series of changes in the FCC's licensing rules and argue convincingly that such changes have essentially extended the rights of licensees. These developments signaled a steady shift towards the property rights regime through the 1990's.

Just as the property rights proposal was gaining ground, tremendous progress was made in wireless technology and the Internet, leading to proposals for a totally different approach to spectrum management. In sharp contrast to privatization, the new approach suggests a commons model in which stakeholders (such as service providers and equipment manufacturers) collectively govern the spectrum and users can access the airwaves as they do public parks and roads (Lessig, 2001; Benkler, 2003; Werbach, 2004).

The philosophy behind the commons approach is drastically different from the property rights concept, as Benkler explains:

> ...instead of creating and enforcing a market in property rights in spectrum blocks, we could rely on a market...that would allow people to communicate without anyone having to control "the spectrum." Just as no one "owns the Internet," but intelligent computers communicate with each other using widely accepted sharing protocols, so too could computationally intensive radios...[A] "spectrum commons" approach...[regards] bandwidth as a common resource that all equipment can call on, subject to sharing protocols, rather than as a controlled resource that is always under the control of someone, be it a property owner, a government agency, or both.

In this view, the optimization object is communication capacity rather than the resource "spectrum," and the goal of technical restrictions is to ensure coexistence rather than protection of individual properties. To serve these goals, commons proponents in general agree that some rules or etiquettes governing communication in a commons may be necessary. Based on the influential work of Elinor Ostrom on commons governance (1990), Buck (2002) analyzes institutional designs that may facilitate coordination within a spectrum commons.

The significant differences between the two approaches have, not surprisingly, led to heated debates. Proponents of the different regimes have found themselves deeply divided over fundamental issues. For example, commons proponents argue that advances in cooperative and adaptive technologies will eradicate spectrum scarcity. They contend that by dividing spectrum into blocks and granting monopoly rights to license holders (or spectrum owners in the property rights regime), administrative licensing and property rights regimes create an artificial scarcity in spectrum and dead weight loss due to the monopolization of spectrum. The additional capacity brought about by the new technologies and the ability to utilize currently unused spectrum[2] will increase the amount of usable spectrum tremendously and allow everyone to use it freely and orderly. They also claim that in an open commons regime, more firms and inventors will have access to spectrum; thus price and product competition will increase and lead to greater innovation and welfare for the society (Benkler, 2003; Werbach, 2004). Noam (1998) also shares these beliefs, although he takes a different approach towards open commons. In his proposal, users dynamically bid for access to spectrum so that pricing is still used to assign access when scarcity is an issue.

On the other hand, the property rights proponents predict tragedies under the commons regime, arguing that exclusive rights to spectrum are required to ensure market efficiency and long run viability. Whereas Faulhaber and Farber (2003) and Hazlett (2001) acknowledge that a commons regime might work as long as spectrum is not scarce, they also argue that demand growth will eventually lead to scarcity. Benjamin (2003) contends that most of the technologies that would make possible the development of an open commons can work just as well under a property rights regime given adequate design of rights and their assignments; in most situations, he claims a property rights regime is more efficient. From the property rights perspective, the solution to this resource allocation problem is institutional measures rather than technical.

[2] New America Foundation and Shared Spectrum Company (2003), "Dupont Circle Spectrum Utilization During Peak Hours". This survey found most of the spectrum blocks are underutilized under the current allocation. Available at http://www.newamerica.net/Download_Docs/pdfs/Doc_File_183_1.pdf

2.2 Empirical and Comparative Studies on Performance of Spectrum Governance Regimes

Empirical studies of the inefficiencies created by the administrative licensing regime have been an important catalyst for the movement towards spectrum policy reform. Hazlett is the most prolific and influential in this area. He examined FCC regulation of radio broadcasting and argued that the administrative licensing regime hinders innovation because limiting firms' ability to trade spectrum diminishes the incentive to innovate for licensees (Hazlett and Sosa, 1997). Hazlett (1997, 1998) also provides detailed analysis of how the incumbent licensees have successfully managed to establish entry barriers under the administrative licensing regime and have enjoyed government protection at the expense of the society.

On the other hand, empirical studies on alternative spectrum governance regimes have been scant. In spite of the intense debate, literature on spectrum management to date has been abstract and characterized by speculative arguments backed by anecdotal evidence. Hazlett and Ibarguen (2002) cited the experience of the mobile phone markets in Guatemala and El Salvador as examples of success in privatizing spectrum on a small scale. Buck (2002) sees the successful spectrum sharing agreement struck by the Chicago Wireless Club (consisted of 100 amateur radio operators) and commercial radio stations in 1910 as evidence that open commons will work.

To a great extent, proponents on both sides simply talk past each other. While there have been some attempts to provide comparative analysis of these different regimes, results are rather sketchy because there have been few services governed by alternative regimes, and even if they resemble these proposed regimes in some aspects, their administrative licensing element often dictates the outcome (Ting, Bauer, & Wildman, 2003; Carter, 2004).

2.3 Engineering Studies

Advances in wireless technology that enable wireless devices to operate in an adaptive or cooperative fashion have been an important stimulus for the commons approach. Four types of technologies are most frequently cited as enablers of the commons regime: spread spectrum, software-defined radio, mesh networks, and smart antennas.

Spread spectrum technology allows users to share the spectrum by transmitting at lower power but using a wider bandwidth. Receivers using spread spectrum technologies can decipher the low power signals based on specific signal coding patterns. Those not fitting the patterns will be rendered as random noise. In their in-depth engineering-legal study on the policy implications of spread spectrum technology, Buck et al. (1998) claim that this technology is a critical technical building block for open access. Software-defined radios are adaptive radios with cognitive ability. These radios can gauge the level of activity in the radio environment and adjust their operating frequencies to avoid congested frequency bands. Merino (2002) examines their impact and concludes that software-defined radios can potentially increase the intensity of spectrum sharing and promote competition. Drawing on Shepard's work on multi-hop spread spectrum networks (1995), Reed (2002) contends that cooperative mesh networks, in which users relay one another's signals at low power, can increase system capacity and thereby eradicate spectrum scarcity. Smart antennas take advantage of antenna arrays and the locational information they can detect to distinguish desired signals from interference.

For a review of these technologies' implications for the property vs. commons debate, see Ting (2004).

On a more technical front, in recent years there have been many studies on designing network protocols that improve coordination and network performance under various settings and for different network architectures. Such studies model incentives for users to "hoard" or "abuse" system resources and seek to establish design principles that mitigate such incentives. Satapathy and Peha's work (1996, 2000, 2002) on unlicensed spectrum coordination mechanisms (including power limits and real-time sharing) is representative in this regard. They find that FCC stipulated etiquettes for unlicensed PCS devices may not be sufficient for preventing overuse of spectrum and suggest alternative design principles as remedies.

In summary, this chapter briefly reviewed literature on: (1) The institutional design of spectrum governance regimes, (2) empirical studies on the performance of various spectrum governance regimes, and (3) engineering studies on the policy impact of new technologies and design principles that can help coordinate devices and improve the efficiency of spectrum usage. The review of institutional design summarizes the current thinking of the alternative spectrum regimes and provides useful background information for identifying the critical policy instruments for spectrum governance. Moreover, in reviewing empirical and comparative studies we see that research to date has provided little information on the relative merits of the proposed alternatives to administrative licensing, a gap this dissertation can help fill.

Chapter 3 Spectrum Governance Regimes and Policy Instruments

As mentioned in Chapter 2, under different spectrum governance regimes wireless service industries may perform very differently in terms of policy measures such as scarcity, welfare and technological innovations. An overall evaluation of the regimes must take into account all factors that influence performance and their interplay and focuses on differences in governance regimes and their performance in terms of control over a set of key policy instruments.

The chapter starts by discussing the roles of three major policy instruments: entry restrictions, transmission power and receiver robustness in Section 3.1. Building on Section 3.1, Section 3.2 identifies eight governance regimes based on different configurations of the policy instruments and discusses their relevance to the ongoing policy debate.

3.1 Major Policy Instruments and the Their Roles

The debate over spectrum governance is often simplified to the choice between two regimes: one, a spectrum commons, allows entry through acquiring devices that adhere to certain usage rules and the other, spectrum ownership, allows entry through acquiring spectrum ownership. This characterization might serve well as a quick-and-dirty guide to spectrum policy, but without a closer look at how spectrum ownership is defined and how the usage rules work under a spectrum commons, it is not possible for us to evaluate different regimes. Worse yet, oftentimes people are arguing without realizing that they have very different implicit assumptions about how a spectrum commons or ownership regime works. To avoid such pitfalls, this section focuses on the role of the major policy instruments under the proposed regimes, and the next section defines the regimes of primary interest in terms of control of these policy instruments.

A spectrum property rights or ownership regime is still a fairly new idea,[3] with most of its details still to be worked out. Nevertheless, as mentioned in Chapter 2, it is widely anticipated that a property rights regime will have the following characteristic: (1) A spectrum band is sliced into blocks with exclusive usage rights. (2) Government determines the initial number of blocks and their assignments to users through titles of ownership or licenses. (3) Maximum acceptable interference levels that are initially defined by the government and maintained through a combination of technical specifications and spectral separation between the signals of different service providers. Under some proposed property rights regimes, the spectrum owners can consolidate or further divide spectrum blocks, and they may negotiate acceptable interference levels with their neighbors. These possibilities are not considered in this study.

In general, what the commons proponents advocate is essentially an open access regime subject to minimum requirements (Anyone who buys a certified device can access the spectrum resource.) Consistent with this interpretation, we use the term "open commons" instead of simply "commons" to refer to the type of commons regime (there are others) modeled in this dissertation. Open commons proposals generally have the following characteristics: (1) Coordination (interference avoidance) is achieved through technical restrictions (e.g., transmission power limits) and/or etiquettes (e.g., listen-before-talk) built into devices. (2) Subject to compliance with the technical restrictions and etiquettes,

[3] Strictly speaking, all regimes are property rights regimes. They differ only in the way the rights are configured. Ownership is a more accurate term.

there is no restriction on entry. (3) A collective agency (probably consisting of equipment manufacturers and service providers) determines the technical specifications required for coordination, such as a maximum power limit, communications protocols (e.g. listen-before-talk), or a required level of interference robustness for devices such as minimum signal-to-interference tolerance.

There are several types of both ownership and open commons regimes. Open commons regimes are distinguished from ownership regimes by whether the government does or does not control entry into the market. Different types of open commons and ownership regimes are then determined by whether the government or the market determines transmission power and/or receiver robustness.

Comparing these two sets of characteristics, we identify the following policy instruments as the major components distinguishing the regimes. The welfare consequences of different uses of these policy instruments restrictions (including not using them) will be the focus of this study:

(1) *Entry*: while the open commons regime sets no limit on number of firms that can enter a market, the number of firms granted access to the spectrum under the property rights regime will be determined by the government through a rights assignment. This study treats the number of firms as a policy instrument, recognizing this is equivalent to analyzing spectrum usage rights directly on the initial assignment of rights with a government-set number of firms, which can be treated as exogenous.

(2) *Transmission power*: restrictions on signal power can limit the potential incidents of interference under both regimes. Firms' signal powers may be determined by market

processes or limited by government in both regimes. For both regimes government restrictions are limitations on usage rights.

(3) *Device robustness*: defined as a device's ability to reduce the effect of interference upon user perceived communication quality. While there are other ways to improve robustness, in general more sophisticated mechanisms can be employed in receiver designs to mitigate the degradation in service quality due to interference. Some have argued that under an open commons regime firms will produce more sophisticated devices to cope with an increasingly noisy radio environment (Shepard, 2002; Benkler, 2003), but firms might have similar incentives in an ownership regime as well. There may or may not be a government-mandated minimum robustness level in both types of regimes. By making device robustness a policy instrument in our models, we can examine the plausibility of these arguments.

3.2 Spectrum Governance Regimes as Configurations of Policy Instruments

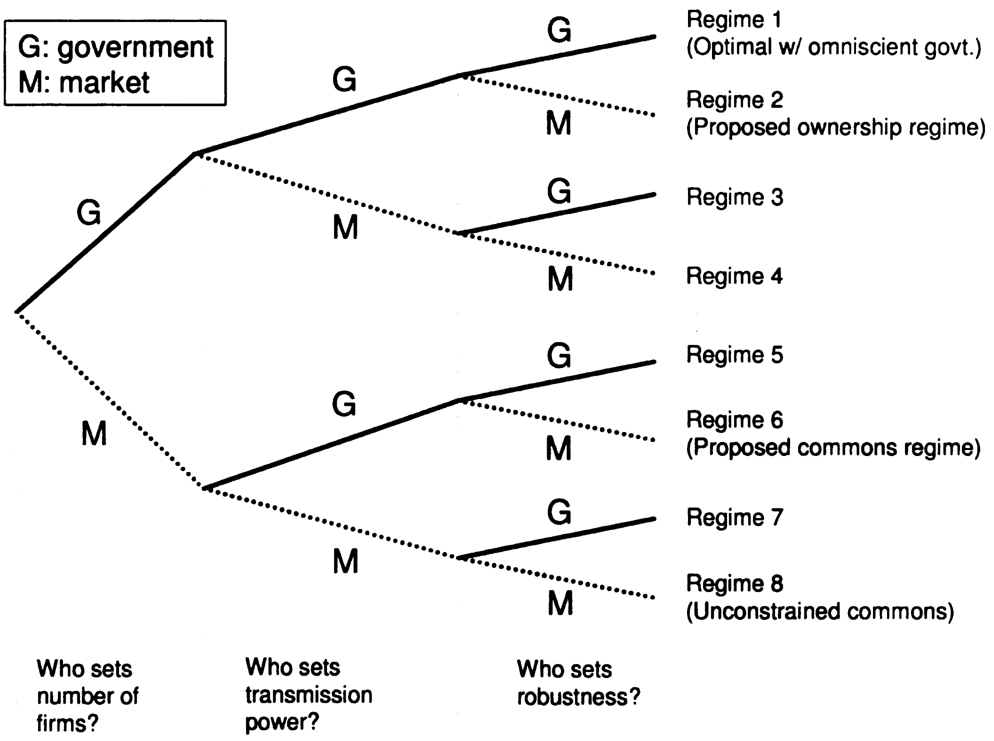
Building on discussion over policy instruments in Section 3.1, this section defines the regimes investigated in this study in terms of application of these policy instruments.

Figure 3.1 shows eight different spectrum governance regimes based on combinations of entry conditions, transmission power restrictions and robustness requirements. A solid line indicates that a policy instrument is set by the government, and a dotted line means that instrument is left for the market to decide. The four branches on the upper half are variations of ownership regimes because the number of firms is controlled. The four branches on the lower half are commons regimes because the number of firms is determined by market forces.

Among the eight regimes, Regimes 1, 2, 5, 6, and 8 are of particular interest. Regimes 1 and 8 are two polar-opposite cases in that in Regime 1 government controls all three policy instruments and Regime 8 is absolutely laissez-faire. When a government is omniscient, it can always set the policy instruments correctly and do at least as well as laissez-faire. Both can be used as benchmarks to evaluate the merits of other types of regimes. Regime 2 (where both number of firms and transmission power are set by government) is of interest because, reflecting literature review in Chapter 2, this combination describes major proposed ownership regime(s). In contrast, Regime 6 (an open commons regime with transmission power restrictions) corresponds to the regime currently applied to unlicensed spectrum in the US. Regime 5 is a world where both transmission power and entry are controlled by the government; whether adding the robustness requirement can further improve welfare in a spectrum commons is worth examining. Thus a comparison of Regime 5 to Regime 6 is instructive.

What policy instruments are controlled determines what is left for the firms to decide. This affects their profit-maximizing output decisions. With a model of demand for a wireless service, we can see how firms' decisions change under different regimes and how welfare changes by incorporating the demand model in a model of a wireless service market. The next two chapters will develop a model of demand for a wireless service.

Figure 3.1 Classification of Spectrum Governance Regimes



Chapter 4 Technical Aspects of Spectrum Management

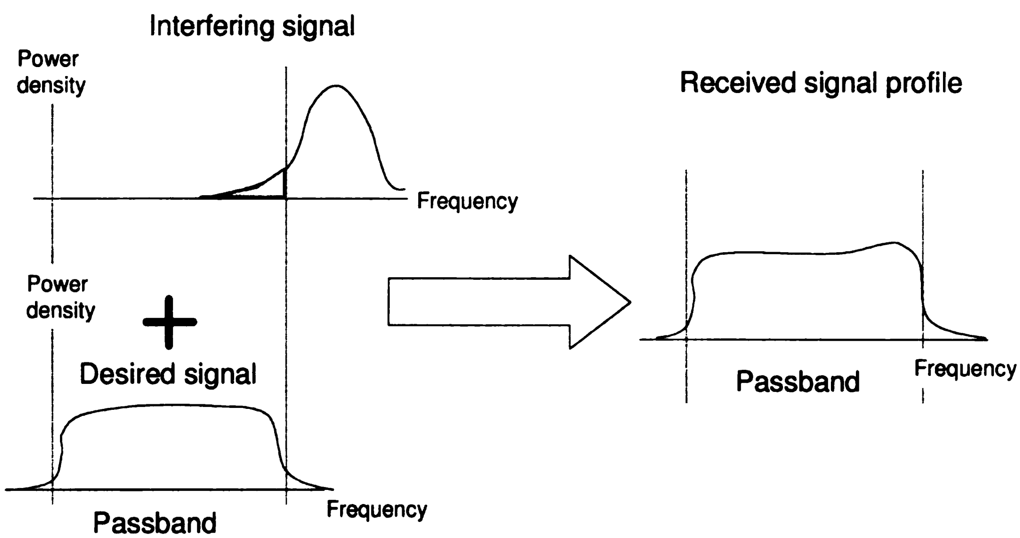
This chapter provides the technical information necessary for modeling the demand for wireless services, which is the topic of the next chapter and a critical element of the model in the chapter after that. We start off by defining interference in Section 4.1; Section 4.2 proceeds to identify the factors determining the actual effect of interference on utility. In Section 4.3 we focus on the relationship between network architecture and the demand and cost characteristics for wireless services, followed by a discussion of some practical issues involved in the modeling of markets for wireless services in 4.4.

