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Path and speed of spectrum management reform under uncertain costs and benefits

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Abstract

The unsolved question in spectrum management is no longer if a reform is necessary to enable higher market participation but the optimal path and speed of reform. We offer an expression to determine when to choose a gradual or big bang reform depending on current and expected technology and an expression to determine whether to wait or not for new technology. Gradual is better if the technological advance coefficient is high, the reversibility of the reforms is costly, the duration of the second reform is long, the probability of an outcome lower than expected is considerable or the reforms are not too complementary.

Key words: Radio-electric spectrum, efficiency, externalities, technological change.

JEL Classification: O33, D61, D62.

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1. Introduction

Since the launching of the first service using radio spectrum in the late 19th century, wireless telegraphy, we have witnessed the emergence of innumerable new services competing for the access to a portion of the limited radio spectrum resources. Examples of services using the spectrum are radio, television, voice and video telephony, internet, national security and defense, whether forecasting, emergency assistance, guidance for navigation of all kinds of means of transport by air, ground and sea, the exploration of the cosmos and many others. Digital services, many of which use the spectrum, have an increasing impact in the economy. For example, they reduce information and coordination costs in the whole economy - activities became cheaper, faster and more convenient-, ease transactions and increase productivity, World Bank (2016).

The allocation of spectrum to services has been planned by governmental agencies practically since the early days of radio communications. Governmental planning has been the response to the complex definition of property rights, high enforcement and transaction costs linked to the existence of harmful electromagnetic interferences, services that are pure public goods, externalities associated to services, and economies of scale when spectrum allocation is harmonized.

In the last decades, improved technology enabling services to share the same portion of spectrum, a better understanding of interference solving and of spectrum markets and especially the extraordinary growth in the demand for spectrum, have put deep pressure to traditional allocation methods. As a result, the reform of spectrum has become a salient policy issue and multiple new approaches to spectrum management have emerged. Examples of spectrum management reforms are the use of auctions to grant licenses, the authorization of secondary market transactions -transfer, leasing, mutualisation of usage rights- , the use of administered incentive pricing, spectrum sharing techniques and the definition of licenses in terms of acceptable interference parameters.

Some remarkably anticipated very early, the need for more efficient approaches to spectrum management, Coase (1959, 1960), Levin (1970). Many more followed these claims supporting the exchange of usage rights in the market and market participation for a better allocation of radio spectrum, Hazlett (1998, 2003), Kwerel and Williams (2002), Baumol and Robyn (2006). Others proposed collective use of spectrum as an alternative solution to scarcity, Noam (1998), Benkler (2002), Werbach (2004). More recently, a number of authors pointed out the importance of incorporating the definition of acceptable interference in spectrum licenses to reduce transaction costs, Webb (2009), ITU (2009), Kwerel and Williams (2010) and Cave and Web (2012).

Spectrum management reform should not be regarded solely as a conflict where we only have two options; either choosing governmental planning or market liberalization. An important component of inefficiency may account for the spectrum allocation process but yet a significant source stems from the intrinsic nature of radio-spectrum. Spectrum physical features together with the attributes of services provided using the spectrum produce market failure. The response should be a combination of a sound regulatory framework, the internalization of technological progress in regulation to overcome market failure, and market participation in spectrum management in order to increase efficiency of spectrum allocation.

Electromagnetic interference, a feature of spectrum usage, is a negative externality that makes the definition of property rights difficult, the respect for these rights hard to enforce and the cost of inter-service and also intra-service spectrum transactions uncertain. Not only the costs but also the benefits of a spectrum management reform are uncertain due to, inter alia, of the existence of hard to measure external value linked to services. García and Valiño (2013), Bazelon and McHenery (2013), Alden (2012), Prasad (2014) and Cave et al (2016) contributed to define methodologies for estimating the value of spectrum and the externalities linked to services. A more general framework to take account of externalities but yet highly applicable to the topic can be found in Cornes and Sandler (1996).

The unsolved question in spectrum management is no longer if a reform enabling higher market participation is necessary or not but the path and speed of reform with current and expected technology evolution, and market and regulatory structure. This paper aims to contribute to answer this question by offering a model to ascertain the optimal speed of spectrum management reform. We first study uncertainty sources to unravel causes and the potential policy responses since uncertainty of benefits and costs of reform is a key element of the porblem. We continue developing the analogy between the case of spectrum reform and the reform of economies in transition commenced by Minervini (2014). We depart from the model in Dewatripont and Roland (1995) adding the idiosyncrasies of spectrum management, namely the fast evolution of digital technologies using the spectrum, and the existence of market failure in the provision of wireless services. We also gained inside from the literature on investment under uncertain benefits e.g. Dixit (1992), Dixit and Pindyck (1994), and the literature about uncertain costs of reform, Pindyck (1993).

This paper is structured as follows section 2 analyzes the different types of reform and the available policy options, section 3 presents sources of uncertainty, section 4 offers a discussion on the optimal path and sequencing of spectrum management reform and section 5 concludes.

2. Types of spectrum management reform

We define a spectrum management reform as the regulatory change intended to enable increased efficiency of spectrum usage so that total welfare is maximized. Reforms can be categorized by the type of efficiency gain that they are intended to produce. Productive efficiency ensure that a service is provided with no more than the spectrum required, allocative efficiency that the assortment of services using the spectrum maximizes social welfare and dynamic efficiency that the compound of services can be changed when a new higher social welfare allocation emerges.

Reforms take account of regulatory and technology innovation. An innovative regulatory change may consist of a new approach for defining property rights that reduces inter service transaction costs and/or the costs to enforce respect to spectrum usage rights, innovative ways to enable intra service transactions or the internalization of technology advance into spectrum usage rights. Specific policy recommendations exemplifying spectrum management reform types can be found in García-Zaballos and Foditsch (2015).