4.1 Interference

For the most part, in the policy debate over spectrum management regimes interference is an abstract term commonly interpreted as unwanted signals that reduce the value of a communication service to its users by reducing the rate of data transmission or the clarity of a desired signal. To model the effects of interference on user valuation of a service, a more formal and accurate description of how it works is necessary.

Figure 4.1 depicts what happens at a receiver when it experiences interference that affects its reception of the desired signal. In these signal profile representations, the horizontal axis is frequency and the vertical axis is the power density at given frequencies. If the original signal is not altered during transmission, the receiver will be able to recover the original signal within its design-specified passband, which is the band of frequencies that passes through a filter with essentially no attenuation. As a measure to suppress distortion introduced during transmission, receivers are equipped with filters whose function is to block unwanted signals.[4] However, for a number of reasons such as imperfect filtering and multi-path propagation, unwanted signals (the shaded region of the interfering signal in Figure 4.1) will always sneak into the passband of the receiver and distort the desired signal profile, and the receiver will not be able to recover the desired signal as it was originally generated. The practical question, then, is not whether there is interference, but to what degree interference affects service quality and user utility. From a user's perspective, this is the question of to what extent her data transmission slows down (for data communication) or the degree to which she has trouble telling the conversation from noise (for voice communication) due to the operation of other devices.

Figure 4.1 An Illustration of Interference



[4] A filter in a receiver is designed to allow signals falling within the passband to go through unaltered but suppress those falling outside of the passband.

For clarity of exposition, we need to distinguish two concepts, *aggregate power from unwanted signals* (hereafter *APFUS*) and *effective interference*, which are defined as follows. APFUS is the sum of interfering signals' power at a receiver's location. But what really determines the loss of utility due to the interfering signals is effective interference, which is what remains of APFUS after the interfering signals are processed by interference-countering mechanisms in the receiver. This difference is important in expressing the effect of interference on user utility.

The engineering concept of throughput, defined as the amount of data transmitted over a specific period of time (usually measured in Gbps or Mbps), has been widely used as a proxy for utility in engineering studies of network resource management. In addition to being easy to observe and measure, using throughput as a measure for utility has the advantage that there are engineering models expressing throughput directly as a function of effective interference.

The throughput model used in this study represents throughput, S, as:

$$S = G(1 - e^{-k \cdot SIR}) \qquad (4.1)$$

where G is a constant reflecting traffic volume, k is a constant with a value determined by the modulation scheme used, and SIR stands for signal-to-interference ratio, which is the received signal strength divided by effective interference.[5] Using throughput as a proxy for utility allows us to directly link utility to interference. An important point about Equation (4.1) is that it is a signal's power relative to the effective power of interfering signals, rather than its absolute power, that determines utility. Factors determining SIR will be discussed in 4.2.

[5] The channel is assumed to be noiseless, otherwise interference should include channel noise as well.

It should be noted that using throughput as a direct measure for utility has drawbacks, too. In particular, the rate at which subjective utility (a user's experience of personal satisfaction) increases with throughput is likely to fall as throughput rises, just as utility is typically expected to increase at a diminishing rate with the consumption of other goods. In addition, throughput may not be as good a measure for voice communications as for data communications. For data communications, higher throughput means faster transmission and a larger amount of data sent in a specified amount of time, which is likely to always increase subjective utility. Although the rate at which utility increases with throughput will probably be diminishing in throughput, this can be easily dealt with by assuming a non-linear relationship between utility and throughput. On the other hand, for voice communication, as long as throughput is high enough to deliver the sound quality beyond which human ears cannot sense further improvement, increases in throughput will not affect utility. For example, most people probably agree that CD quality sound is as good as they will ever experience. In other words, utility for voice communications is likely to plateau at some point. A more realistic model of utility can be created by assuming diminishing returns in utility to throughput and taking the nature of different types of services into account, but this comes at the price of a more complex model.

4.2 Factors Determining the Effect of Interference on Utility

For the throughput model described in Equation (4.1), both G and k can be exogenously specified without loss of generality, but SIR depends on both signal and effective interference strengths at the receiver, which are determined by several factors that are affected by the choices made by suppliers. These factors include transmission power, spatial distance between receivers and transmitters, number of devices in use, spectral separation between systems,[6] and the robustness/quality of the receiver.

4.2.1 Factors Determining Signal Strength: Transmission Power and Spatial Separation

Electromagnetic signals attenuate as they travel. As a result, signal strength at the receiver depends on both the original level of the *transmission power* at which the signal is emitted and the distance between the sender and the receiver (referred to as *spatial separation* hereafter). Given the same spatial separation, the greater the transmission power the greater the signal strength at the receiver. On the other hand, as a receiver moves away from a signal source, received signal strength goes down because the signal attenuates the farther it travels.

Equation (4.2) states the free space path loss model, which describes how power from a signal source attenuates with distance in a theoretical space devoid of all matter:

$$P_r = P_s\left(\frac{\lambda}{4\pi r}\right)^2. \tag{4.2}$$

In Equatin (4.2), P_r and P_s are signal's powers at the receiver and the sender, respectively; λ is wavelength of the signal and r is the spatial separation. Both λ and r are measured in meters. Equation (4.2) says that power falls in inverse proportion to spatial separation and signals attenuate faster at higher frequencies. Later on this model will be used to derive cell size and expected signal strength for different types of networks.

[6] A system refers to all the devices provided by one service supplier.

4.2.2 Factors Determining Strength of Effective Interference

Transmission Power and Spatial Separation

The principles determining desired signal strength at the receiver also determine the strength of an unwanted signal at the receiver. Everything else being the same, increasing transmission power or moving the source of an unwanted signal closer to the receiver will produce greater interference.

Number of Interfering Devices

The powers of received signals are additive. As the number of interfering devices in the environment increases, APFUS (aggregate power from unwanted signals) and the interference the user experiences goes up as well. This is true even when we are talking about devices transmitting at very low power—if the number of these devices becomes very large they can cause significant interference to other devices.

Spectral Separation

Theoretically, communication systems should generate signals perfectly confined within the designed band/channel, but in practice, due to imperfect devices, adjacent-channel interference is commonplace. Conventionally, governments limit interference through spectrum allocation, through which they separate the signal profiles of different systems with buffer bands to prevent the scenario described in Figure 4.1.

Except for wireless network engineers or policymakers, today most people tend to take the seemingly rare incidence of interference between adjacent systems as a rule of physics, not realizing it is a product of rules implemented by a administrative licensing regime that is under increasing criticism. To see the effect of relaxing such rules, our models need to explicitly account for the effect of *spectral separation*, which is defined in this study as the bandwidth between the operating frequencies of an unwanted signal and the receiver it interferes with.

The relationship between spectral separation and APFUS and effective interference is largely dependent on the signal profiles and filter properties of the systems in question. Take Figure 4.1 as an example. Given the same spectral separation between the central frequencies of the desired and the interfering signals, if the power density of the interfering signal is doubled at all frequencies, the effective interference will increase. Similarly, if the interfering signal still occupies the same bandwidth but now has constant power density across the band it occupies, effective interference will also change depending on its power density level. In spite of these complications, in general the greater the spectral distance between two systems, the less the effective interference a receiver user experiences.

Robustness/Quality of the Receiver

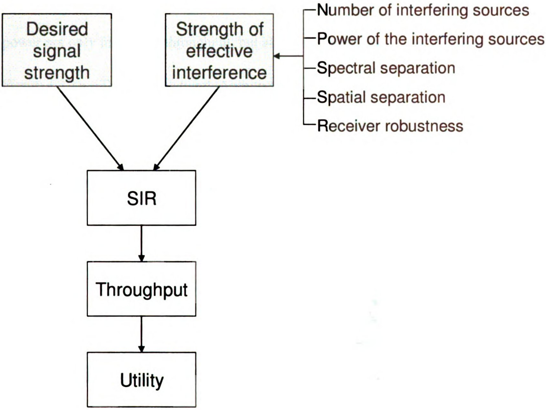
In Section 4.1 we emphasized the importance of the distinction between effective interference and APFUS. The difference between the two is that effective interference is the residual APFUS after interfering signals are processed by the interference-suppressing mechanisms built into a receiver. In this study, the receiver's ability to suppress or distinguish the interfering signals from the desired signal is referred to as the *robustness* or quality of the receiver.

Based on this definition, the relationship between effective interference and APFUS is determined by the robustness of a receiver. The more robust a receiver is, the less the effective interference and the higher the throughput and user utility. The most direct way to improve receiver robustness is to use filters that can more effectively reject signals falling outside of the desired signal passband. In recent years, smart antennas have found their way into many wireless access networks; these are basically antenna arrays that collect signals at different locations and take advantage of the additional location information to separate the desired signal from unwanted ones. Of course, implementing these additional measures increases the cost for the devices; hence, while more robust devices can deliver better service quality, they also tend to be more costly.

In addition to these mechanisms that seek to directly pick out interfering signals, indirect interference-countering methods have also been widely used in communication systems. These methods aim at reducing the negative impacts of the interfering signals the receiver fails to intercept. Examples of indirect interference-countering mechanisms include diversity (using multiple stations in a redundant configuration), interleaving (rearranging data in a noncontiguous way to mitigate the effect of bursty interference) and error-correction mechanisms (using computational algorithms to identify potential errors and self-correct).

Figure 4.2 schematically represents the relationships described in Section 4.2. SIR and throughput are increasing in the transmission power of the desired signal and the robustness of the receiver but are decreasing in the number of interfering devices and their transmission powers. SIR and throughput also increase with the spectral and spatial separations between the receiver and the interfering devices.

Figure 4.2 Factors Determining Interference Level and Utility

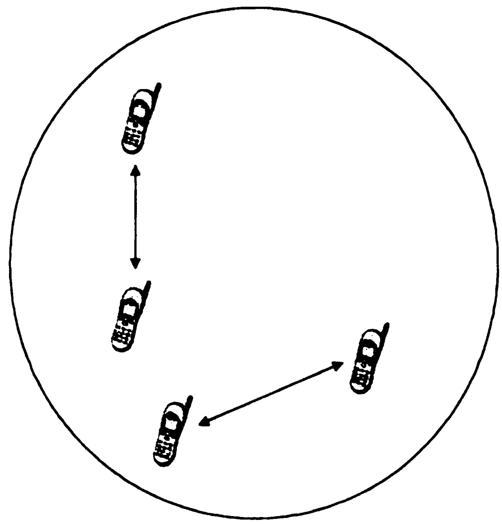


4.3 The Role of Network Architecture

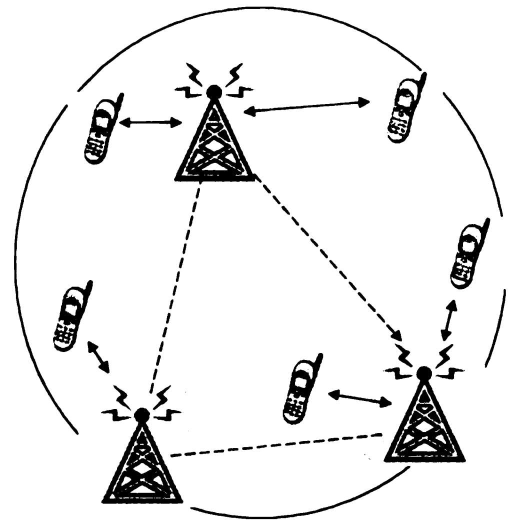
Different types of networks are designed to provide different services and serve different needs; therefore there often is a relationship between type of service and network architecture, which determines the cost structure of the service.

For example, FRS (Family Radio Service) and CB radio are dynamically configured networks with no backbone infrastructure to relay signals from one device to another. Many unlicensed devices work similarly. We refer to this type of network as a *direct two-way point-to-point (P2P) network.* In such a network, users may want to communicate between any two points in the service area. With *signal reach* defined as the distance a signal can travel before its power drops below the level required for satisfactory communication given the receiver technology, utility is a direct function of signal reach and transmission power, and individual users might be tempted to increase power not only for higher throughput, but also for communicating over longer ranges.

Figure 4.3 Two Different Network Architectures



A direct 2-way point-to-point network



A cellular-type network

On the other hand, in a *cellular-type network* where full coverage is guaranteed by service providers, signal reach is not a concern for users and utility is connected to transmission power only through throughput. Firms can guarantee full coverage by covering the service area with cells within which the power level of received signals is greater than the minimum level required to ensure acceptable communication quality. To illustrate this, we set the guaranteed minimum power level of received signals within a cell of cell size R (which is the radius of the cell) at 1 Watt. The original signal has transmission power $TP>1$. Based on the free path loss model of Equation (4.2), to meet such a minimum level requirement, TP must meet the following condition

$$TP\left(\frac{\lambda}{4\pi R}\right)^2 \geq 1 \ .$$

If this condition is binding at the edge of the cell, then

$$TP = \left(\frac{4\pi R}{\lambda}\right)^2 . \qquad (4.3)$$

This implies that the transmission power required to cover a cell is proportional to the area of the cell (or the square of the cell radius).

In a cellular-type network, firms can mitigate the contention for throughput by substituting base stations for transmission power. That is, putting in more base stations and letting each base station serve a smaller area (cell size). In this way, transmission power can be reduced and each cell covers fewer users who may interfere with each other. While this may increase user utility and overall demand for the service, reducing cell size has large cost impacts for service providers.

It is commonly known that cell sites are the major cost component of a cellular-type network (Loizillon et al., 2002). For complete coverage of a given area, reduction in cell size must be compensated by an increased number of base stations. While on a per-cell basis equipment required for covering larger cells is more costly, the costs of serving smaller cells quickly add up. According to the study on the relation between base station characteristics and cost structure by Johansson et al. (2004), as the traffic volume per unit area increases, smaller cells and greater cell density become more economical.[7] The same study also points out that, depending on the capacity requirement per unit area, total infrastructure cost (cost of cell sites, base stations and connecting the base stations) of covering the entire area with larger cells may be either higher or lower than covering the

[7] The observation that most wireless service providers start with larger cell size and split cells as demand increases reflects this cost concern.

area with smaller cells. However, in general as the traffic volume per unit area goes down, total infrastructure cost can be reduced by employing larger cells and higher transmission power. The tradeoff between investment in infrastructure and interference is built into the second model of a wireless market presented in Chapter 6.

In brief, this discussion illustrates how different network architectures can be associated with different utility/demand and cost characteristics. A model of demand and supply of wireless services must take such differences into account.

4.4 Other Technical Issues

Networks may differ in many ways in addition to architecture. This section discusses two technology concepts incorporated in the models presented in Chapter 6: duplex mechanisms and asymmetric transmission power in a cellular type network.

Duplex

Just like two people talking at the same time, if the two sides of a communication link transmit at the same time using the same frequency, the incoming and outgoing signals will interfere with each other. Duplex is the mechanism by which the signals coming into a device and those it sends are coordinated. The two most commonly used duplex techniques are time-division duplex (TDD) and frequency-division duplex (FDD). Their pros and cons are beyond the scope of this study. Here we focus on why they should be modeled differently.

A good example of TDD is CB radio or traditional walkie-talkies, which require users to turn over the channel to each other by saying "over!". The incoming and outgoing signals share the same channel. In other words, they operate at the same frequency but are separated into different time slots. Modern TDD systems are much more sophisticated and the switch-over's are done automatically in very quick succession so users do not perceive any interruption. With a TDD service, each service provider operates at its own unique central frequency. In modeling a TDD service we can assume the device a user uses to send and receive signals and the device at the other end of the communication do not contribute to the interference she perceives.

To the contrary, in a FDD system both the incoming and outgoing signals are continuous in time but are separated in the frequency domain. Most wireless telephony systems are FDD systems. With FDD, each system occupies two sub-bands within the overall band for the service, one for the uplink (mobile device to base station) and the other for the downlink (base station to mobile device). In this case, each system operates at two different frequencies, and for an individual user, the signals emitted by the destination receiver and the intermediate base station will add to the interference she receives.

Asymmetry in Uplinks and Downlinks in a Cellular-Type Network

Antenna arrays have been widely used in the base stations of modern wireless telephony networks, allowing mobile devices to transmit at lower power, thereby prolonging users' battery lives. The use of such technology results in an asymmetry in the power of uplink and downlink transmissions and needs to be addressed explicitly in a model of a cellular-type service.

Given the additive nature of power, an 8-element antenna array can combine inputs from all eight antennas and increase the received signal strength by eight fold. Taking advantage of the fact that signals arriving at different locations will have different phases, devices with such antenna arrays have higher sensitivity in detecting and deciphering incoming signals; this allows devices sending to them to transmit with lower power. However, the usefulness of antenna arrays is severely limited by mobility and cost concerns--in addition to high costs, an eight-element 900 MHz antenna would be about 4 feet wide and a 2 GHz eight element antenna would be about 2 feet wide (Lehne and Pettersen, 1999). The large physical size of antenna arrays makes them unsuitable for mobile users, so they are mostly deployed at base stations. As a result, the uplink power in a cellular type network is typically only a fraction of the downlink power from the base stations. This asymmetry in power of uplink and downlink signals may lead to different throughput levels for uplinks and downlinks, and the overall utility of such services will depend on users' valuation of the uplink and downlink communication quality.

Chapter 5 Nature of Demand for Wireless Services

This chapter describes in general terms how interference affects the demand for wireless services based on the discussion of interference in Chapter 4. This description of the demand for wireless services serves as the foundation for the model of competitive markets for wireless services that will be presented in Chapter 6.

Consider a market for a direct two-way P2P wireless service where there are n firms competing for customers. Each firm occupies a unique operating frequency within the band allocated to the service and each customer buys one unit of the service along with the necessary access device. In this case, market demand is a schedule of consumers' willingness-to-pay for the product. In the absence of interference (sans interference, *SI*), customers view the firms' services as homogeneous as long as their devices transmit at the same power level (this restriction will be relaxed later). Assume that in the absence of interference market demand for the service at a given fixed power level is characterized by the linear downward-sloping demand curve (or inverse demand function)

$$P = a - bQ,$$

where P and Q represent the market price and quantity, respectively, and a and b are positive constants. This will be referred to as the SI demand curve hereafter.

Adding interference to this picture makes it considerably more complicated. From a customer's viewpoint, services offered by different firms may no longer be homogeneous when interference is taken into account. Chapter 4 points out that the interference a user experiences increases with the number of interfering devices and their transmission power (which is fixed at a common value for the time being for this discussion), but decreases with the interfering devices' spatial and spectral distance from the interfered device. Depending on firms' output levels and the location and operating frequencies of their devices, some firms' services may suffer from greater interference than others, which translates to a greater loss in utility.[8] The user makes her purchasing decision based on which firm's service provides her with the highest net surplus (the difference between the interference-discounted utility and price charged). This study assumes that the utility loss associated with a given level of interference is independent of a user's SI valuation of the service.

We assume that each service provider knows the market demand function and the interference that other firms' users cause for its own customers. Moreover, firms' beliefs about rivals are assumed to be Nash in output levels and interference. That is, a firm takes rivals' output levels and the interference they cause as given and see them as independent of its own choices. A representative firm's perceived demand curve is therefore the demand it anticipates for its service in response to its choices of transmission power, device robustness and price given its Nash beliefs.

In Figure 5.1, Q_{-i} and q_i are total quantities sold by the rivals of representative firm i and by firm i itself, respectively, and Γ_{-i} and $\gamma(q_i)$ are the loss of utility for a representative i customer caused by interference from its rivals' and its own devices. Since the utility

[8] A user's utility depends on the quality of both the signals she receives and those she sends; therefore her overall utility should be a weighted sum of the utility levels associated with the quality of received signals at both ends of her communication link. In this chapter we illustrate the nature of demand for wireless services using a direct two-way P2P service. The utility levels associated with incoming and outgoing signal quality are not distinguished because such service is symmetric in both incoming and outgoing direction. Complications arising with asymmetry will be discussed in further detail in Chapter 6.

loss resulting from the interference associated with Q_{-i} is the same for all potential i customers, the price firm i can charge for its first device will be $a - bQ_{-i} - \Gamma_{-i}$. If mutual interference between firm i's devices is ignored, firm i's demand curve will be the SI residual demand curve given Q_{-i} shifted down by Γ_{-i}, which is the innermost of the three parallel lines in Figure 5.1. However, mutual interference between firm i's devices further reduces the price firm i can charge. The more devices firm i sells, the stronger the mutual interference between them and the further the price drop due to interference. Graphically, firm i's perceived demand is the lower concave curve in Figure 5.1, which is described by Equation (5.1).

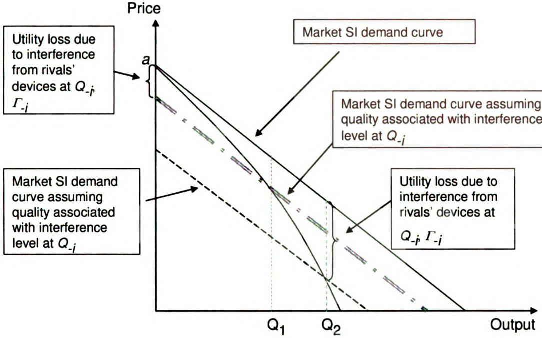
$$P_i = a - b(q_i + Q_{-i}) - \gamma_i(q_i) - \Gamma_{-i} \tag{5.1}$$

What this demand curve says is that the price firm i can charge for its service is contingent on the aggregate loss of utility due to interference from devices sold by rivals (Γ_{-i}) and itself ($\gamma(q_i)$), as well as total quantity sold in the market. A functional form for the aggregate loss of utility due to interference ($\Gamma_{-i} + \gamma(q_i)$) will be specified in the next chapter.

As mentioned in Section 4.2, the loss of utility due to interference experienced by a user depends not only on the strengths of interfering signals generated by other devices but also on receiver quality. Firms can actively respond to interference by producing receivers that reduce the effect of interference though various mechanisms, although implementing these mechanisms is typically costly. More specifically, we assume that firms can influence magnitude of the utility loss caused by interference through their choices among alternative interference suppressing mechanisms that can be built into their devices. Devices that do a better job of handling interference will be referred to as more robust devices. Given that the effect of interference on utility is the same for all users, so is the effect of robustness on utility. Therefore an increase in robustness can be depicted as a parallel upward shift of the firm's perceived demand curve.

If the assumption of fixed transmission power is relaxed so that firms can change their transmission power, power may also be modeled as shifting a firm's perceived demand curve. For example, in a two-way point-to-point network, customers' valuations of the service potentially can increase with signal reach (Section 4.3). In this case, firms may produce devices with higher transmission power and charge higher prices for these devices.

Figure 5.1 An individual firm's perspective on demand for its service



Chapter 6 Models of Markets for Wireless Services

Building on the technical properties of wireless services described in Chapter 4 and the description of demand for wireless services presented in Chapter 5, this chapter presents two models of a market for a wireless service.

As stated in Section 4.3, cost structures and demand characteristics for different wireless services may vary with applications and technology. Therefore, in modeling the market for a wireless service, it is important to recognize differences in technologies that can lead to different incentives and behavior. This study focuses on two types of wireless networks: (1) a wireless network where all users directly communicate with others without any type of backbone or relay (e.g. walkie-talkie); (2) a wireless network where users' signals are relayed to their destinations via base stations and backbone relay (e.g. mobile telephony). While there is a range of technological alternatives, this study focuses on these two network configurations because they are representative of two major types of mass market wireless services at the present time. The models presented in this chapter reveal the tradeoffs involved in spectrum management and enable welfare comparisons of various spectrum governance regimes. They can also be modified to study other types of network configurations.

Drawing on the technical properties discussed in Chapter 4, this chapter starts out by specifying functional representations of interference and the signal-to-interference ratio (SIR). Utilizing the specification of SIR, Section 6.2 fleshes out the demand models. Section 6.3 specifies the cost structures for the services and describes firms' profit and welfare functions, which are derived from the demand function and the cost structures. Section 6.4 describes the derivation of equilibrium outcomes.

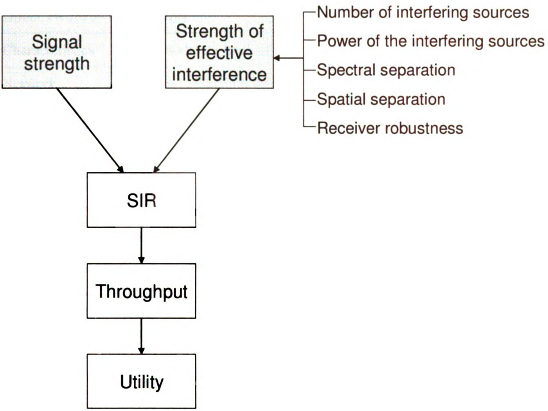
6.1 Mathematical Representations for Interference and SIR

Chapter 5 discusses how interference affects demand for a wireless service in general terms. However, explicit functional forms are required for the simulation exercises described later. This section describes and explains these functional representations of interference and SIR.

Some of the variables introduced in this section are related to the production of a wireless service and to competition among firms as well as interference and SIR. It is important to clarify in advance how these variables enter into the specification of the demand function. Figure 6.1 depicts the chain of relationships described earlier in Sections 4.1 and 4.2. Regardless of network configuration and the technology employed, a wireless service user's utility ultimately depends on the signal strength of the service and strength of effective interference, while the strength of effective interference depends on an array of factors.

On the other hand, in modeling effective interference and SIR, we also need to recognize the differences between network configurations and technologies described in Sections 4.3 and 4.4. Table 6.1 summarizes those differences discussed in Chapter 4 and lists the characteristics of the two types of networks modeled in this chapter.

Figure 6.1 Factors Determining Interference Level and Utility



Next we describe the expression for signal strength and break down effective interference into its components. The engineering concepts summarized in Figure 6.1 and Table 6.1 will be incorporated in the specifications.

Table 6.1 Comparisons of a Direct Two-way P2P Network and a Cellular-Type Network

Direct Two-way P2P Network	
Characteristics	Modeling Implications
Network configuration: No backbone relay	1. Individual user's utility increases with signal reach 2. On average, spatial distance between a receiver and a desired source is the same as that between the receiver and an unwanted source 3. No significant fixed cost investment and fixed cost is independent of firm choice variables
Duplex: TDD	1. Each firm operates at only one frequency band 2. The device used by the person a user is communicating with does not contribute to the interference she experiences
Symmetric uplink and downlink transmission power	Devices communicate with each other directly and all transmit with the same power; therefore throughput specifications for sending and receiving links are the same
Cellular-type Network	
Characteristics	Implications
Network configuration: Users assigned to cells connected through backbone relay	1. Utility independent of signal reach 2. Spatial distance between a receiver and a desired source (within cell radius) is the smaller on average than that between the receiver and an unwanted source (anywhere in the service area)

	3. Significant fixed cost, which depends on cell size and transmission power
Duplex: FDD	1. Each firm operates at two frequency bands; one for uplink and one for downlink 2. The device used by the person a user is communicating with and the base station transmitters contribute to the interference she experiences
Asymmetric uplink and downlink transmission power	Devices communicate with each other via base stations. Base stations transmit at higher power than mobile device; therefore throughput specifications for sending and receiving links differ

6.1.1 Signal strength

Applying the definition of SIR in Section 4.2, signal strength is measured at the location of the receiver in question. Because signals attenuate as they travel, signal strength at the receiver depends on the spatial distance between the signal source and the receiver.

In this study, we assume that devices are mobile, but at any given time all firms' devices are distributed uniformly on a sphere with fixed surface area. This is a common assumption employed in engineering studies as it bypasses the complications that arise due to edge of territory asymmetries.

We will discuss signal strength in a direct two-way P2P network and a cellular-type network separately because expected signal strength depends on network configuration.

6.1.1.1 Direct Two-way P2P Networks

Unlike a cellular-type network, where desired signals only need to reach pre-assigned base stations, in a direct two-way P2P network, devices communicate with each other directly and the signals they send out usually travel far enough to reach receivers anywhere in the service area. With a uniform distribution of devices on a sphere, the expected signal strength from a transmitter measured at the location of any given receiver can be obtained by averaging the signal level measured at locations across the entire surface of the sphere. Given a uniform distribution of devices, the expected signal strength will be independent of the locations of the transmitter and receiver. Let *TP* be the transmission power of a signal source. The uniform distribution assumption allows us to define a spatial averaging factor, s', so that the expected signal strength for a receiver at any given location is $s' \cdot TP$. For a given base station transmission power and a minimum acceptable signal power level, Equation (4.2) can be used to determine cell size of a cellular-type network.

6.1.1.2 Cellular-Type Networks

Expected signal strength in a cellular network depends partially on cell size. Let the expected strength of a signal of transmission power *TP* from distance *R* be $s(R) \times TP$, where $s(R)$ is referred to as the *averaging factor*. Applying the free space path loss model described by Equation (4.2),

$$s(R) = \frac{\int_1^R \left(\frac{\lambda}{4\pi r}\right)^2 \times 2\pi r dr}{\int_1^R 2\pi r dr} = \frac{\lambda^2 LogR}{8\pi^2 (R^2 - 1)},$$ [9]

which is decreasing in R.

Rearranging Equation (4.3), which describes the relationship between *TP* and *R* for a guaranteed minimum power level of 1 within a cell of size *R*, we have $R^2 = TP\left(\frac{\lambda}{4\pi}\right)^2$.

Plug this into the above expression for $s(R)$ and we can obtain s as a function of *TP*:

$$s(TP) = \frac{LogTP - 2Log(4\pi/\lambda)}{TP - (4\pi/\lambda)^2}, \qquad (6.1)$$

As Figure 6.2 shows, $s(TP)$ is decreasing in *TP*. This implies that $s(TP)$ should always be greater than $s' = s(TP_{\max})$, where TP_{max} is the transmission power required to serve the entire service area with a single cell.

Figure 6.3 shows the expected signal strength, $s(TP) \times TP$, as a function of *TP*. The pattern suggests that, in spite of the fact that the averaging factor diminishes with *TP* and cell size (which increases with *TP*), increasing transmission power in a cellular-type network tends to increase expected signal strength.

[9] To avoid the technical problem that this integral will be indeterminate if the lower bound is zero, the assumption is made that the device is not used for communication needs with a range of less than 1 meter. Reducing this range will make the averaging factor, *s*, decrease at a greater rate with *R*, but the overall shape does not change.

Figure 6.2 *s(TP)* vs. *TP*

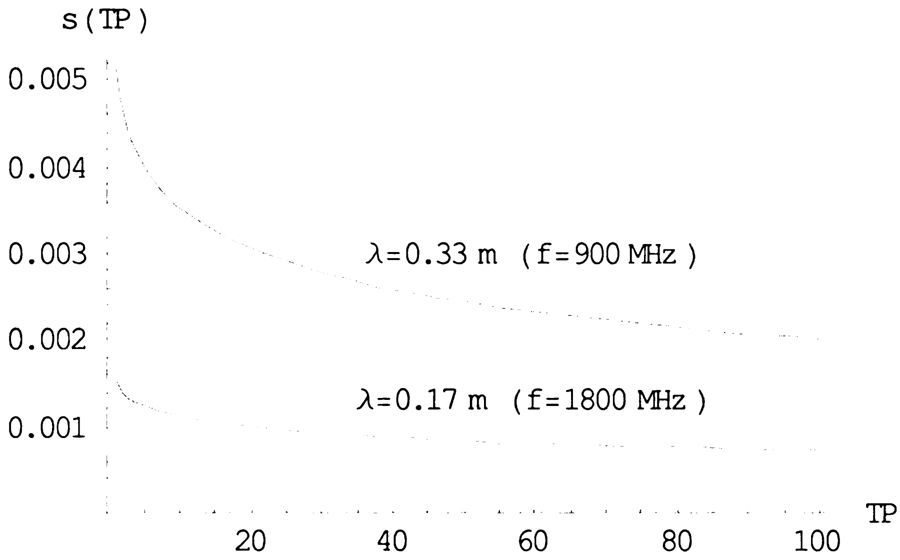
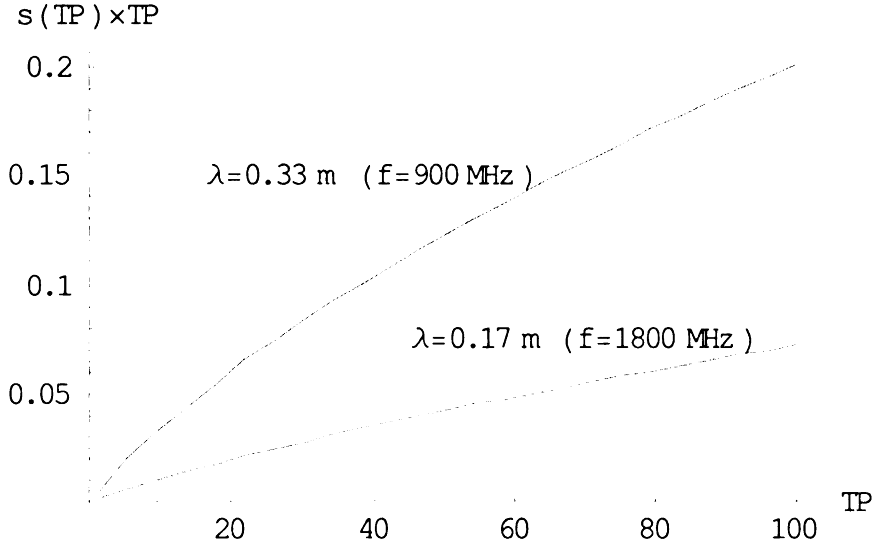


Figure 6.3 Expected Signal Strength as a Function of Transmission Power



Note that with the assumption of a uniform distribution of devices on a sphere, geographic locations of individual devices do not directly enter the demand functions for both types of networks.