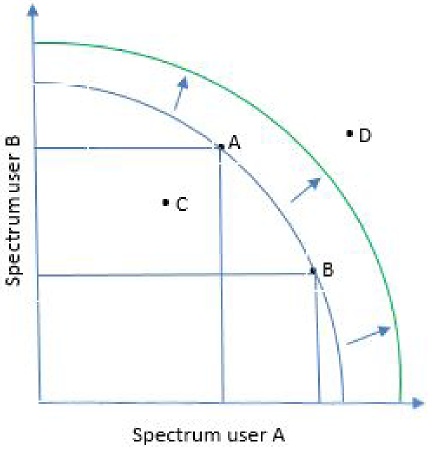
We define two types of technological progress of spectrum usage. A technology advancement improving the delivery of services happens when a new technology allows either using less amount of spectrum to provide a service, or it improves service features and capacity or both at the same time. For example, the second generation of mobile telephony allowed peak speed data rates of 9.6 kbps whereas fourth generation, the so called LTE, allows peak data rates of 1 Gbit/s. Another example is the migration from analogue to digital television. Digital television technologies can provide a minimum of four times more television channels than analogue using the same amount of spectrum. However, new technology such as this, does not improve the allocation of spectrum to services.

A technology advancement improving the allocation of spectrum arises when a new technology enables for a better allocation of spectrum. Better allocations may be obtained from reducing inter service and intra service transaction costs, from allowing the usage of the same portion of spectrum by several services or from reducing the costs to enforce respect to spectrum usage rights. Carrying out spectrum inventories that identify spectrum supply and demand may help to figure out the expected return of a reform. Next section identifies the different types of spectrum management reform and some policy options to implement them.

2.1 Reforms achieving greater productive efficiency

Productive efficiency of a given allocation of spectrum to services is achieved when a firm delivering a service cannot employ an additional unit of spectrum to increase production without reducing the production of another firm delivering the same service. When this condition is met the service is delivered at the lowest average total cost, and it uses the minimum possible amount of spectrum. In other words, the use of a portion of spectrum is productively efficient if service delivery is at the production possibility frontier. Figure 2.1 shows two firms A and B using a certain amount of spectrum to provide the same service. Points A, B are productively efficient, point C is inefficient and point D is not possible

Figure 2.7 Production possibility frontier of spectrum use with technology advancement



Source: Authors

with current technology. The figure also depicts the effect of applying a new technology to the production of a service. A new technology improving productive efficiency would move right the productive possibility frontier curve.

Auctions of spectrum rights of use and the authorization of secondary market transactions are spectrum reforms intended to grant spectrum rights to those that value the spectrum the most and can deliver services using the minimum possible amount of spectrum. In figure 2.1, point C is not productively efficient. Auctions and secondary market transactions may move C closer to the production possibility frontier.

One way of achieving higher productive efficiency of a new allocation of spectrum is to auction the rights of use. If licenses have already been granted, the authorization of secondary market transactions may help to improve the initial distribution of spectrum to firms. Examples of secondary market transactions are the possibility to transfer or leasing the spectrum rights of use to a different user providing the same service or the mutualisation of spectrum rights. Mutualisation consists of sharing all or part of the spectrum license among two or more firms providing the same service in the same or in different spectrum bands.

As we can see in figure 2.1, the production possibility frontier curve shifts right if a new technology enables to use less spectrum or it improves service features. In this case, productive efficiency gains can be achieved immediately if spectrum licenses allow spectrum users to change technology without prior administrative authorization. For efficiency gains to be obtained technology change must not cause harmful interference to spectrum users in the same or adjacent bands. An example of an authorization of technology change is the so called spectrum re-farming authorizing the migration of spectrum use to more advanced generation of mobile technologies. If technology change is not allowed and there is technological change, points A and B in figure 2.1 that before the new technology were efficient would be situated below the new production possibility frontier.

2.2 Reforms achieving greater allocative efficiency

Allocative efficiency is achieved when the distribution of services into spectrum portions is optimal so that social welfare is maximized. Optimality includes not only the private value of spectrum, - the willingness to pay of the firm using the spectrum -, but also its social value -externalities linked to the delivery of services-. Allocative efficiency is achieved when the marginal benefit of spectrum use equals the marginal cost of service delivery for all applications using the spectrum.

Achievement of productive efficiency does not preclude the attainment of allocative efficiency. Let's consider a service A using the spectrum with lower value for society than service B. Service A enjoys the allocation of a higher amount of spectrum than B. The introduction of a productively efficient reform in both, A and B, may increase total welfare less than changing the allocation of spectrum in order to grant more spectrum to the service A with higher social value. Table 2.1 shows a spectrum reform increasing productive efficiency in A and B. Table 2.2 represents a reform changing the allocation of spectrum to increase social welfare. As it can be observed total welfare is higher in reform 2 than in reform 1. It is important to note that for the calculations in table 2.2 we have considered diminishing returns to the amount of spectrum allocated to a service. This is because social value per unit of spectrum allocated to a service decreases when the amount of spectrum allocated to this service increases.

Table 2.1: Productive efficiency reform

Service	Units of spectrum allocated	Social value per unit of spectrum	Productive efficiency (Before reform)	Productive efficiency (After reform)	Total Welfare
A	10	1	75%	90%	9
B	2	5	75%	90%	9
A+B	12	1.664 (Avg)	75% (Avg)	90% (Avg)	18

Source: Authors

Table 2.2: Change of allocation reform

Service	Units of spectrum allocated	Social value per unit of spectrum	Productive efficiency	Total Welfare
A	6	2	75%	9
B	6	4	75%	18
A+B	12	3 (Avg)	75% (Avg)	27

Source: Authors

Examples of reforms increasing allocative efficiency are the use of administered incentive pricing, incentive auctions and spectrum sharing licenses. Administered incentive pricing[1] (AIP) consists of charging a fee for the use of spectrum which is related to the opportunity cost of using this portion of spectrum, Smith-Nera (1996) and Cave, Doyle and Webb (2007). Different portions have distinct values, so using AIP requires calculating the opportunity cost of using each frequency band. The purpose of AIP is making license owners to return the spectrum if they are using a band inefficiently. The fee should take account of the costs borne by another services not using the band. Costs may come from using the service with means different to spectrum, or with a less valuable spectrum band. AIP can be a good measure to increase allocative efficiency when it is possible to calculate spectrum value, both private and social. However, a state agency may lack the monetary measure of costs and profits of spectrum use because it does not have all the relevant information regarding consumer preferences and spectrum users' willingness to pay.