6.1.2 Strength of Effective Interference

The basic principles discussed in Sections 4.1 and 4.2 determine the strength of effective interference in both direct two-way P2P networks and cellular-type networks; however, the detailed functional forms vary with network configuration and the technologies employed (Sections 4.3 and 4.4). In this subsection we first look at the specification of effective interference for a direct two-way P2P network, the specification will then be modified to describe effective interference for a cellular-type network.

6.1.2.1 Direct Two-way P2P Network

Section 4.1 defines effective interference as the residual APFUS (aggregate power from unwanted signals) not intercepted by the receiver's interference-suppressing mechanisms. For a given APFUS, effective interference is determined by robustness (Section 4.2.2).

Section 4.2.2 states that an unwanted signal's contribution to APFUS at a receiver increases with the transmission power of the unwanted signal but decreases with the spectral separation between the source and the receiver. Since firms may operate at different frequencies, their contributions to APFUS at a given receiver may differ.

Assume there are n firms and each firm chooses a unique operating frequency within the band allocated to the service. Let i be a representative firm and index its rivals by j, $j=1, 2, \ldots, n, j \neq i$. For an i customer, we assume the contribution to APFUS at her location by firm j is proportional to $\frac{1}{1+\eta d_{ij}}$, where d_{ij} is the spectral separation between systems i and j, and the scaling factor η can be adjusted to allow for variation in the magnitude of the effect of spectral separation depending on the spectral characteristics of the technology employed. Given this specification, for a direct two-way P2P network, we can write the APFUS firm i's other devices and firm j's devices cause for an i customer as $\beta_i(q_i, TP_i)$ and $\frac{\beta_j(q_j, TP_j)}{1+\eta d_{ij}}$, respectively, where TP_j is firm j's transmission power.

To avoid the modeling complications that arise from locational asymmetry at the edges of the band, we assume the band is circular. This is an assumption commonly used to avoid the edge-of-the-territory problem in the economics literature; it can considerably simplify the analysis when firms are symmetrically spread around the circle (Salop, 1979).

The analysis of the previous subsection applies to interfering signals as well. Since power cannot be confined within any specific region, unwanted signals can interfere with any device within the service area (although the practical effect may be small). The expected strength from an interfering device (with transmission power TP) measured at any given receiver should therefore be $s' \times TP$, which is obtained by averaging the power levels of the received interfering signals across the entire service area and s' is the corresponding averaging factor.

As shown in Table 6.1, in a direct two-way P2P network, devices communicate with each other directly and all transmit with the same power. We also assume that TDD (Time Division Duplex) is employed, so that each firm operates at one central frequency and incoming and outgoing signals do not interfere with each other. That is, for an i customer, the contribution to APFUS by other firm i devices is $\beta(q_i, TP_i) = s' \cdot TP_i \cdot (q_i - 2)$, the product of expected signal strength and the number of interfering devices. Note that the number of interfering devices is $q_i - 2$ because the user's own device and the device the individual user is communicating with do not create interference for the user.

Similarly, the contribution to APFUS for an *i* device by firm *j*'s devices is $\frac{s' \cdot TP_j \cdot q_j}{1+\eta d_{ij}}$, and APFUS can be written as $s' \cdot TP_i \cdot (q_i - 2) + \sum_{\substack{j=1 \\ j \neq i}}^{n} \frac{s' \cdot TP_j \cdot q_j}{1+\eta d_{ij}}$.

In specifying effective interference, we use c_{Ri}, the cost of the receiver unit, as a proxy for robustness of a device and assume effective interference varies inversely with c_{Ri}^{δ}, where δ is a positive parameter that determines the rate at which increases in expenditures on robustness are manifest in reductions in effective interference. For $\delta = 1$, robustness is inversely proportional to c_{Ri}^{δ}. For $\delta < 1$, robustness increases less than in proportion to c_{Ri}^{δ} and for $\delta > 1$, robustness increases more than in proportion to c_{Ri}^{δ}. Now the SIR for an *i* device in a direct two-way P2P network can be expressed as

$$SIR_i = \frac{s' \cdot TP_i}{\left[s' \cdot TP_i \cdot (q_i - 2) + \sum_{\substack{j=1 \\ j \neq i}}^{n} \frac{s' \cdot TP_j \cdot q_j}{1+\eta d_{ij}} \right] / c_{Ri}^{\delta}}$$

$$= \frac{c_{Ri}^{\delta} \cdot TP_i}{\left[TP_i \cdot (q_i - 2) + \sum_{\substack{j=1 \\ j \neq i}}^{n} \frac{TP_j \cdot q_j}{1+\eta d_{ij}} \right]} \tag{6.2}$$

In this study we focus only on symmetric equilibria. Since firms have an incentive to stay as far apart from each others' operating frequencies as possible to minimize inter-system interference, in equilibrium the n identical firms will spread out across the band evenly. Let the overall bandwidth allocated to this service be L, d_{ij} is then $\frac{L}{n}|j-i|$.

In the discussion up to this point we have not explicitly distinguished the SIR for the signals a user receives and the SIR for the signals others receive from her, both of which should affect her utility. The reason is that in a direct two-way P2P network these two SIR's should be the same, and we further assume equal contributions to the user's overall utility from the quality of reception of signals she receives from others and the quality of reception of signals others receive from her. The SIR for the signals a user receives and the SIR for the signals others receive from her are the same in a direct two-way P2P network because all devices in a firm's network have the same transmission power and robustness and devices are distributed uniformly in both geographic and spectral space, which leads to same expected signal strength and expected strength of effective interference at all devices.

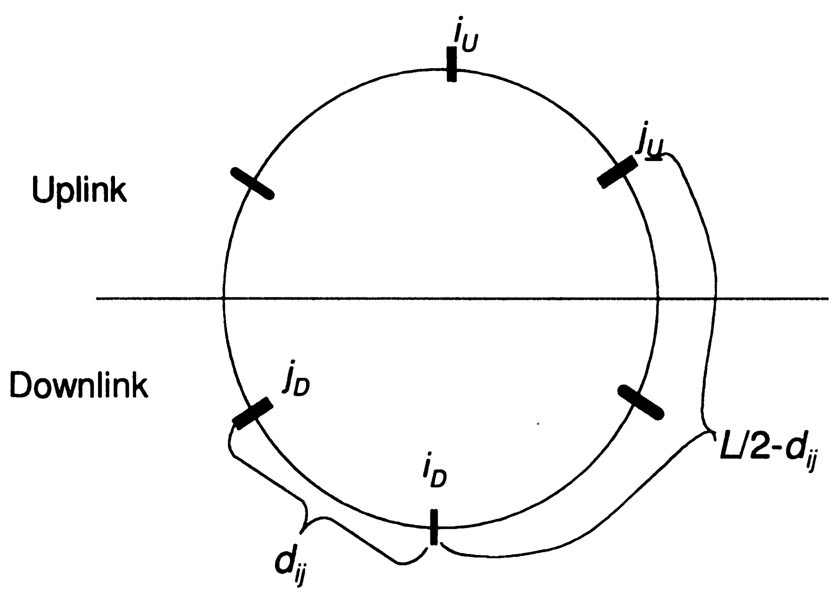
6.1.2.2 Cellular-Type Services

With FDD and asymmetry in uplinks and downlinks in a cellular network, expected signal strengths, expected effective interference and the SIR for uplinks and downlinks may no longer be the same. Since both uplinks and downlinks contribute to a user's utility, we need to specify uplink and downlink SIR's separately. Next we modify the specifications for effective interference and SIR to account for the complications arising from FDD and asymmetry in uplinks and downlinks in a cellular network.

First, I assume the duplex mechanism in the cellular-type service to be FDD as in most cellular networks. With FDD each firm operates at two frequencies, one for uplink and the other downlink. Assume the bandwidth of the band allocated to this service is L. Without loss of generality, we simplify the analysis by assuming that each firm's uplink and downlink frequencies are $\frac{L}{2}$ apart and all firms' uplinks operate in the upper half of the circular band while the lower half of the band is for downlinks (Figure 6.4).

The locations of the uplink and downlink frequencies for firms i and j are indicated by i_U, i_D and j_U, j_D, respectively in Figure 6.4. The spectral separation between firm i's downlink frequency, i_D, and that of firm j, j_D, is d_{ij}. Since j_D is $\frac{L}{2}$ away from firm j's uplink frequency j_U, the spectral distance between i_D and j_U is $\frac{L}{2} - d_{ij}$.

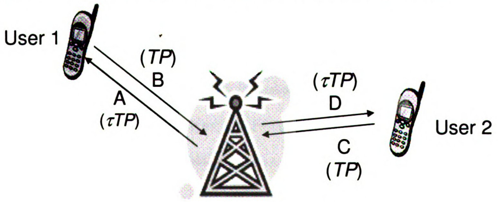
Figure 6.4 Frequency Allocation in an FDD System



Next, let the uplink (from terminal device to base station) and downlink (from base station to terminal) transmission power be TP and τTP, respectively. The ratio τ, which can be greater than or equal to 1, reflects the power asymmetry resulting from using receiving antenna arrays at the base station (Section 4.4). If transmission power and robustness of the mobile device are fixed, τ can be increased if more sophisticated receiver units are used at the base station.

Figure 6.5 illustrates mutual interference between devices in a cellular-type network. User 1 communicates with User 2 via the base station. Although not shown in the figure, there are other devices operating in the same environment. While in a TDD direct two-way P2P network user 1 and user 2 do not interfere with each other (Section 4.4), in a FDD cellular-type network each of the communication links A, B, C, D is interfered with by the other three. Given that firm i sells q_i devices, there will be q_i uplinks (at TP) and q_i downlinks (at τTP) in the network. For User 1's uplink, B, the contribution to APFUS from other i devices are from all the other q_i-1 uplinks and q_i downlinks.

Figure 6.5 Mutual interference between devices in a cellular-type network



For a representative firm i customer's uplink, the contribution from all other i devices to the APFUS for this uplink is $s'TP_i \cdot (q_i - 1) + \frac{s'\tau TP_i \cdot q_i}{1+\eta L/2}$, the sum of the products of expected strength of unwanted signals and the number of sources of such signals. Note that here the term $L/2$ replaces d_{ij} in the previous specification of effect of spectral separation because i_U and i_D are $L/2$ apart. Similarly, the contribution from firm j's devices to the APFUS for this uplink is $\frac{s'TP_j \cdot q_j}{1+\eta d_{ij}} + \frac{s'\tau TP_j \cdot q_j}{1+\eta(L/2-d_{ij})}$. Let c_{RUi} be the robustness of receiver at the base station and assume effective interference varies in inverse proportion with c_{RUi}^{δ}. Then the effective interference for this uplink is

$$\left[s'TP_i \cdot (q_i - 1) + \frac{s'\tau TP_i \cdot q_i}{1+\eta L/2} + \sum_{\substack{j=1 \\ j \neq i}}^{n} \left(\frac{s'TP_j \cdot q_j}{1+\eta d_{ij}} + \frac{s'\tau TP_j \cdot q_j}{1+\eta(L/2-d_{ij})} \right) \right] / c_{RUi}^{\delta},$$

and the uplink SIR for an i device is

$$SIR_{Ui} = \frac{s(TP_i) \cdot TP_i}{s'\left[TP_i \cdot (q_i - 1) + \frac{\tau TP_i \cdot q_i}{1+\eta L/2} + \sum_{\substack{j=1 \\ j \neq i}}^{n} \left(\frac{TP_j \cdot q_j}{1+\eta d_{ij}} + \frac{\tau TP_j \cdot q_j}{1+\eta(L/2-d_{ij})} \right) \right] / c_{RUi}^{\delta}} \tag{6.3}$$

It is worth noting that the expected signal strength $s(TP_i) \cdot TP_i$ must be greater than the expected strength from an unwanted signal $s'TP_i$ in a cellular network (unless the entire service area is served by a single cell). The reason is that while desired signals only travel within cells, interfering signals on average travels longer since they can come from anywhere in the territory, and thus attenuate more.

Similarly, the SIR for the downlink of an i device is

$$SIR_{Di} = \frac{s(TP_i) \cdot \tau TP_i}{s'\left[\tau TP_i \cdot (q_i - 1) + \frac{TP_i \cdot q_i}{1 + \eta L/2} + \sum_{\substack{j=1 \\ j \neq i}}^{n} \left(\frac{\tau TP_j \cdot q_j}{1 + \eta d_{ij}} + \frac{TP_j \cdot q_j}{1 + \eta (L/2 - d_{ij})} \right) \right] / c_{RDi}^{\delta}} \quad (6.4)$$

where c_{RDi} is the cost of the receiver unit in the access device (which reflects robustness).

There is little information about the relationship between c_{RUi}^{δ} (uplink or base station robustness) and c_{RDi}^{δ} (downlink or the robustness at the mobile terminal), although it should be a function of τ. For analytical tractability, we specify the relationship as

$$c_{RUi}^{\delta} = \tau \cdot c_{RDi}^{\delta} = \tau \cdot c_{Ri}^{\delta}, \quad (6.5)$$

so that τ is the ratio of base station robustness to the robustness of mobile terminals as well as the ratio of downlink to uplink power.

6.2 Specification of the Demand Functions

This section builds the demand functions for a direct two-way P2P network and a cellular-type network based on the framework laid out in Chapter 5, as well as the throughput model of Equation (4.1) and the SIR specifications presented in Section 6.1.

6.2.1 Direct Two-way P2P Network

It is stated in Section 4.3 that an individual user's utility is likely to increase with signal reach and transmission power in a direct two-way P2P network. In this case, firms can increase the transmission power of their devices and charge higher prices for their services (if other firms' transmission powers do not change). As discussed in Chapter 5, the effect of such a unilateral increase in power is an upward shift in a firm's perceived demand curve.

Assume each user's utility increases linearly with TP^x, where TP is transmission power, and x is a positive constant, the value of which reflects the benefits associated with increased signal reach to a user. User valuation may increase due to increased signal reach or a larger area covered, or both. For example, if signal reach is the major concern and utility varies linearly with signal reach, x should be about 0.5 since signal reach increases proportionally with the square-root of the transmission power. And if utility is linearly dependent on signal coverage area, x should be about 1 because the area covered by a signal increases proportionally with transmission power. When utility increases less than in proportion to signal reach or coverage, which is likely to be the case, x should be less than 0.5.

Given that utility increases with TP^x, we let the utility of the customer with the highest valuation for the service be $a \cdot TP^x$ in the absence of interference, which is the new intercept (or the choke price) for the SI demand curve.

In specifying the demand function for a wireless service, we assume that utility realized from using the service is increasing in throughput. Section 4.1 points out that the rate at which utility increases with throughput is likely to be diminishing in throughput, which increases linearly with $(1-e^{-k \cdot SIR})$. To allow utility to increase at a diminishing rate with throughput, we assume utility to be proportional to $(1-e^{-k \cdot SIR})^g$, where $0 < g < 1$. As mentioned in Section 6.1, in a direct two-way P2P network, the specification of SIR for the signals a user receives is the same as that for the signals others receive from her, so the expected incoming and outgoing throughput should be the same. With the assumption that a user values quality of reception of signals from others and the quality of others' reception of signals from her equally, the average throughput and utility should be the same for the incoming and outgoing links and it is not necessary to distinguish between the incoming and outgoing signal paths.

In addition, we assume the effects of signal reach and throughput on utility are multiplicative and the same for all users. The intercept for firm *i*'s perceived demand curve thus becomes $aTP_i^x(1-e^{-k \cdot SIR_i})^g$, and the perceived demand for firm *i*'s service is

$$P_i = a \cdot TP_i^x (1-e^{-k \cdot SIR_i})^g - b(q_i + Q_{-i}), \tag{6.6}$$

where SIR_i has the functional form given in Equation (6.2).

Comparing Equations (6.6) and (5.1), we have

$$\Gamma_{-i} + \gamma(q_i) = a \cdot TP_i^x \left[1-(1-e^{-k \cdot SIR_i})^g \right].$$

6.2.2 Cellular-Type Network

This subsection modifies the demand function derived in the previous subsection to model demand for a cellular-type service.

As mentioned in Section 4.3, in a cellular-type network where full coverage is guaranteed by the service provider, signal reach has no direct impact on utility as in a direct two-way P2P network and the only channel through which transmission power affects utility is

SIR. In other words, x=0. Another difference here is that since uplink and downlink powers are asymmetric in a cellular-type network, we need to determine uplink and downlink throughput levels separately and use a weighted sum of them as a measure for overall utility. As before, we assume users value the quality of reception for both signals they send and receive equally. The overall utility is then an average of the utility levels associated with the uplink and downlink throughput, and the demand function is

$$P_i = \frac{1}{2}\left[a\left(1-e^{-k \cdot SIR_{Ui}}\right)^g + a\left(1-e^{-k \cdot SIR_{Di}}\right)^g\right] - b(q_i + \sum_{\substack{i=1 \\ i \neq j}}^{n} q_j), \tag{6.7}$$

where

$$SIR_{Ui} = \frac{s(TP_i) \cdot TP_i}{s' \cdot \left[TP_i \cdot (q_i - 1) + \frac{\tau TP_i \cdot q_i}{1+\eta L/2} + \sum_{\substack{j=1 \\ j \neq i}}^{n}\left(\frac{TP_j \cdot q_j}{1+\eta d_{ij}} + \frac{\tau TP_j \cdot q_j}{1+\eta(L/2 - d_{ij})}\right)\right] / \left(\tau \cdot c_{RUi}^{\delta}\right)} \tag{6.8}$$

and

$$SIR_{Di} = \frac{s(TP_i) \cdot \tau TP_i}{s' \cdot \left[\tau TP_i \cdot (q_i - 1) + \frac{TP_i \cdot q_i}{1+\eta L/2} + \sum_{\substack{j=1 \\ j \neq i}}^{n}\left(\frac{\tau TP_j \cdot q_j}{1+\eta d_{ij}} + \frac{TP_j \cdot q_j}{1+\eta(L/2 - d_{ij})}\right)\right] / c_{RDi}^{\delta}} \tag{6.9}$$

Equation (6.8) is obtained by combining Equations (6.3) and (6.5), and Equation (6.9) by combining Equations (6.4) and (6.5). $s(TP_i)$ is as specified in Equation (6.1).

In a cellular-type network each firm operates at two frequencies; therefore in a symmetric equilibrium the spectral spacing between operating frequencies will be $\frac{L}{2n}$, and d_{ij} in Equations (6.7) and (6.8) will be $\frac{L}{2n}|i-j|$.

6.3 Transmitter Cost, Fixed Cost and the Profit Function

The analysis up to this point has focused on transmission power, *TP*, as a potential policy variable or firm choice variable. In this section we introduce c_T, the cost of the transmitter unit in the access device, as a proxy for *TP*. By doing so we can also examine the profit implications of a firm's choice of transmission power. The relationship between *TP* and c_T is represented as $TP = w \cdot c_T^z$, where w is a constant scaling factor and $0<z<1$ because over the long run power is likely to increase less than in proportion with the cost of the transmitter unit.

Fixed costs limit the number of firms that can profitably operate in a market. Therefore, even in a direct two-way P2P service where there is no fixed cost for building a network infrastructure, we still need to take the cost of setting up and managing a firm as a limiting factor. For a service where users directly communicate with each other without going through base stations and/or other infrastructure, it is reasonable to assume that this cost, denoted as F, is a constant independent of firms' choice variables, q, c_T and c_R.

In sum, with a direct two-way P2P network, firm i's profit is

$$\begin{aligned}\pi_i &= (P_i - c_{Ri} - c_{Ti})q_i - F \\ &= A \cdot (wc_{Ti}^z)^x (1 - e^{-k \cdot SIR_i})^g q_i - (c_{Ti} + c_{Ri})q_i - b(q_i + \sum_{\substack{i=1 \\ i \neq j}}^{n} q_j)q_i - F\end{aligned} \quad , \quad (6.10)$$

where SIR_i is represented as Equation (6.2).

On the other hand, in a cellular-type network, cell size has a significant impact on fixed cost. As discussed in Section 4.3, depending on traffic volume per unit area, total fixed cost could be either increasing or decreasing in cell size, which is determined by downlink power $\tau \cdot TP(c_{Ti})$. We assume the relationship between fixed cost and transmission power is proportional to $s1(\tau \cdot TP(c_{Ti}))^{-2} + s2(\tau \cdot TP(c_{Ti}))^{s3}$, where *s1*, *s2* and *s3* are constants. For very small values of c_{Ti}, the $s1(\tau \cdot TP(c_{Ti}))^{-2}$ term will become very large, which means that firms cannot increase profit by reducing cell size and increasing cell density without limit. Depending on the values of *s2* and *s3*, fixed cost could be increasing or decreasing in cell size. This functional form can be used to describe cost functions with a wide range of shapes by varying *s1*, *s2* and *s3.*

Moreover, given the same cell size, increasing τ, while allowing terminals to transmit at lower power, requires more expensive receiving equipment at the base station, adding to the fixed cost. It is reasonable to assume that this additional cost will be increasing with cell size since more users will be served in a larger cell and more processing power will be required. Therefore, we represent total fixed cost as a function of transmission power and τ, as

$$F(c_{Ti}, \tau) = \tau^{t}\left[s1(\tau \cdot TP(c_{Ti}))^{-2} + s2(\tau \cdot TP(c_{Ti}))^{s3} \right], \text{ with } t > 0.$$

Equation (6.11) gives the profit function for firm *i*, which provides a cellular-type service, as:

$$\pi_i = \frac{a}{2}\left[\left(1 - e^{-k \cdot SIR_{Ui}}\right)^{g} + \left(1 - e^{-k \cdot SIR_{Di}}\right)^{g} \right] q_i - (c_{Ti} + c_{Ri}) q_i - b(q_i + \sum_{\substack{i=1 \\ i \neq j}}^{n} q_j)$$
$$- \tau^{t}\left[s1(\tau \cdot TP(c_{Ti}))^{-2} + s2(\tau \cdot TP(c_{Ti}))^{s3} \right] \qquad (6.11)$$

where SIR_{Ui} and SIR_{Di} are specified by Equations (6.8) and (6.9).

6.4 Derivation of Equilibria and Welfare Outcomes

With the two profit functions specified by Equations (6.10) and (6.11), we can calculate market equilibria for all eight policy regimes described in Chapter 3. Absent any government regulations, firms can adjust their output levels, transmission power and robustness levels for profit maximization, but firms' freedom in setting power and robustness is limited in some regimes. Also, while the number of firms will be set by the government in a property rights regime, it is determined by market forces in an open commons. In economic terms, the first order profit-maximizing conditions with respect to variables that firms can control should hold in all regimes and the zero-profit condition should be satisfied in an open commons regime.

Table 6.2 lists the eight regimes along with the policy instruments set by government, as well as the market equilibrium conditions for each regime.

The equilibrium values of firms' choices of q, c_T and c_R can be obtained by solving these conditions. Prices and profits can then be determined by plugging the equilibrium values of firms' choices of q, c_T and c_R into the demand and profit functions.

Calculation of equilibrium welfare is a little more complicated. The assumptions of a symmetric equilibrium and linear SI demand curve make it relatively simple to incorporate the utility reducing effects of interference in welfare calculations. The interference experienced by a user reduces the amount she is willing to pay for a provider's wireless service by the dollar equivalent of the reduction in utility delivered by the service. Recall that we have assumed that for a given amount of interference all users experience the same reduction in utility regardless of how much they would value the service in the absence of interference. Because all users experience the same level of interference in a symmetric equilibrium, the effect of equilibrium interference on demand can be represented by a downward and parallel shift in the market SI inverse demand function, with the amount of the shift equal to Γ^*, the reduction in each subscriber's willingness to pay at the equilibrium level of interference.

Table 6.2 Regimes and Equilibrium Conditions

Regime	Variables set by government	Equilibrium conditions
1	n, c_T, c_R	$\frac{\partial \pi_i}{\partial q_i}=0$
2	n, c_T	$\frac{\partial \pi_i}{\partial q_i}=0,\ \frac{\partial \pi_i}{\partial c_{Ri}}=0$
3	n, c_R	$\frac{\partial \pi_i}{\partial q_i}=0,\ \frac{\partial \pi_i}{\partial c_{Ti}}=0$
4	n	$\frac{\partial \pi_i}{\partial q_i}=0,\ \frac{\partial \pi_i}{\partial c_{Ri}}=0,\ \frac{\partial \pi_i}{\partial c_{Ti}}=0$
5	c_T, c_R	$\frac{\partial \pi_i}{\partial q_i}=0,\ \pi_i \to 0$
6	c_T	$\frac{\partial \pi_i}{\partial q_i}=0,\ \frac{\partial \pi_i}{\partial c_{Ri}}=0,\ \pi_i \to 0$
7	c_R	$\frac{\partial \pi_i}{\partial q_i}=0,\ \frac{\partial \pi_i}{\partial c_{Ti}}=0,\ \pi_i \to 0$
8	-	$\frac{\partial \pi_i}{\partial q_i}=0,\ \frac{\partial \pi_i}{\partial c_{Ri}}=0,\ \frac{\partial \pi_i}{\partial c_{Ti}}=0,\ \pi_i \to 0$

Let c_{Ti}^*,c_{Ri}^*, n^*, q^*, $Q^*\equiv q^*n^*$ and F (or $F^*(c_{Ti}^*)$ in a cellular-type network) represent the equilibrium values for the per unit cost of a transmitter and a receiver unit in a device, the number of wireless service providers, the number of customers for a representative firm, and the number of customers served by the industry and fixed cost. Then the industry's net contribution to social welfare is given by:

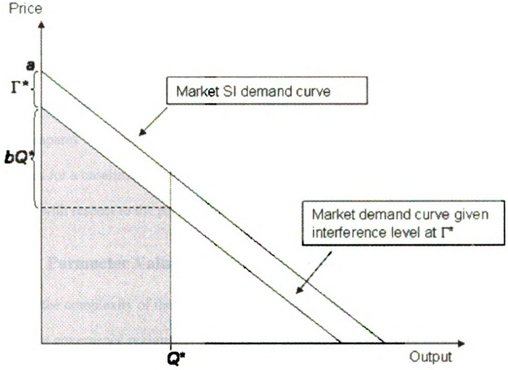
$$\begin{aligned} W &= \int_0^{Q*} (aTP^x - \Gamma * - bq)dq - (c_T + c_R)Q * - n * F \\ &= (aTP^x - bQ * - \Gamma *)Q * + \frac{b}{2}(Q *)^2 - (c_T + c_R)Q * - n * F \end{aligned} \quad (6.12),$$

where $a - bQ * - \Gamma *$ is the equilibrium market price.

$\int_0^{Q*}(a - \Gamma * - bq)dq$ is the gross value of the service to consumers and is represented by the shaded region in Figure 6.6. Consumer surplus is the triangular portion of the shaded region above the dashed line. Aggregate revenue collected by the wireless service providers is the rectangular region below this line. For the two open commons regimes, free entry drives profits to zero, so this rectangle is also equal to total industry costs ($c_TQ*+c_RQ*+n*F$). As profits may be positive when government sets the number of firms at its optimal level through the assignment of property rights, some portion of the rectangle below the dashed line may be industry profits for the two property rights regimes.

With the chosen parameter values, the equilibrium conditions in Table 6.2 determine the equilibrium values of output (q), robustness (proxied by c_R, the cost of the receiver unit in the access device), transmission power (proxied by c_T, cost of receiver unit in the access device), price, profit, and welfare. Solving for equilibria, however, is not so straight-forward due to the complex form of the first-order conditions. The profit function and the first order conditions are highly non-linear and cannot be solved analytically; therefore we solve the equation or equation systems computationally for specified parameter values using Mathematica. Procedures for solving the equilibrium conditions vary somewhat from regime to regime. The procedures for implementing the calculations required for each regime are presented in the Appendix to this dissertation.

Figure 6.6 Equilibrium Consumer Surplus



Chapter 7 Welfare Analysis

This chapter presents the results of a welfare analysis based on the models presented in Chapter 6. For clarity, the research findings are presented in the same order as the corresponding research questions posed in Section 1.2. Section 7.1 discusses the parameter values used to derive the results for both models. The findings reported in Section 7.2 describe the effects of policy instruments. Based on these findings, Section 7.3 compares welfare outcomes under property rights regimes and the open commons regimes for a baseline set of parameter values. Section 7.4 examines the sensitivity of the results with respect to the parameter values.

7.1 Parameter Values Used in the Baseline Analyses

Due to the complexity of the profit functions, investigating the welfare properties of different governance regimes by algebraically solving the models for different parameter values is impractical. Instead, we compare computed numerical solutions for a wide range of values for critical parameters. Tables 7.1 and 7.2 list the parameter values used in the baseline analyses for both the models described by Equations (6.10) and (6.11), respectively.

A key difficulty of this study is that for many parameters there is little information as to what a reasonable base case value might be. When there is no literature or studies suggesting a value for a parameter, the base case parameter value is chosen by first limiting the possible range of values by excluding obviously unreasonable values and then selecting the mid point value for the resulting range of values, when this approach cannot be used, we start with a best guess and vary the parameter values across a wide range to see whether the initial value chosen tilted the results.

Table 7.1 Parameter Values for Baseline Case in a Two-way Point-to-Point Network

Category	Symbol and Interpretation	Parameter Value
Technology	η: scaling factor reflecting the effect of inter-system interference on SIR	1
	k: scaling factor for the effect of SIR on throughput, the value of which depending on modulation technique used	0.6
Demand	a: intercept of the SI demand curve	100
	b: slope of the SI demand curve	1
	x: exponent determining the relative effect of signal reach on utility (x>1: increasing; x<1: decreasing; x=1: constant)	0.5
	g: exponent determining the relative effect of throughput on utility	0.5
Cost	F: fixed cost	10
	δ: exponent determining the relative effect of cost of receiver unit in the access device on robustness	0.9
	z: exponent determining the relative effect of cost of transmitter unit in the access device on transmission power	0.3
	w: scaling factor for the effect of transmitter unit cost on output power	1
Bandwidth	L: total bandwidth allocated to the service	10

The base case value of η is 1 and is varied from 0.1 to 10 in the sensitivity analysis to see how variation in η changes the welfare comparison. The value of k depends greatly on the technology, application and environment, and the initial value is chosen to be 0.6, based on the modeling work of Mehta and Goldsmith (2001).

The effects of signal reach and throughput on utility, while both positive, are likely to be diminishing; therefore we chose values smaller than one. Similarly, returns to investment in robustness and transmission are likely to be positive but diminishing as well, so δ and z are both chosen to be smaller than one. Parameters a and b together determine market size. We choose an initial value for b that produces a market demand curve with non-extreme slope.

Table 7.2 lists the choice of base case parameter values for the model of a cellular-type service. For a cellular-type network, τ is at least one, and the baseline study sets it at 2. Unlike the two-way P2P network model, λ explicitly enters into the cellular-type network model because λ determines the rate of attenuation for power, which depends on cell size in this case. We choose λ=1/6m for the base case value, which is the wavelength at 1.8 GHz. As discussed in Sections 4.3, depending on per area traffic volume, total cost can be increasing or decreasing in cell size so $s3$ does not necessarily have to be smaller than zero. We start the baseline case with $s3<0$, and in the sensitivity analysis we will also look at the result when $s3>0$. Section 6.3 states that t, the effect on total fixed cost of increasing τ while fixing cell size, will be positive, but since the receiver antennas only account for a fraction of total infrastructure cost, the value of this parameter should not be large.

Table 7.2 Parameter Values for Baseline Case in a Cellular Type Network

Category	Symbol and Interpretation	Parameter Value
Technology	η: scaling factor of the effect of inter-system interference on SIR	1
	k: scaling factor for the effect of SIR, depending on modulation scheme	0.6
	τ: ratio of downlink power to uplink power (or base station robustness to that of mobile terminal)	2
	λ: wave length of the technology employed	1/6
Demand	a: intercept of the SI demand curve	100
	b: slope of the SI demand curve	1
	g: exponent determining the relative effect of throughput on utility (g>1: increasing; g<1: decreasing; g=1: constant)	0.5
	$s1$: scaling factor determining the effect of reduce cell size on fixed cost at high cell density	300
Cost	$s2$: scaling factor for the effect of $s3$ on fixed cost	1
	$s3$: exponent determining the relative effect of transmission power on fixed cost at given τ	-0.3
	t: exponent determining the relative effect of τ on fixed cost	0.2
	δ: exponent determining the relative effect of cost of thd receiver unit in the access device on robustness	0.9
	z: exponent determining the relative effect of cost of the transmitter unit in the access device on transmission power	0.3
	w: scaling factor for the effect of transmitter unit cost on output power	1
Bandwidth	L: total bandwidth allocated to the service	10

7.2 Effects of the Policy Instruments

The choice of spectrum governance regimes is as much about how to set the policy instruments as what policy instruments should be regulated. Ideally, by controlling policy instruments a social planner can mitigate negative externalities and maximize overall welfare. In reality, even with powerful policy instruments in hand, the social planner may not have all the information necessary for welfare maximization, and this might lead to bad policies that actually reduce welfare relative to what an unregulated market might produce. This section provides a more complete picture of the effects of policy instruments by showing what may happen when the policy instruments are set optimally and when they are not.