Incentive auctions[2] consists of two related auctions, a forward auction where it is determined a firm's willingness to pay to access the spectrum and a reverse auction which establish the price for which the firm using the spectrum is willing to sell it. Prior to the auction, it is necessary to design a frequency repacking process analyzing the potential transaction costs of spectrum reallocation in order to reduce the uncertainty of the process. Incentive auctions enable the change of use of spectrum, thus increasing not only allocative efficiency but also productive efficiency. The allocation change is valued by the market instead of administratively determined, so reducing the possibility to cross-subsidize one of the services involved in the transaction. An example of an incentive auction design can be found in FCC (2012).

The term spectrum sharing encompasses a set of different spectrum management concepts. It may refer to the collective use of spectrum, the dynamic spectrum management, or the underlay spectrum management. Definitions can be found in RSPG (2011). The collective use of spectrum is the use of spectrum without license under a set of well-defined set of technical conditions. Spectrum user can access the spectrum provided that they use devices in compliance with the conditions previously defined. Collective use does not increase allocative efficiency since it can be used neither to migrate to a more efficient allocation of spectrum nor to allow the delivery of several services in the same portion of spectrum. Collective use is a way of delivering services that doesn't require the grant of rights of use. It is normally employed for allocating spectrum to short-range devices such as Wi-Fi or RFID applications.

Spectrum underlay also known as spread spectrum technologies consist of the emission of very low spectral power density signals that can coexist with other spectrum uses in the same frequency, with the effect of slightly increasing the noise floor -electromagnetic interference- to incumbent spectrum users. Spectrum underlay is a way to increase allocative efficiency in spectrum management since it allows the use of the same portion of spectrum by different services and it also enables future changes of use.

Dynamic spectrum management includes both, regulatory instruments and technical approaches. It is intended to allow using a portion of spectrum by an entrant and an incumbent spectrum user taking advantage of the fact that the incumbent is not using a frequency in a particular geographical area or time slot. Examples of technical approaches are cognitive radio, sensing of frequencies being used, geo-location beacons or databases of spectrum usage. A regulatory instrument enabling dynamic use of spectrum is the definition of shared access licenses. Such licenses delimit usage conditions of a particular portion of spectrum being used by an incumbent for a defined time period or area. Table 2.3 shows total welfare after introducing both a new allocation and a spectrum sharing reform.

Table 2.3: Spectrum sharing reform

Service	Units of spectrum allocated	Social value per unit of spectrum	Productive efficiency	Total Welfare
A	6	2	75%	9
B	6	4	75%	18
C	2	2	75%	3
A+B+C	12	3 (Avg)	75% (Avg)	30

Source: Authors

2.3 Reforms achieving greater dynamic efficiency

Dynamic efficiency is achieved when it is possible to change the allocation of spectrum in response to either the emergence of new services with high social value or when there is a change in the value generated by services that turns inefficient current allocation. For example, the increasing number of applications offered through mobile broadband increase the social value of this service over time.

Spectrum reforms intended to increase dynamic efficiency also increment allocative efficiency. The significant difference between reforms increasing allocative efficiency and reforms enhancing both is that the latter can be used not only in a particular case but also in future changes of allocation. The line delimitating whether a reform increases only allocative or also dynamic efficiency is sometimes blurred. For example, the design and processes of an incentive auction may be re-used in the future if the service demanding to access the spectrum share technical features with the services for which the incentive auction was designed, but in other situations the incentive auction should be redesigned.

Examples of reforms dynamically efficient are those enabling future changes of spectrum allocations. Two examples are the authorization of spectrum underlay technologies, and the definition of licenses in terms of acceptable interference. Spectrum underlay technologies are able to use the spectrum that is already in use by other service without interfering with the incumbent user. Future changes of the underlay spectrum use are possible.

The definition of spectrum licenses in terms of the maximum acceptable interference, that devices are willing to accept, facilitates inter-service spectrum transactions, thus the dynamic allocation of spectrum without administrative intervention. Let's define an interference limit that the devices using a frequency band are willing to accept, for example -110 dBm per MHz[3]. Transaction costs of a change of spectrum allocation would be greatly reduced if an entrant service is able to comply with this limit and it is willing to pay for the access to the portion of the spectrum for which limits of acceptable interference has been defined. The lowered transaction costs stems from the reduced risk of interference. Even if a frequency repackaging process is necessary in the reallocation process, uncertainty and transaction cost will have been greatly reduced. An increasing number of authors have claimed for the importance of incorporating the definition of acceptable interference in spectrum licenses, Webb (2009), Kwerel and Williams (2010) and Cave and Web (2012).

2.4 Mixed reforms

Spectrum reforms rarely have economic sense implemented individually. Reforms usually come in packages that need to be carried out sequentially. Table 2.4 shows total welfare of a productively efficient reform followed by a reform improving allocative efficiency. The initia allocation is described in table 2.1.

Normally it is not possible to make a choice on the order of spectrum reforms. However, it is possible to choose the starting time and speed of the first and subsequent changes. To exemplify how a mixed reform is carried out, let's consider technology advancement allowing the provision of a service using less amount of spectrum. The result of reform implementation is a new portion of available spectrum that can be used either to increase the amount produced of the existing service or to allocate a new service with expected higher social value. If the latter option is carried out then a second reform is required to accommodate the entrant service to the available spectrum.

A real example of such situation is the transition from analogue to digital television in the UHF band, the so called digital dividend. Transition resulted in the availability of new frequencies in a band highly demanded. After the transition part of the frequencies of the digital dividend were allocated to mobile broadband. The new allocation required a series of complex technical studies in order to reduce interference problems between mobile broadband and digital television services.