7.2.1 Welfare Comparison of Governance Regimes

To facilitate comparisons of regimes, the typology of governance regimes in Figure 3.1is presented again as Figure 7.1. Figure 7.2 compares the best possible welfare outcomes (solid markers) for all eight regimes for base case parameter values and a two-way P2Pservice. The welfare optima are achieved when the policy instruments controlled by government are set at their optimum. The hollow markers also indicate outcomes under property rights regimes, although in those cases the number of firms is not set at it optimum.

Figure 7.2 illustrates several important findings of this research:

(1) The effect of robustness regulation is negligible

It might seem that only four regimes are presented here. Actually, outcomes under all eight regimes are graphed, but the paired outcomes (Regimes 1 vs. 2, Regimes 3 vs. 4, etc.) are so close that the difference cannot be discerned at this scale. This pattern has been observed for all other sets of parameter values examined as well.

Figure 7.1 Classification of Spectrum Governance Regimes

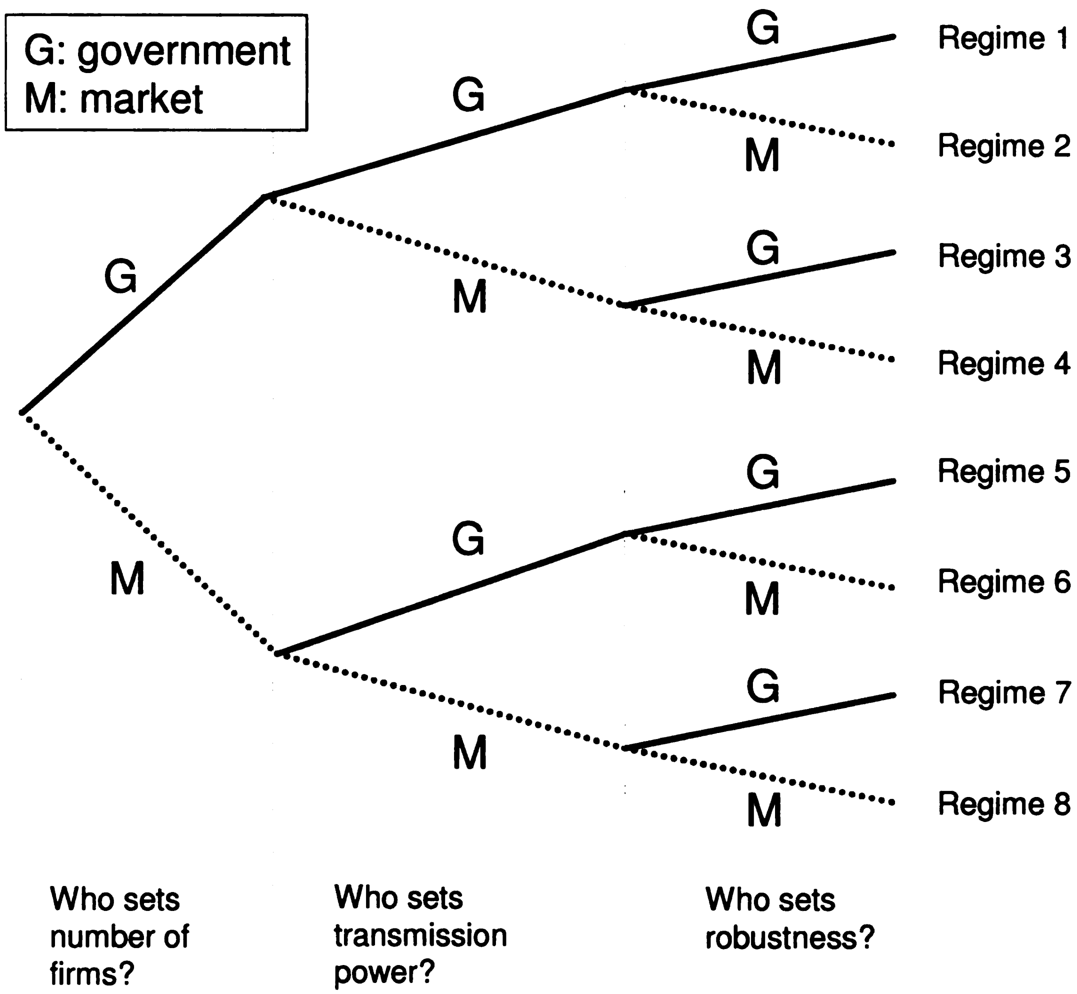
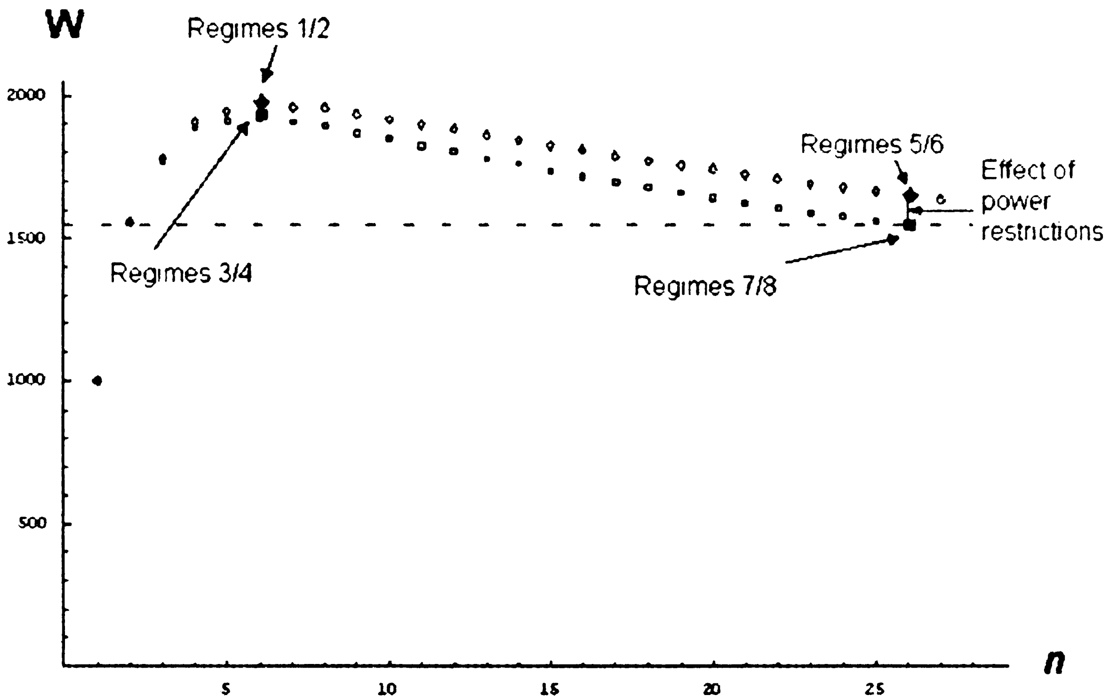


Figure 7.2 Welfare Optima under Eight Regimes (Two-way point-to-point network)



Although the firms' first order conditions for profit maximization are not exactly the same with or without a robustness requirement, simulation results show that profit-maximizing and welfare-maximizing levels of robustness are always very close. This is likely due to the fact that there is no spill-over effect in robustness. As implicit in the demand function, a firm's choice of robustness level, unlike transmission power, does not impact others' profit calculations and their choices of output, transmission power or robustness. This is because one firm's choice of robustness does not affect the utility experienced by other firms' customers and because each firm's Nash beliefs lead it to raise its price by an amount equal to the value of improved robustness to its customers. As a result, other firms' sales are not affected and its value of increase robustness at the margin is largely internalized by the firm.

Given the finding that welfare optima are very close under the paired regimes (Regimes 1 and 2, Regimes 3 and 4, etc.,) in the following we will just report the welfare optimum for the regime with robustness regulation (the odd numbered regimes).

(2) The effects of transmission power and entry regulations are interdependent

Comparing the welfare optima under different regimes can reveal the effects of individual policy instruments. Since transmission power is set at its optimum level in both Regimes 1 and 5, the difference in welfare between the welfare outcomes for these regimes is the effect of limiting entry. Similarly, the difference between Regimes 1 and 3 (as well as between Regimes 5 and 7) is the effect of transmission power regulations.

Obviously, the effect of transmission power regulations on welfare depends on the number of firms in the market. When the number of firms is set at 6, which is the optimum number for Regimes 1-4, the welfare difference is relatively small (1,927 for Regime 3 vs. 1,970.4 for Regime 1, or about 2.2%), and the difference increases with the number of firms. In an open commons regime, where the number of firms is larger, the potential welfare improvement from regulating transmission power is larger (1,547.4 for Regime 3 vs. 1,652.8 for Regime 1, or 6.4%. Depending on parameter values, this difference can be as much as 58%.) This makes intuitive sense. The negative externality associated with power increases with the number of firms; therefore the benefit of limiting that negative externality should be greater when there are more firms competing with each other.

(3) The potential loss associated with a "tragedy of the spectrum commons" is not great for most sets of parameter values

The notion of a "tragedy of the spectrum commons" hinges on the prediction that there will be excessive entry and an escalating power war resulting in excessive interference. If the predicted tragedy is about a power fight that negatively affects social welfare, the results seem to suggest that its potential magnitude is not as dramatic as the term "tragedy" implies.

When the government controls power in a spectrum commons (Regime 5), the difference between the welfare outcome and the global maximum (Regime 1), i.e. the effect of n, mostly has to do with redundant investment in fixed costs, an effect not unique to spectrum and the wireless industry. This examination of theoretical optima suggests that the potential loss associated with a "tragedy of the commons" is not great when government sets power.

Figure 7.3 shows how the welfare-maximizing values of receiver cost (c_R), which is a proxy for robustness, and transmitter cost (c_T), which proxies transmission power, vary with the number of firms when the government sets both c_R and c_T (Regime 1), and Figure 7.4 shows the relationship between the welfare-maximizing c_R and n when c_T is set by firms (Regime 3). The two patterns for c_R are very similar.

Figure 7.3 Welfare-Maximizing c_R and c_T as a function of n

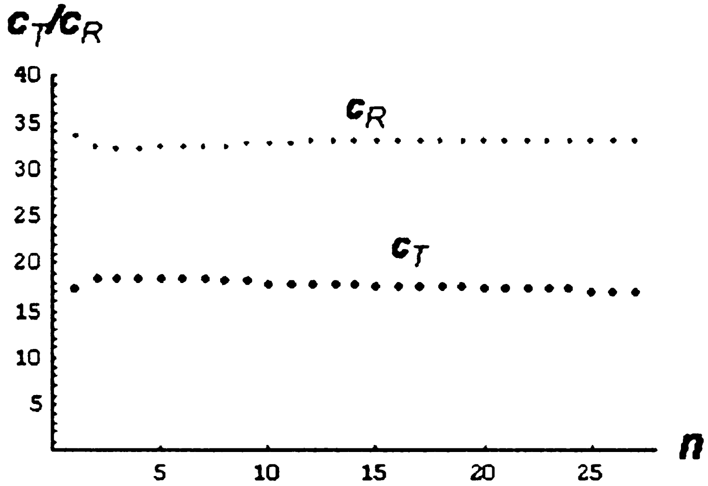


Figure 7.4 Welfare-Maximizing c_R and Profit-Maximizing c_T as a function of n

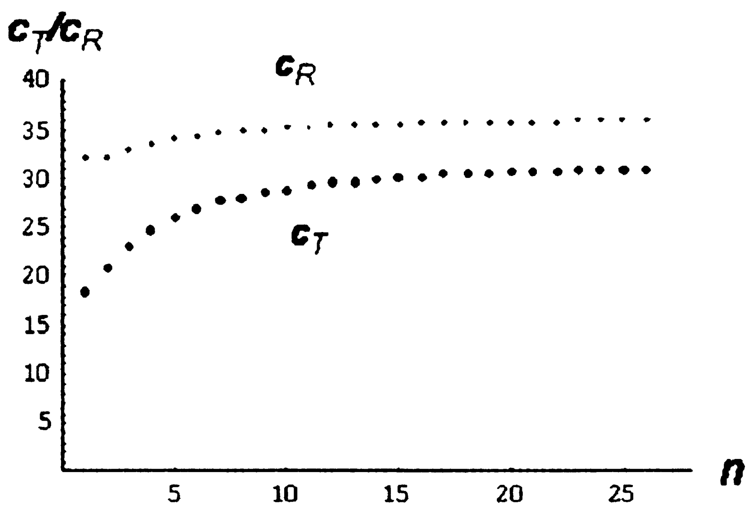


Figure 7.3 suggests that the optimal c_T should not vary much with the number of firms. However, when c_T is set by firms, Figure 7.4 shows there indeed will be a power war that escalates as the number of firms increases, which is what leads to the welfare difference between the two trend lines in Figure 7.2. When the number of firms is small, price is higher and the overall number of devices and the aggregate interference in the market is small. At this stage, interference is less of a problem, and by reducing c_R and price, the increase in the number of users and its positive welfare effect outweighs the cost of the increase in interference due to more devices. As the number of firms increases, countering interference becomes more important than increasing the number of users and the welfare-maximizing c_R increases as well. This is why in both Figures 7.3 and 7.4 the welfare-maximizing c_R first declines and then goes up again as the number of firms increases.

Similar patterns are observed with a cellular-type network (Figures 7.5, 7.6 and 7.7). Again, the welfare outcomes with and without robustness requirements are too close to distinguish, and the potential benefit of regulating transmission power is dependent on the number of firms in the market.

Whereas in the two-way point-to-point network model it is the benefits of increased communication range and throughput that motivate firms to increase power, in the cellular-type network the incentive to increase power comes from lower infrastructure costs and higher throughput. Although a smaller cell size can reduce interference, it requires higher base station density across the service area and leads to higher total fixed cost. Similar to Figures 7.3 and 7.4, Figures 7.6 and 7.7 show the welfare-maximizing c_T and c_R as functions of n for Regimes 1 and 3, respectively. The gradual increase in the optimal c_T in Regime 1 indicates that the welfare gain associated with smaller cell size and less interference is outweighed by the increase in fixed cost resulting from smaller cells. Under Regime 3, where firms set their own power, the incentive to use higher power to reduce fixed cost is even stronger when the number of competitors is larger, since competition reduces individual firms' revenues.

Figure 7.5 Welfare Optima for Eight Regimes (Cellular-Type Network)

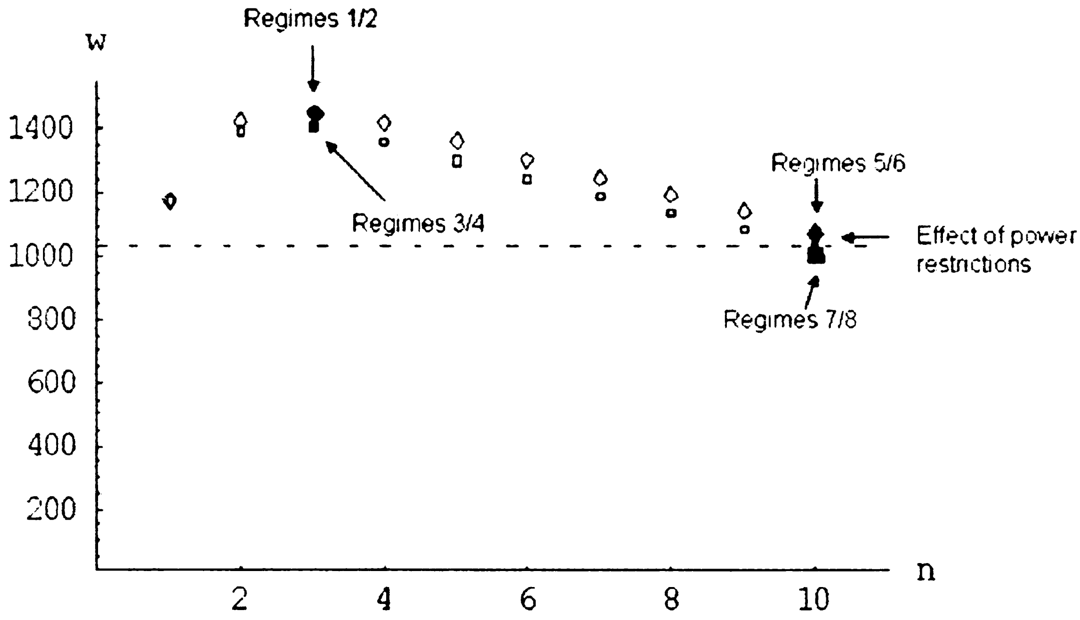


Figure 7.6 Welfare-Maximizing c_R and c_T as a function of n (Cellular-Type Network)

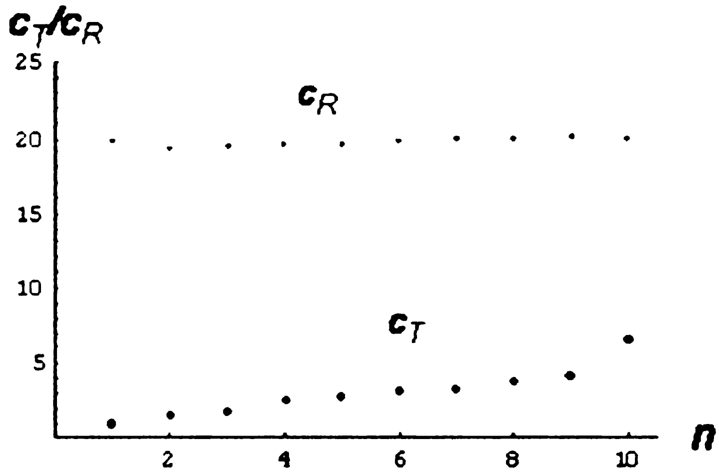
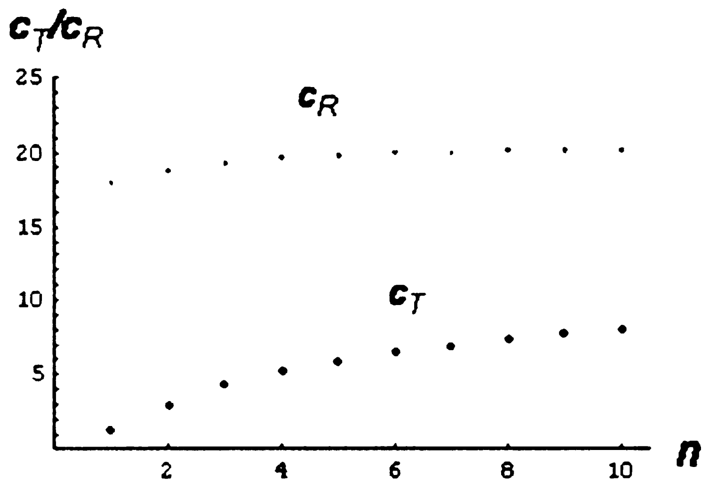


Figure 7.7 Welfare-Maximizing c_R and Profit-Maximizing c_T as a function of n (Cellular-Type Network)



Underlying the comparisons just presented is the assumption that no errors are made in setting government-controlled policy variables. The next subsection discusses the potential loss associated with errors in setting the policy instruments.