3. Uncertainty associated to spectrum management reform

Spectrum management reforms intended to increase productive efficiency are usually less prone to uncertain results. Consequently, once regulatory mechanisms are created, transactions can be carried out by market agents provided that there is sufficient supervision on effective competition[4]. Examples are transfers, leases, or mutualisation of spectrum rights among firms providing the same service.

The incorporation of technology change in licenses, the so-called frequency re-farming, enables market agents to efficiently carry out inter-band technology change since interference problems that may arise would be solved as described in the Coase theorem. The theorem conditions, well defined property rights and low transaction costs are usually met in spectrum re-farming type of transactions. However, market agent behavior might not always be efficient. If the adoption of a new technology results in increased competition, market agents might not have the incentive to embrace it in order to keep the privileges of reduced competition. In such cases, a regulatory action would be required. Lack of incentives to adopt new technology may explain why in most countries radio FM services are still being provided using analogue technologies while much more efficient digital technologies are available[5].

Reforms intended to change the allocation of spectrum and mixed reforms where an allocation change is included are usually expected to produce the highest benefit if carried out in the right moment. However, such reforms have not only uncertain returns, especially uncertain external benefit fulfillment, but also uncertain costs. Lack of information about the cost of reforms is an important reason for the market to refrain to carry out transactions. Regulatory mechanisms such as the design of incentive auctions or the definition of licenses in terms of maximum acceptable interference might help market agents to increase efficiency of changes of spectrum allocation. The following sections analyze uncertainty of spectrum management reform both in the return and the cost of reform.

3.1 Uncertain return of a spectrum management reform

The return of a spectrum management reform is uncertain because of the existence of externalities, services that are pure public goods and economies of scale when the use of spectrum is harmonized. The following sections analyze each of the causes of uncertainty.

3.1.1 Externalities

The analysis of the social efficiency of a spectrum reform should include the reform effects on economic growth, equal opportunities for marginal groups in society and the promotion of effective competition; see Cave (2002), ITU (2009).

Positive externalities appear as a result of the increased number of possibilities for producing goods and services, easier access to information, reduced transaction costs and new chances for consuming new products and services. If these externalities are not included in spectrum management decisions some services would be provided at a below-the-optimum amount. For example broadband, a service that can be provided using the spectrum, has been associated to GDP growth and productivity increase, Gillet et al (2006), Litan and Rivlin (2001), Goss (2001), López Sánchez et al (2004, 2006).

Production below the optimum may happen for a variety of reasons. One is the economies of density associated to network deployment. Rural areas coverage may be socially desirable but privately unprofitable. Urban-rural cross subsidy or public funding are socially efficient in these cases to achieve the optimal social production. Another one is sunk costs[6], subsidies and/or public private partnerships may help mitigate the problem.

The expected value of a reform may be biased by miscalculating the external value. The social value of spectrum includes what spectrum users are willing to pay plus the externalities associated with the services using the spectrum. Whereas making an educated guess about the private value may be possible, the value of the spillover effects is much more uncertain and difficult to assess.

Private value may be calculated with some precision by carefully studying the result of previous auctions, applying the cash flow method[7], measuring the difference in the total cost of ownership of deploying a network without a spectrum band, Frias et al (2016), or even using production functions see R. Prasad (2014). Sometimes, the calculation of the external value may not be necessary if the loss of spectrum resulting from a reform can be compensated by non-spectrum inputs, e.g. a higher number of radio stations, see J.M. Garcia and A. Valiño (2013), M. Cave (2016). In this case, the calculation of externalities may be substituted by the calculation of the cost of providing the service by other means. In other cases, such substitution is either technically unfeasible or financially impossible since the cost of alternative inputs is unbearable. Then, there is no alternative to calculating the cost of externality loss in order to assess the expected return of the reform.

3.1.2 Pure public goods

Some spectrum services provide goods non-excludable and non-rivalrous. Examples are national security and defense, emergency assistance, scientific research, whether forecasting or climate change monitoring. These services are not delivered by the market and are usually financed with public budget for everyone's benefit. How much spectrum has to be allocated to those services is uncertain since the calculation of the benefits they produce is complex.

Spectrum management reform based on the increased use of spectrum sharing has been proposed in the US and Europe as a means to increase efficiency, especially in bands currently used to provide pure public goods. However, there must be mechanisms to maintain the optimal production of these public goods ensuring both an optimal amount of spectrum and a service provision free from harmful interference.

For example, a US Government Report, PCAST (2012) found that clearing and reallocation of Federal spectrum[8] -the spectrum used to deliver pure public goods- would be expensive and lengthy and reallocation a not sustainable basis for spectrum policy. Instead, it is proposed to use spectrum sharing as a means to increase efficiency under a licensed regime. In Europe, a Communication from the European Commission to the Parliament, EC (2012) defined the conditions to promote the shared use of spectrum.

The definition of clear and effective sharing rules may help to formulate better defined property rights and reduced transaction costs, thus satisfying Coasian schemes. However, the expected result of the Coase theorem, the achievement of an optimal agreement mutually advantageous between spectrum users, may work only for spectrum sharing between commercial uses. In the case of social production, even if public goods have higher social value, the public service provider will not be able to pay for interference solution when it happens. Thus, when the spectrum is shared between services producing pure public goods and commercial goods there must be mechanisms to enforce property rights and avoiding harmful interference.

3.1.3 Economies of scale

The allocation of the same portion of spectrum in a broad geographical area, known as spectrum harmonization, produces important economies of scale which reduces the cost of manufacturing transmitting and receiving devices. Savings stem from the distribution among a larger number of users of the cost of designing the electronics needed for using a frequency band. It also arises from the diminished technical complexity of the device resulting from the reduced amount of frequencies it has to operate with. The latter effect is especially important in services that are supplied using several frequency bands such as mobile telephony.

For some services, there are additional benefits of harmonization. For example, the allocation of the same spectrum band to mobile networks in several countries enables to continue using the same mobile terminal in different countries via “roaming”[9] agreements. In such case, not only devices cost less but also service utility is enhanced. Harmonization of a portion of spectrum may lead to the harmonization of the adjacent portions. The use of an adjacent spectrum band may exponentially reduce the cost of deployment of a new network because it enables re-using infrastructure of existing sites[10] and it creates economies of scale in network deployment.