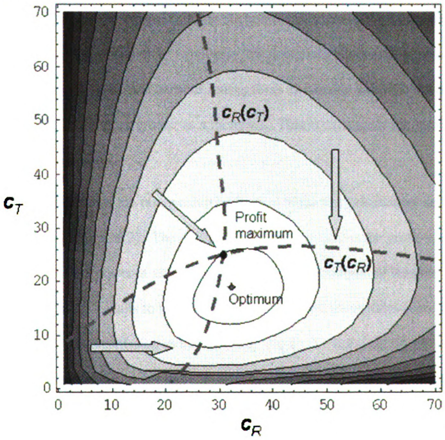
7.2.2 Effects of Poor Policy Choices

When set at levels that depart significantly from their optimum values, government control of all three policy instruments can have significant negative impacts on social welfare.

Figure 7.8 shows for the direct two-way P2P model under Regime 1 (all three variables set by government) how welfare varies with c_R and c_T when n=6. At low c_R levels (left edge of the contour map), loss associated with interference more than offsets the benefit of lower cost and more affordable devices. In this region increasing c_R improves both profits and social welfare. The dashed line in Figure 7.8 labeled $c_R(c_T)$ gives the profit-maximizing value of c_R for each value of c_T. Similarly, the dashed line in Figure 7.8 labeled $c_T(c_R)$ gives the profit-maximizing value of c_T for each value of c_R. Because robustness requirements only set a lower bound on robustness, in the region to the left of $c_R(c_T)$, firms can do better by setting robustness above the floor. Any c_R requirement in this region has no effect. The arrows pointing to $c_R(c_T)$ indicate this tendency. Only when the government-set c_R exceeds the profit-maximizing level of c_R are c_R requirements binding and firms are forced to invest more in robustness than they would in the absence of robustness requirements. However, welfare does not increase with robustness indefinitely. Beyond a certain level, the welfare increase associated with the reduced interference is outweighed by the loss associated with the users who are driven out of the market by a higher price, and welfare drops as a result.

Similarly, when c_T is set too low (lower edge of the contour map), society suffers from under-investment in transmission power because the reduction in utility associated with lower power and shorter transmission range is greater than the gain from reduced interference and lower cost for the transmitter unit. In the region below $c_T(c_R)$, the c_T limits are binding and firms can only produce devices with very low transmission power, which have little value to customers and firms' profits suffer too. In the lower part of this region, government can improve both welfare and firm profits by relaxing the power limit. However, when the power limit is relaxed beyond the welfare-maximizing level, firms will take advantage of it and produce devices that transmit at overly high power levels and reduce welfare. This is shown by the fact that $c_T(c_R)$ is located above the welfare optimum. When the c_T limit is set above $c_T(c_R)$, the c_T limit is also non-binding and firms will choose the profit-maximizing levels of c_R, a tendency indicated by the downward-pointing arrows.

Figure 7.8 Welfare as a Function of c_R and c_T for n =6 under Regime 1



Together, $c_T(c_R)$ and $c_R(c_T)$ divide the graph into four regions. In the lower right region both power and robustness restrictions are binding. On the other hand, since neither a power cap higher than the profit-maximizing c_T nor a robustness requirement lower than the profit-maximizing c_R is binding, any government requirements in the two upper regions will lead to equilibrium outcomes on $c_T(c_R)$ and any government requirements in the two left regions in the figure will lead to equilibrium outcomes on $c_R(c_T)$. Any combination of government requirements in the upper-left corner will lead to market equilibrium at the intersection of $c_T(c_R)$ and $c_R(c_T)$.

The difference between the maximum welfare and welfare at the profit-maximum is the potential gain from regulating c_R and c_T, and the difference between welfare at the profit-maximum and any point in the lower right region outside of the inner most contour is the potential harm from errors in setting the policy instruments. Similar patterns can be observed for all values of n. Obviously, the potential gain from regulating c_R and c_T is smaller than the potential harm of setting them incorrectly although the potential gain of regulating c_T becomes greater as n increases. This is essentially the same finding as seen in Subsection 7.2.1.

Figure 7.9 presents the relationship between welfare and government-set n and c_T when firms set c_R (Regime 2). The dashed line labeled as $c_T(n)$ is the profit-maximizing level of transmission power at any given n. Similar to the analysis of Regime 1, when government-set c_T falls to the right of $c_T(n)$, the power restrictions have no effect and firms will set transmission power on $c_T(n)$. Figure 7.9 suggests that the potential benefit of power restrictions is not large, but under-investment in transmission power due to incorrectly set c_T can significantly reduce welfare. When the predetermined number of firms is far from the optimum, welfare is also considerably lower.

The relationship between welfare and government-set n and c_R under Regime 3 when firms set c_T is shown in Figure 7.10. The dashed line labeled as $c_R(n)$ is the profit-maximizing level of robustness at any given n. When government-set c_R falls to the left of $c_R(n)$, the robustness requirements have no effect and firms will set robustness on $c_R(n)$. The danger of setting robustness overly high or setting n at extremely low values can also be significant.

Figure 7.9 Welfare as a Function of n and c_T under Regime 2

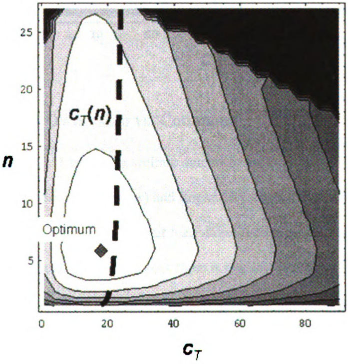
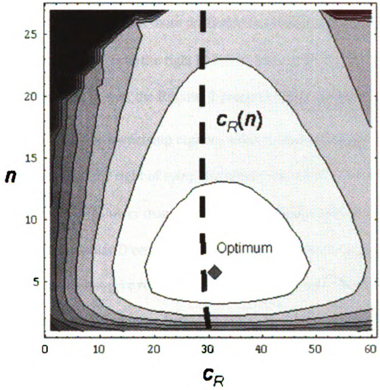


Figure 7.10 Welfare as a Function of n and c_R under Regime 3



7.3 Ownership vs. Commons

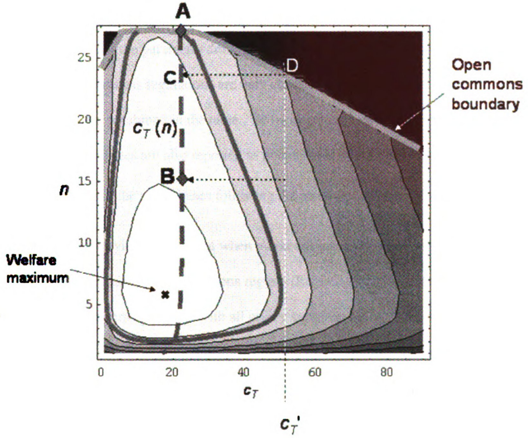
Figure 7.11 compares welfare outcomes for Regime 2 (ownership regime with no robustness requirements) and Regime 6 (open commons with no robustness requirements). The contour map shows welfare levels for government set n and c_T levels. Since the difference between them is that n is set by the government in the ownership regime while in the commons regime it is left for the market to decide, the open commons boundary is characterized by the set of zero-profit equilibria under the ownership regime.

In the absence of power restrictions and robustness requirements, for each n there is a profit-maximizing value of c_T, indicated by the dashed line labeled as $c_T(n)$, which tends to exceed the welfare-maximizing level of c_T. For example, if government sets n=15 and $c_T = c_T'$, firms will find it more profitable to produce devices with lower transmission power because c_T' is to the right of $c_T(n)$. Since a power limit does not prevent firms from lowering power, the Regime 2 property rights equilibrium will be at point B.

Same as under an ownership regime, when c_T under the open commons regime is set at c_T', which is to the right of $c_T(n)$, the power restriction is not binding as the profit-maximizing c_T is lower than c_T'. Firms will depart from c_T' and set power levels on $c_T(n)$, moving from point D on the open commons boundary to point C. This move will yield higher profits but give room to new entrants as point C is below the open commons boundary, indicating more firms can enter the market profitably. Consequently, the number of firms will keep increasing until it hits the open commons boundary again (moving from point C to point A). Similarly, for any c_T to the right of $c_T(n)$, the open commons equilibrium will be at point A. The welfare level at point A is marked as the thick welfare contour for comparison with the ownership regime.

Obviously, the welfare level at point B is greater than that at point A, indicating better performance under the ownership regime. It can be seen from the graph that except when n is very small, the equilibrium always falls within the thick welfare contour. In other words, given the same c_T restrictions, unless n under the ownership regime is set significantly below the optimal n, an ownership regime always performs better than an open commons regime. Moreover, given the same c_T on the left-hand side of the locus of profit-maximizing c_T'x, Figure 7.11 also suggests that the ownership regime tends to outperform the commons regime as long as n is not set too low.

Figure 7.11 Spectrum Ownership vs. Open Commons



7.4 Parameter Values and Sensitivity

This subsection examines the sensitivity of the welfare comparisons to variation in parameter values. The parameters will be examined one at a time, and except for the variable under discussion all the others will be held at the baseline case values.

Table 7.3 reports the results of the sensitivity analysis and provides definitions for the parameters varied for the direct two-way P2P network model. MW stands for maximum welfare with a subscript indicating the regime to which it applies. For example, $MW_{\text{Regimes}1/2}$ refers to the maximum welfare for Regimes 1 and 2. *n* indicates the number of firms at these welfare maxima. The results for the baseline case are italicized. The entries in the data (number of firms and welfare) cells corresponds to the parameter values listed under the parameter definition (in the same order). Since the outcomes with and without robustness regulations are very close, results for Regimes 1 and 2 (Regimes 3 and 4, etc.) are combined in the table. To facilitate comparison, the MW outcomes under various regimes are also reported as percentages of the global optimum welfare ($MW_{Regime1/2}$) in the parentheses following the absolute welfare values.

The results for varying *b* show that when market demand becomes very flat the welfare under an unconstrained open commons regime (Regime 8) can deviate significantly from that under an ownership regime with all policy variables set at their optimum (Regime 1). For example, at *b*=0.01 the unconstrained commons welfare is only about 42.2% of the global optimum. By comparing $MW_{Regime5/6}$ to the global optimum, we can see that the effect of entry restrictions is greater when the demand is flatter. Similarly, comparison of $MW_{Regime5/6}$ and $MW_{Regime7/8}$ shows the effect of power regulations, which is also stronger with a flatter demand.

Because it affects the number of firms an open entry market can support, *F* does seem to have some effect on the relative merits of the regimes in non-extreme ranges. When *F* becomes larger, welfare under Regime 6 as a percentage of the global optimum drops from 92.8% to 79.6%, indicating that open commons (even with power control) is less attractive relative to ownership when fixed costs are high.

A larger η means lower level of spillover signal power from neighboring systems in the spectral space. Obviously, a larger η will be associated with higher welfare outcomes and the band can support more firms. It is also not surprising to see that the difference between $MW_{Regime5/6}$ and the global optimum increases as η goes down, since a smaller η means more interference and the beneficial effect of limiting entry will be more pronounced. Similarly, comparing $MW_{Regime5/6}$ to $MW_{Regime7/8}$ while varying n shows the effect of power restriction is also bigger at smaller values of η.

Because k is a constant multiplier of the SIR term in the demand function, a larger k reduces the effect of interference on throughout and user utility and hence leads to greater welfare. Similar to the pattern described for η, a greater value for k is also associated with a smaller difference between $MW_{Regime5/6}$ and the global optimum. This means that the potential benefit of restricting entry diminishes with k. On the other hand, the differences between $MW_{Regime5/6}$ and $MW_{Regime7/8}$ are small so the effect of k on the effectiveness of power restrictions is not significant.

x reflects the relative effect of signal reach (which is assumed to be a function of power, or c_T) on utility. A larger value for x means that utility increases more rapidly with power. x's effect on the relative advantages of regimes and the benefits of regulations of entry and power is also unclear, as when we vary the value of x, the difference between $MW_{Regime5/6}$ and $MW_{Regime7/8}$ is very small.

On the other hand, the results suggest that increasing g, which means that utility increases more rapidly with throughput, leads to greater loss associated with open entry. However, the effect of g on the effectiveness of power restrictions is also not clear as the difference between $MW_{Regime5/6}$ and $MW_{Regime7/8}$ is small, too.

δ determines the relative effect of investment in receiver quality on robustness. When firms can more effectively improve robustness by investing in receiver units, welfare tends to increase and the effects of power and entry regulations on welfare are smaller. These results are fairly intuitive.

Lastly, z shows how effectively investment in cost for the transmitter unit can increase power. Comparing $MW_{Regime5/6}$ (or $MW_{Regime7/8}$) to the global optimum shows that when it is less costly to boost power (z is smaller), the relative welfare difference between and $MW_{Regime5/6}$ gets bigger, so does the difference between $MW_{Regime5/6}$ and $MW_{Regime7/8}$. These patterns suggest that entry and power restrictions are more desirable when firms can increase power at lower cost.

In summary, the major findings of the study are as follows: First, left to themselves, firms do have an incentive to produce devices transmitting at power levels significantly in excess of the welfare-maximizing level. This can be countered by setting power limits; however, in an unconstrained open access regime, the greatest potential improvement achievable by setting power limits alone is smaller than that from setting entry restrictions alone. The potential benefit of setting power limits is further reduced as the government-set number of firms approaches the optimum. Second, robustness regulations can do little to improve welfare but might have very negative impacts when set inappropriately.

These observations hold across the parameter ranges examined in the sensitivity analysis. Three factors have a particularly strong effect on the relative advantages of commons and open access regimes: the flatness of the demand curve, the level of inter-system interference (interference from neighboring systems in the spectral space) and the cost-effectiveness of investment in transmitters to increase power. Ceteris paribus, the difference between the welfare performance of an ownership regime with its government-set policy instruments set optimally and the corresponding open access regime increases the smaller is b. In addition, the welfare difference between an ownership regime with all policy instruments set at their optimal values by the government and the unconstrained open access regimes increases considerably (up to about 40%) as the level of inter-system interference goes up or as increasing transmission power becomes less costly.

Table 7.4 shows the result of sensitivity analysis for the cellular-type network model. The effects of b, η, k, δ, z and g on the welfare comparison of regimes are quite consistent with what was found for the two-way point-to-point network model.

Because higher frequency signals attenuate faster, at a wavelength (λ) of 1/800 m (2.4 GHz) path loss is much greater than that for the base case, where λ is 1/3 m (900 MHz). Therefore, welfare levels are significantly lower for $\lambda = 1/800$ m for all regimes, but the little variation in relative welfare levels under different regimes suggests this factor do not have much impact on the choice of regimes.