Regulators and market agents involved should act concertedly to make harmonization of certain bands possible in order to achieve the benefits of the economies of scale. Worldwide harmonization is desirable in certain occasions. The calculation of the return of a spectrum management reform is uncertain since it may depend on the agent coordination success.

3.2 Uncertain cost of spectrum management reform

Changes in the allocation of spectrum may create harmful interference, fragmentation and costs associated to the reallocation of existing services. A high level of spectrum exploitation is associated with higher adaptation costs of existing devices, higher cost for reallocating spectrum, and compensations to spectrum users with licenses still in force.

3.2.1 Uncertain interference levels

Changes in allocation of spectrum may create harmful interference to existing services stemming from the different emission parameters, density of stations and typical power of the new services.

Different emission parameters

The relevant parameters involved in the characterization of harmful interference[11] are the design of transmitters and receivers[12] and the emission parameters and techniques[13]. Main emission parameters are frequency, power, location and direction. The emission techniques depend on technology[14]. These techniques are normally intended to increase coverage or service capacity but may also have an impact on the existence of or shielding to harmful interference. Transmitters are designed to produce a certain limited amount of out of band emission[15] without interfering neighboring spectrum users and receivers are able to accept certain amount and still performing well. Consequently, the existence of harmful interference depends on how sensitive to harmful interference are the devices of the incumbent services to the emissions of the entrant and vice versa.

Compatibility between stations providing a service and frequency adjacent services is achieved through the setup of limits on emission parameters that are set forth in the spectrum license by a Governmental agency. Devices and emission techniques are designed to on the one hand maximize capacity and on the other hand to avoid harmful interference among radio stations of the same and adjacent services. If there is a change in spectrum allocation, the existing emission parameters and /or devices may interfere with or be interfered by new devices using the adjacent band since they were not initially designed to deal with the new sources of interference. The cost to cope with interference is uncertain not only from the point of view of the engineering process, complex compatibility studies are required, but also from the point of view of the coordination of all involved agents.

A spectrum allocation approach with reduced interference problems is the use of underlay spectrum sharing techniques. Under such approach, new devices are able to co-exists with incumbent users in the same frequency band under a set of well-defined conditions, but this kind of solutions are limited to low power applications. Dynamic sharing is an additional approach that may be used when incumbent services are not using the spectrum in a particular geographical area or time slot.

A more global solution is the reform of spectrum licenses in order to include the maximum interference that devices should be able to tolerate instead of defining their emission parameters. Doing so, would enable future changes in the allocation of spectrum that would be much less complex and uncertain.

Density of stations, the cumulative effect

The greater the density of radio-stations in an area the higher it will be the probability of harmful interference due to the accumulation of interfering signals of multiple nearby stations. Webb (2009) maintains that when there is a change in spectrum allocation the cumulative interference effect may have a higher impact on the entrants than on the incumbent service. Networks using the initial allocation of spectrum are usually deployed in parallel, thus, the density of stations is similar and the cumulative interference problems are solved dynamically during network deployment. However, when there is a new allocation of spectrum, the network of the entrant service is not yet deployed and it is more exposed to the potential cumulative inference of a much denser network in an adjacent band. The cumulative effect increases the interference problems suffered by the entrants.

A well-designed spectrum license should incorporate a set of parameters including not only the maximum acceptable interference from a station but also taking account of the cumulative effect. Such parameter definition complicates license design but diminish future transaction costs.

Differences in the typical power of stations

Problems such as coverage holes[16] or receiver's blocking[17] may appear if there is a significant difference between the typical power of stations of the incumbent service and the stations of a new spectrum allocation. When the typical power of stations is similar, the location of both the entrant and the incumbent services' stations tend to be similar and such problems are much less important.

A solution to the problem may be to create different frequency bands bearing in mind the typical power of stations providing the service. These frequency bands would be separated by guard bands to mitigate potential interferences among services. Within these bands, changes in the allocation of spectrum to services with similar features would be much easy to be carried out. A potential optimal organization of such frequency groups would be the creation of bands for unidirectional high power networks -broadcasting-; for unidirectional low power- mobile multimedia-; and low power bidirectional networks-mobile broadband.

3.2.2 Fragmentation of spectrum allocation

Reallocation of spectrum might create gaps and fragmentation of spectrum use. The minimum number of spectrum units used by each service is usually different. Consequently, reallocation may result in unused portions of spectrum. For example, let's consider service A using multiples of eight units of spectrum to provide a service and service B using multiples of five. If service A is willing to relinquish eight units in exchange for compensation and service B is willing to pay the compensation, three units would be left unused until a new service is willing and it is able to use them. If service B would require 10 units, then the result is either the impossibility to make the transaction or the creation of a band of six units of unused spectrum, provided that B is willing to relinquish 16 units. 7

Furthermore, the provision of services on adjacent frequency bands usually requires the creation of a guard band[18] whose size may be one or several units of spectrum in order to avoid harmful interference among services.

3.2.3 Uncertain costs associated to the existing licenses and devices

A higher level of usage of a frequency band by incumbents is associated with higher adaptation costs of existing devices, higher cost for reallocating the spectrum, and compensations to spectrum users with licenses still in force when there is a reallocation process.

Compensation costs

Reforms changing spectrum allocation may pose important compensation costs. In some cases licenses have not expired and current licensees have the right to receive compensation for loss of earnings before a spectrum band is made available to a new service. When licenses have different expiration periods it may be more difficult to make the frequencies available, Minervini and Piacentino (2007).

Reallocation costs during the transition period

Reforms making available a portion of spectrum tor a new service involve financial costs beyond the compensations for loss of earnings. Such reforms require adaptations like changing the transmission frequency, or adapting receivers so that they are no longer able to receive the frequencies allocated to the new entrant service. Receiver adaptation can be done by placing filters at the input of the receiver. Additionally, in some cases it may be necessary to simulcast[19] new and old frequencies during a period which imply higher network operation costs for the incumbent during the transition period.