The finding that welfare increases with τ suggests the use of more sensitive antenna arrays at base stations has positive welfare impacts, although at some point this gain presumably will be outweighed by the higher cost of more sensitive antennas. Also relevant is the effect of t, which reflects the rate at which fixed cost increases with the use of more sensitive antenna arrays at base stations. Higher t means fixed cost increases at a faster rate, and not surprisingly, we find that welfare is declining in *t*. However, neither τ nor *t* seem to have significant impact on the relative merits of the regimes.

s3, which is negative is fixed cost is decreasing in cell size (this would be the case if traffic volume is low) and positive when fixed cost increases with cell size (this would be the case if traffic volume is high), does not seem to have much impact on either welfare magnitudes or the relative merits of the regimes, although the difference between $MW_{Regime1/2}$ and $MW_{Regime5/6}$ increases moderately with *s3*, suggesting that it may be desirable to restrict entry when fixed cost increases with cell size. *s2* is a scaling factor for the term describing the effect of cell size on fixed cost and its impact depends on the value of *s3*. In general, increasing *s2* increases fixed cost and the gap between $MW_{Regime1/2}$ and $MW_{Regime5/6}$, but the change is rather small. Comparing $MW_{Regime5/6}$ to $MW_{Regime7/8}$, we find little evidence suggesting a significant impact of *s2* and *s3* on the effectiveness of power restrictions.

Table 7.3 Result of Sensitivity Analysis (two-way point-to-point type network)

	b: the slope of the demand curve (b = 0.01, 0.1, *1*, 10)	F: fixed cost (F=1, *10*, 100)	η: scaling factor of the interference effect of neighboring systems in the spectral space on SIR (η=0.1, *1*, 10)	k: a constant multiplier of aggregate interference, affecting the effect of SIR on throughput (k=0.3, 0.6, 0.9)
n Regime1/2	4 4 *6* 4	8 *6* 4	2 *6* 32	6 *6* 6
MW Regime1/2	2763.7 2714.7 *1970.4* 639.1	2027.7 *1970.4* 1551.5	1186.6 *1970.4* 4570.2	1219.1 *1970.4* 2541.1
n Regime3/4	4 4 *6* 4	6 *6* 4	2 *6* 30	5 *6* 6
MW Regime3/4	2659.5 (96.2%) 2685.5 (98.9%) *1926.9 (97.8%)* 636.4 (99.6%)	1980.9 (97.7%) *1926.9 (97.8%)* 1527.9 (98.5%)	1170.5 (98.6%) *1926.9 (97.8%)* 4497.5 (98.4%)	1187.9 (97.4%) *1926.9 (97.8%)* 2493.8 (98.1%)
n Regime5/6	40 41 *26* 4	26 *26* 8	18 *26* 43	19 *26* 31
MW Regime5/6	1323.6 (47.9%) 1708.3 (3.6%) *1652.8* (85.8%) 639.1 (100%)	1886.7 (93.0%) *1652.8* (85.8%) 1235.7 (79.6%)	773.0 (65.1%) *1652.8* (85.8%) 4533.9 (99.2%)	985.4 (80.8%) *1652.8* (85.8%) 2179.1 (85.8%)
n Regime7/8	40 41 26 4	26 *26* 8	18 *26* 43	19 *26* 31
MW Regime7/8	1165.1 (42.2%) 1511.8 (55.7%) *1547.4* (78.5%) 636.4 (99.6%)	1781.4 (87.9%) *1547.4* (78.5%) 1177.4 (75.9%)	697.7 (58.8%) *1547.4* (78.5%) 4443.6 (97.2%)	912.1 (74.8%) *1547.4* (78.5%) 2060.9 (81.1%)

Table 7-3 Result of Sensitivity Analysis (two-way point-to-point type network) (Continued)

	x: exponent determining the relative effect of signal reach on utility (x=0.25, *0.5*, 0.75)	*g*: exponent determining the relative effect of throughput on utility (g=*0.5*, 1)	δ: exponent determining the relative effect of receiver cost for access device on robustness (δ =*0.3*, 0.6, 0.9)	*z*: exponent determining the relative effect of transmitter cost for access device on transmission power (z=*0.3*, 0.6, 0.9)
n Regime1/2	6 *6* 6	*6* 6	4 6 *6*	*6* 6 6
MW Regime1/2	1326.5 *1970.4* 3533.8	*1970.4* 1458.4	550.2 975.3 *1970.4*	*1970.4* 7868.3 101171
n Regime3/4	6 *6* 6	*6* 5	4 5 *6*	*6* 6 4
MW Regime3/4	1279.1 (96.4%) *1926.9* (*97.8%*) 3478.1 (98.4%)	*1926.9* (*97.8%*) 1410.4 (96.7%)	543.4 (98.8%) 953.9 (97.8%) *1926.9* (*97.8%*)	*1926.9* (*97.8%*) 7467.1 (94.9%) 93227.7 (92.1%)
n Regime5/6	21 *26* 36	*26* 20	12 17 *26*	*26* 50 159
MW Regime5/6	1122.4 (84.6%) *1652.8* (85.8%) 2925.5 (82.8%)	*1652.8* (*85.8%*) 1324.6 (90.8%)	444.0 (80.7%) 782.5 (80.2%) *1652.8* (85.8%)	*1652.8* (*85.8%*) 6495.3 (82.6%) 77887.1(77.0%)
n Regime7/8	21 *26* 36	*26* 20	12 17 *26*	*26* 50 159
MW Regime7/8	1024.9 (77.3%) *1547.4* (78.5%) 2764.3 (78.2%)	*1547.4* (78.5%) 1034.7 (70.9%)	412.3 (74.9%) 720.6 (73.9%) *1547.4* (78.5%)	*1547.4* (78.5%) 5395.9 (68.6%) 52756.8 (52.1%)

Table 7.4 Result of Sensitivity Analysis (Cellular-Type network)

	s2: scaling factor for the effect of *s3* on fixed cosst (*s2=1*, 10, 100)	*s3*: exponent determining the relative effect of transmission power on fixed cost at given τ (*s3= -0.3*, 0.1, 0.5)	τ: ratio of downlink to uplink power (τ=1, 2, 3)	*t*: exponent determining the relative effect of τ on fixed cost (*t=0.2*, 0.5)	λ: wavelength (λ=*1/6*, 1/800)
$n_{Regime1/2}$	*3* 3 2	*3* 3 3	2 *3* 3	*3* 3	*3* 3
$MW_{Regime1/2}$	*1456.4* 1432.3 1250.6	*1456.4* 1454.8 1453.2	1029.8 *1456.4* 1625.5	*1456.4* 1416.0	*1456.4* 881.3
$n_{Regime3/4}$	*3* 2 2	*3* 3 3	2 *3* -	*3* 3	*3* 2
$MW_{Regime3/4}$	*1405.8* *(96.5%)* 1383.5 (96.6%) 1223.4 (97.8%)	*1405.8* *(96.5%)* 1404.6 (96.5%) 1402.9 (96.5%)	1014.6 (98.5%) *1405.8* *(96.5%)* - ()	*1405.8* *(96.5%)* 1371.6 (96.9%)	*1405.8* *(96.5%)* 868.5 (98.5%)
$n_{Regime5/6}$	*10* 9 5	*10* 10 10	5 *10* 13	*10* 9	*10* 8
$MW_{Regime5/6}$	*1066.9* *(73.3%)* 1056.6 (73.8%) 945.0 (75.6%)	*1066.9* *(73.3%)* 1054.6 (72.5%) 1025.3 (70.5%)	786.4 (76.4%) *1066.9* *(73.3%)* 1189.3 (73.2%)	*1066.9* *(73.3%)* 1059.4 (74.8%)	*1066.9* *(73.3%)* 616.9 (70.7%)
$n_{Regime7/8}$	*10* 9 5	*10* 10 10	5 *10* 13	*10* 9	*10* 8
$MW_{Regime7/8}$	*1036.0* *(71.1%)* 1020.2 (71.2%) 894.8 (71.5%)	*1036.0* *(71.1%)* 1031.0 (70.9%) 1023.1 (70.4%)	766.7 (74.5%) *1036.0* *(71.1%)* 1158.4 (71.3%)	*1036.0* *(71.1%)* 1020.2 (72.0%)	*1036.0* *(71.1%)* 599.2 (68.0%)

Table 7-4 Result of Sensitivity Analysis (Cellular-Type network) (Continued)

	g: exponent determining the relative effect of throughput on utility (g=*0.5*, 1)	δ: exponent determining the relative effect of receiver cost for access device on robustness (δ =*0.3*, 0.6, 0.9)	z: exponent determining the relative effect of transmitter cost for access device on transmission power (z=*0.3*, 0.6, 0.9)	η: scaling factor of the interference effect of neighboring systems in the spectral space on SIR (η=0.1, *1*, 10)	k: a constant multiplier of aggregate interference, affecting the effect of SIR on throughput (k=0.3, 0.6, 0.9)
$n_{Regime1/2}$	*3* 3	2 2 *3*	*3* 3 3	2 *3* 8	2 *3* 3
$MW_{Regime1/2}$	*1456.4* 1456.0	465.2 795.4 *1456.4*	*1456.4* 1491.1 1506.2	949.7 *1456.4* 2363.7	923.9 *1456.4* 1811.5
$n_{Regime3/4}$	*3* 3	2 2 *3*	*3* 2 2	2 *3* 8	2 *3* 2
$MW_{Regime3/4}$	*1405.8 (96.5%)* 1405.8 (96.5%)	456.4 (98.1%) 795.0 (100%) *1405.8 (96.5%)*	*1405.8 (96.5%)* 1373.2 (92.1%) 1319.4 (87.6%)	909.9 (95.8%) *1405.8 (96.5%)* 2341.6 (99.1%)	902.3 (97.7%) *1405.8 (96.5%)* 1758.9 (97.1%)
$n_{Regime5/6}$	*10* 10	6 7 *10*	*10* 15 16	7 *10* 15	8 *10* 11
$MW_{Regime5/6}$	*1066.9* (73.3%) 1060.0 (72.8%)	287.0 (61.7%) 557.0 (70.0%) *1066.9* (73.3%)	*1066.9* (73.3%) 978.0 (65.6%) 1132.9 (75.2%)	600.7 (63.3%) *1066.9* (73.3%) 2190.0 (92.6%)	650.4 (70.4%) *1066.9* (73.3%) 1360.3 (75.1%)
$n_{Regime7/8}$	*10* 10	6 7 *10*	*10* 15 16	7 *10* 15	8 *10* 11
$MW_{Regime7/8}$	*1036.0 (71.1%)* 1036.0 (71.2%)	280.9 (60.4%) 561.1 (70.5%) *1036.0 (71.1%)*	*1036.0 (71.1%)* 907.7 (60.9%) 731.2 (48.5%)	569.6 (60.0%) *1036.0 (71.1%)* 2167.3 (91.7%)	620.8 (67.2%) *1036.0 (71.1%)* 1343.9 (74.2%)

Chapter 8 Conclusions

8.1 Summary of the Dissertation

Up to this point, most studies in this area have taken a top-down approach and sought to predict the relative merits of the regimes based on broad, general assumptions. This study takes a different approach and aims at identifying key policy instruments of spectrum governance regimes and examining how these policy instruments affect welfare outcomes under different regimes.

The present study starts out by summarizing the major proposals for alternative spectrum governance regimes; this leads to identification of three key policy instruments: entry restrictions, transmission power controls, and robustness requirements. A typical property rights regime is characterized by government control over both entry conditions and transmission power, while the entry condition in a commons regime is determined by the market instead. The variants of regimes with robustness requirements are also included for studying of the effect of robustness requirements.

The study also looks at the engineering aspect of spectrum management, exploring the relationships between the engineering properties of wireless communication and the policy instruments. Based on an examination of these relationships, an economic model of a market for a wireless service is constructed, which serves as a framework for tying together policy instruments and their impact on firms' profit-maximizing actions as well as welfare outcomes.

Analysis of the welfare outcomes gives the following findings. First, government regulation on robustness is undesirable. Second, the potential benefit of power restrictions increases with the number of firms in the market. Next, when set incorrectly, all three policy instruments can cause significant welfare loss. Moreover, comparison of a prototype property rights regime and a prototype commons regime suggests, given the same power restrictions, that the property rights regime tends to outperform the commons regime as long as the number of firms is not set significantly below the optimum number, which is often a small fraction of the number that can be supported with an open commons. These observations on the effect of fundamental policy instruments and the theoretical framework are the major conclusions of this study.

8.2 Future Research

This study is the first of its type. As an explorative study, it employs some simplifying assumptions to help keep the analysis tractable. Some of these assumptions, however, put limits on the generality of the findings. Specifically, the services modeled in the study are homogeneous, and the equilibria examined are outcomes of one-shot games among firms with identical cost structures. These assumptions rule out the possibility of investigating a market in which spectrum blocks can be dynamically reallocated to other services and firms can trade their blocks as they see fit. Such a possibility, however, is the major selling point of the spectrum property rights proposal; therefore it is desirable to relax these limiting assumptions.

There are two approaches to tackling the problem of non-identical firms and heterogeneous services. First, as commonly seen in economic and engineering studies, we can start with a two-firm, two-service model, which is a common compromise between tractability and generality. For such simplified setting, it is also possible to extend the model to a two-period game, which can be used to examine dynamic aspects of market development. Alternatively, with more advanced analytical tools, e.g. multiobjectivity optimization techniques, the optimization procedures can be less time-consuming and the computed results can be more accurate. The major difficulty of this approach is that it is very mathematically involved.

Another direction for extending the study is to examine how network effects and scale economies affect the findings. Network effects tends to increase utility, and scale economies tend to reduce costs as the number of users increases. Both of these factors contribute to firms' incentive to expand output; therefore studying their impacts on firms' output decisions in a dynamic setting can further our understanding of optimal policy choices for spectrum governance.

Appendix I Implementing Calculations for Equilibria

Direct Two-way P2P Network

Regime 1

1. Plug the chosen parameter values into the profit function
2. Derive the first order condition with respect to q_i
3. Choose a region of feasible combinations of c_T and c_R where the equilibrium q^*, c_T and c_R make economic sense ($q^*>2$ so that communication is possible between users; $c_T>1$ and $c_R>1$)
4. Choose a scanning resolution, which determines the number of equilibrium points calculated within the feasible (c_T, c_R) region.
5. Apply symmetry conditions so that all firms' output, transmission power and robustness levels are the same
6. For n starting from one, perform the following steps:
    i. With the scanning resolution chosen in Step 4, for each (c_T, c_R) point in the region of (c_T, c_R) chosen in Step 3, solve the first order condition derived in Step 2 for equilibrium q^*
    ii. Derive equilibrium price and profit at each (c_T, c_R) point by plugging q^*, c_T and c_R back to the demand and profit functions
    iii. Calculate equilibrium total output Q^* at each (c_T, c_R) point

iv. Derive equilibrium welfare at each (c_T, c_R) point using Equation (6.8) and Q^*, q^*, c_T and c_R

v. If the maximum equilibrium profit is positive,[10] increase n by one and repeat these five steps

For all the procedures described in this section, some pilot simulations are needed to ensure all feasible combinations of (c_T, c_R) are covered.

Regime 2

1. Plug the chosen parameter values into the profit function
2. Derive the first order conditions with respect to q_i and c_{Ri}
3. Choose a region of feasible range of c_T where the equilibrium q^* >2 and c_R^* >1
4. Choose a scanning resolution, which determines the number of equilibrium points calculated within the feasible c_T range.
5. Apply symmetry conditions so that all firms' output, transmission power and robustness levels are the same
6. For n starting from one, perform the following steps:

    i. Scan the chosen region of c_T. At each c_T point, solve the first order conditions derived in Step 2 for equilibrium q^* and c_R^*

    ii. Derive equilibrium price and profit at each c_T point by plugging q^*, c_T and c_R^* back to the demand and profit functions

[10] Since there can be numerous feasible combinations of (c_T, c_R), there will be multiple equilibria under Regime 1.

iii. Calculate equilibrium total output Q^* at each c_T point

iv. Derive equilibrium welfare at each c_T point using Equation (6.8) and Q^*, q^*, c_T and c_R^*

v. If the maximum equilibrium profit is positive, increase n by one and repeat these five steps

Procedures for calculating equilibrium outcomes under Regime 3 is the same except that the roles of c_T and c_R are exchanged.

Regime 4

1. Plug chosen parameter values into the profit function

2. Derive the first order condition with respect to q_i, c_{Ti} and c_{Ri}

3. Apply symmetry conditions so that all firms' output, transmission power and robustness levels are the same

4. For n starting from one, perform the following steps:

   i. Solve the first order conditions derived in Step 2 for equilibrium q^*, c_T^* and c_R^*

   ii. Derive equilibrium price and profit by plugging q^*, c_T^* and c_R^* back to the demand and profit functions

   iii. Calculate equilibrium total output Q^*

   iv. Derive equilibrium welfare using Equation (6.8) and Q^*, q^*, c_T^* and c_R^*

v. If the equilibrium profit is positive, increase n by one and repeat these five steps

In this regime, three equilibrium conditions are available to solve for equilbrium value of three variables; therefore for each n there is only one unique equilibrium.

Regimes 5-8

The difference between Regimes 1 and 5 is that n is determined by market forces in Regime 5. This means that the equilibria in Regime 5 are the set of zero-profit equilibria under Regime 1. Therefore the equilibria under Regime 5 can be obtained by collecting the zero-profit equilibria under Regime 1.

Similarly, equilibria under Regime 6/7/8 can be obtained by collecting zero-profit equilibria under Regime 2/3/4 because Regime 6/7/8 differs from Regime 2/3/4 only in that it has to meet the additional condition of zero-profit.

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