Adaptation of existing devices

The sensitivity to the adjacent channel interference is an important parameter of a receiver. The more resilient it is the device the more expensive it becomes the electronics used to mitigate interference. Manufacturers design devices to work in a certain predefined environment. If a new allocation is made in an adjacent band, receiver features may not be sufficient to avoid harmful interference produced by the entrant services. There exist mitigation techniques such as placing filters at the input of the receiver to solve the problem. However, the total cost of the adaptation is uncertain because depends on the features of the stock of receivers, which usually is an unknown variable. Once again, the definition of licenses in terms of acceptable interference would help to manufacture more resilient devices, consequently, lowering transaction costs of changes of spectrum allocation.

4. A model to analyze the path and speed of spectrum management reform

We bring the literature of political economy of reform to the topic of spectrum management. We continue developing the analogy between the case of spectrum reform and the reform of economies in transition set out by Minervini (2014). We depart from the model in Dewatripont and Roland (1995) adding the idiosyncrasies of spectrum management. First, we include the evolution of technology during the first reform process as an endogenous variable then we allow technology change to occur after the first reform period giving the reformer the possibility to wait to take advantage of the new technology. We have changed some of the notations, explained the meaning of some variables from the view of spectrum reform and added new parameters but basic assumptions and definitions remain equal to those used in Dewatripont and Roland (1995).

The most significant difference between the reform of spectrum management and of economies in transition is the pace of technological progress. Whereas in the latter technology is 'sticky' and it doesn´t change much during the timeframe of reform implementation, in spectrum reform it may change during the analyzed timeframe having an impact on the strategy of reformers. Technology is a salient factor to determine whether to implement gradual or big bang type of reforms, consequently, in our model it is an endogenous explanatory variable acting as a multiplier of the expected outcome.

A spectrum management reform can be defined as a set of regulatory changes intended to increase productive, allocative or dynamic efficiency of spectrum use. In most cases, the order of reform implementation cannot be chosen but reformers can decide when to start and the speed of reform.

Big bang reform packages are those introducing several reforms quickly and simultaneously. Gradual reform packages are those where it can be decided whether to proceed with the next package or postpone it. One reason to postpone a reform is waiting for the arrival of a new technology.

Reforms are regulatory changes intended to enable increasing efficiency either productive or allocative or dynamic. Examples were described in section 2. Reforms are carried out sequentially if they are complementary. Although we simplify the model considering only two sequential reforms we do not loss generality since it can be understood as complementary packages of reforms that can be carried out in two sequential moments.

Reform packages can be designed to increase any of the types of efficiency. There may be two productively efficient reforms in different portions of spectrum or geographical locations. For example, the use of auctions in a portion of the spectrum followed by the use of auctions in the rest of portions being used by this service. It can also be mixed reforms packages where it is necessary first a productively efficient reform and then a subsequent reform improving allocative efficiency. An example is the introduction of a new technology that free up spectrum that can be used by an entrant. Finally the definition of spectrum licenses in terms of the maximum acceptable interference may be carried out for a spectrum band and hereinafter in other bands.

The outcome generated by a reform depends on a set of possible states of nature with N_i elements. These elements include the uncertain factors described in section 3.2, interference levels, fragmentation of spectrum, costs associated to the existing licenses and devices and also when applicable what was described in section 3.1, economies of scale, externalities and pure public goods. Other aspects such as political constraints, investment behavior are also included in the composition of the states of nature but for those, technology is not a multiplier.

We consider two complementary reforms $i = 1, 2$ to be executed in a discrete and infinite time horizon. We use a normalized discount factor δ or $(1-\delta)$ where $\delta < 1$ which describe the period of duration of each reform. The outcome of reform i depends on the realizations of a partition of a set of states of nature of N_i elements. The realization of the k th element of a reform is $s_{ik} \in \{s_{i1}, s_{i2} \dots, s_{iN_i}\}$. For example, in reform 1 the realization of the k th element is s_{1k} and in reform 2 the realization of the m th element is s_{2m}. The corresponding outcome for both is $o(s_{1k}, s_{2m}, t)$ which is the outcome of both reforms periods after being implemented but $o(s_{1k}, s_{2m}, t) = o(s_{1k}, s_{2m})$ because we consider the outcome to be time invariant. The present value of $o(s_{1k}, s_{2m})$ after the first period is denoted by $O(s_{1k}, s_{2m}) = o(s_{1k}, s_{2m}) / (1-\delta)$. One of the innovations of our model is the introduction of an exogenous technological advancement coefficient after the first reform that is denoted by $\sigma > 1$.

The outcome of a reform is unknown before it is implemented, for this reason we work with ex ante expected results. We denote expected outcomes depending on the strategy of reform, it can be big bang or gradual, and the moment the value it is analyzed, it can be before any has been realized or when the first reform has already been carried out. $E_{k,m}O(s_{1k}, s_{2m}) \equiv O_{k,m}$ is the expected outcome of a big bang reform before any of them have been realized. $E_mO(s_{1k}, s_{2m}) \equiv O_m$ is the expected outcome of a big bang strategy given that the first period has already passed. $H(s_{1k}) \equiv H_k < 0$ is the outcome of the first reform of a gradual strategy. $O_m > H_k$ because of the required complementarity of reforms. In gradual reforms one can learn about the final total payoff from the implementation of H_k and either postpone or even don't finish the complete set of reforms, whereas in a big bang strategy both reforms have already been compromised and reformers cannot back out. A realization of the state of nature of the first reform k is higher than realization $\tilde{k}$ if

$$k > \tilde{k} \rightarrow E_mO(s_{1k}, s_{2m}) \geq E_mO(\widetilde{s_{1k}}, s_{2m}) \quad (1)$$

There is a probability that once we know $E_mO(s_{1k}, s_{2m})$ the payoff is lower than expected. We denote this situation as $\Pr(k < \ k) \equiv Pr$ whereas the opposite situation is $\Pr(k \geq \ k) \equiv Pr$.

Another important aspect of the model is the degree of reversibility of reforms. If the outcome of a reform is lower than expected it may be reversed. Reversibility doesn´t necessarily mean to completely go back the reform but for example to reduce the planned investment. An example would be to limit the deployment of a network of an entrant service allocation only to the most profitable regions leaving less profitable areas uncovered due to the emergence of interference problems that make unprofitable such areas. In a big bang reform the only possibility is to reverse both reforms, we denote the degree of reversibility of a big bang reform $\xi < 0$.In the case of the gradual approach it is possible to reverse one of the reforms and not carry out one of them, the reversibility of the first and second reforms are defined respectively $\xi_1 < 0$ and $\xi_2 < 0$. We also assume that

$$\xi \leq \xi_1 + \xi_2 \leq 0 \quad (2)$$

We assume that the technological advance coefficient multiplies reform outcome when it is equal or higher than expectations and divide the reversibility coefficient when outcomes are lower than expected thus reducing the negative impact of reversibility. The payoff of a big bang reform is defined by the following expression:

$$BB = (1-\delta)O_m + \delta\sigma PrO_m + \delta\frac{1}{\sigma}\overline{Pr}\xi \quad (3)$$

The payoff of a gradual reform is:

$$GR = \left(1-\delta\right) H_k + \frac{1}{\sigma} \delta \overline{Pr} \xi_1 + \\ + \sigma \delta \Pr[\left(1-\delta\right) O_m + \delta O_m] \tag{4}$$

We are interested in analyzing in which situations a gradual type of reform is better than a big bang strategy depending on the technological advancement coefficient. There is a range of values of the coefficient that fulfill this requirement.

Proposition 1: The range of values of the technological advance coefficient that make gradualist better than big bang strategies are defined by the expression:

$$\sigma < \frac{\delta \overline{Pr}\left[\xi_1 - \xi\right]}{\left(1-\delta\right)\left[O_m - H_k\right]} \tag{5}$$

Proof see appendix.

Proposition 1 holds if $\ll \xi_1, \delta \gg \left(1-\delta\right)$, $\overline{Pr}$ is high or $O_m \cong H_k$ which means that even for small values of the technological advance coefficient a gradual would be better than a big bang reform if the reversibility of both reforms is costly, the duration of the second reform is very long, the probability of obtaining an outcome lower than expected is considerable or the reforms are not too complementary.

However, when $\frac{\overline{Pr}\delta\left[\xi_1 - \xi\right]}{\left(1-\delta\right)\left[O_m - H_k\right]} \le 1$ the inequality can never be true because by definition $\sigma > 1$. In such situations the following inequality holds.

$$\overline{Pr}\delta\left[\xi_1 - \xi\right] \le \left(1-\delta\right)\left[O_m - H_k\right] \tag{6}$$

This means that a big bang reform will always be the best strategy if $\xi \cong \xi_1$ or $\left(1-\delta\right) \gg \delta$ or $\overline{Pr}$ is low or $O_m \gg H_k$.

Let's consider now that after the first period the reformer can learn not only about the final payoff of reform but also about the evolution of technology in a near future time t_0 . The reformer has the option of waiting for the new technology before continuing with the second reform. We assume that waiting is only possible in case of a gradual strategy because big bang configurations imply the realization of both reforms as initially planned. We define $0 < \delta_0 < 1$ as a delay coefficient that captures the reduction of benefits produced by the delay t_0 in the implementation reforms. Therefore we have two competing effects. On the one hand there is a reduction of benefits δ_0 produced by the delay of reforms and on the other there is a profit increase σ produced by the new technology that has positive impact reducing cost and increasing the quality and capacity of the effects of the reform. Under this framework, we define the payoff of a big bang reform with the following expression:

$$BB = \left(1-\delta\right) O_m + \delta Pr O_m + \delta \overline{Pr} \xi \tag{7}$$

The payoff of a gradual reform is

$$GR = \left(1-\delta\right) H_k + \delta \overline{Pr} \xi_1 + \\ + \sigma \delta \delta_0 \Pr[\left(1-\delta\right) O_m + \delta O_m] \tag{8}$$

Now, we are interested in analyzing the values of the delay coefficient that make a gradual reform better than a big bang strategy in cases where waiting a time t_0 would allow the use of a more efficient technology.

Proposition 2: If there is a technological advancement available at time t_0 enabling a higher expected outcome, the range of values of the delay coefficient that makes using a gradual reform strategy better than a big bang reform is described by:

$$\delta_0 > \frac{\left(1-\delta\right)\left[O_m - H_k\right] + \overline{Pr}\delta\left[\xi - \xi_1\right] + \delta Pr O_m}{\delta \sigma Pr O_m} \tag{9}$$

Proof see appendix.

Proposition 2 holds if $\ll \xi_1, \delta \gg \left(1-\delta\right)$, $\overline{Pr}$ is high, $O_m \cong H_k$ and $\sigma \gg 1$ which means that even for big values of the delay coefficient a gradual would be better than a big bang reform if the reversibility of both reforms is costly, the duration of the second reform is very long, the probability of obtaining an outcome lower than expected is considerable, the reforms are not too complementary or the technological advance coefficient is considerable.

However, when

$$\frac{\left(1-\delta\right)\left[O_m - H_k\right] + \overline{Pr}\delta\left[\xi - \xi_1\right] + \delta Pr O_m}{\delta \sigma Pr O_m} \ge 1$$

the inequality in (9) never holds because by definition $\delta_0 < 1$, therefore waiting could never be optimal and a big bang type of reform will always be better than a gradual strategy. When this condition holds we have found that:

$$BB \geq \left(1-\delta\right) H_k + \delta \overline{Pr} \xi_1 + \sigma\delta \mathrm{Pr} O_m \tag{10}$$

Proof see appendix.

That means that for the expression

$$\frac{(1-\delta)[O_m - H_k] + \overline{Pr}\delta[\xi - \xi_1] + \delta Pr O_m}{\delta\sigma Pr O_m} \geq 1$$

to be true, the big bang reform must be better than the gradual for a given σ no matter the value of because it is δ_0 superior even if $\delta_0 \to 1$ and therefore there is no delay incurred waiting for the new technology.

Furthermore, we know that $\delta_0 > 0$ so if

$$\frac{(1-\delta)[O_m - H_k] + \overline{Pr}\delta[\xi - \xi_1] + \delta Pr O_m}{\delta\sigma Pr O_m} \leq 0$$

waiting will always be the optimal response. We know that this is possible because $[\xi - \xi_1] < 0$. Under such condition we found that:

$$BB \leq \left(1-\delta\right) H_k + \delta \overline{Pr} \xi_1 \tag{11}$$

Proof see appendix.

That means that for the expression $\frac{(1-\delta)[O_m - H_k] + \overline{Pr}\delta[\xi - \xi_1] + \delta Pr O_m}{\delta\sigma Pr O_m} \leq 0$ to be true $< \tilde{k}$, then thee second reform is never carried out in case of a gradual reform and the outcome of the big bang reform is always lower than that of the gradual.

We now come back to our initial analysis of the range of values of the technological advance coefficient that make gradualist better than big bang strategies under the new framework where it is possible to wait for a new technology

Proposition 3: If there is a technological advancement enabling higher expected outcome after the first reform period, the range of values of the technological advance coefficient that make gradualist better than big bang strategies is defined by the expression:

$$\sigma > \frac{\left(1-\delta\right)\left[O_m - H_k\right] + \overline{Pr}\delta\left[\xi_1 - \xi\right] + \delta Pr O_m}{\delta\delta_0\sigma Pr O_m} \tag{12}$$

Proof see appendix.

Proposition 3 holds if $\ll \xi_1, \delta \gg \left(1-\delta\right)$, $\overline{Pr}$ is high, $O_m \cong H_k$ and $\sigma \gg 1$ which means that a gradual would be better than a big bang reform the if the technological advance coefficient is high, the reversibility of both reforms is costly, the duration of the second reform is long, the probability of obtaining an outcome lower than expected is considerable, the reforms are not too complementary or the waiting time is short or a sufficient combination of these effects.

However, when

$$\frac{(1-\delta)[O_m - H_k] + \overline{Pr}\delta[\xi - \xi_1] + \delta Pr O_m}{\delta\sigma Pr O_m} \leq 1$$

the inequality in (12) never holds because by definition $\sigma > 1$, therefore waiting could never be optimal and a big bang type of reform will always be better than a gradual strategy. When this condition holds we have found that:

$$BB \leq \left(1-\delta\right) H_k + \delta \overline{Pr} \xi_1 + \delta_0 \delta \mathrm{Pr} O_m \tag{13}$$

Proof see appendix.

That means that for the expression

$$\frac{(1-\delta)[O_m - H_k] + Pr\delta[\xi - \xi_1] + \delta Pr O_m}{\delta\sigma Pr O_m} \leq 1$$

to be true, the gradual reform must be better than the big bang reform for a given δ_0 no matter the value of σ because it is superior even if $\sigma \to 1$ and the new technology is not improving the expected outcome at all.

5. Conclusions

Spectrum management reform can be analyzed from the perspective of the political economy of reform adding the idiosyncrasies of high technology industries. One distinctive feature is the intense technological evolution, thus one cannot assume that technology is constant during the reform period. Another feature is the impossibility of completely reverse reforms. Reversibility here does not mean to return to the status quo but to leave unfinished or incomplete some components of the reform. For example, if the outcome of the deployment of a network is lower than expected, the network may only be built in profitable high densely populated areas leaving rural locations uncovered, or in other cases, the reform could only be carried out where uncertainty is the lowest. An additional characteristic is that the reformers cannot choose the order of reforms because they are not only complementary but have the requirement of being implemented in a particular order. For example, the adoption of a new technology, followed by a new spectrum allocation and a subsequent reallocation of the newly freed up spectrum need to be done in this particular order. The reformer instead must choose the right moment to start the reform and the implementation strategy, either big bang or gradual.

We offer an expression to determine when to choose a gradual or big bang reform depending on current and expected technology and an expression to determine whether to wait or not for a new technological advancement. Gradual is better if the technological advance coefficient is high, the reversibility of both reforms is costly, the duration of the second reform is long, the probability of obtaining an outcome lower than expected is considerable or the reforms are not too complementary

We have also shed some light on the types of spectrum management reform by categorizing them in terms of the type of efficiency gain that the reform is intended to produce,- productive, allocative and dynamic-. Furthermore, we have analyzed market failures responsible for uncertain outcomes to help tackling the underlying causes of failure.

The use of market mechanisms to improve productive efficiency, -intra-band technological change, auctions and secondary market transactions-, has already been fruitful on the portions of spectrum traditionally been used for commercial purposes. In such cases, market forces may result in productively efficient transactions provided that Coasian schemes are fulfilled; low transaction costs and well-defined property rights.

Transactions enabling allocative and dynamic efficiency are not yet possible to be produced solely by the market. New approaches such as the design of incentive auctions give a broader role to market participants but the active contribution of the regulatory authority to design the direct and reverse auction and the repackaging process is still necessary. A different instrument, the authorization of new technologies enabling to share spectrum previously used by an incumbent service, is improving allocative efficiency making market agents more involved in spectrum allocation. However, sharing techniques are usually limited either to short range devices, the case of underlay spectrum techniques, or by the availability of unused spectrum in certain areas or time slots, the case of dynamic spectrum sharing. Spectrum sharing techniques that are useful to improve the efficiency of spectrum allocation cannot be used as means to enable the change of use of a band solely by market forces.

An additional innovative approach to spectrum management is the definition of spectrum licenses in terms of the maximum acceptable interference that devices should be able to accept. This technique may pose a significant advancement to achieve the goal of enabling market transactions changing the allocation of spectrum. However, better knowledge of interference problems and more importantly the design of new types of licenses, would be required to move forward.

The efficiency of changes of spectrum allocation by market forces may be hampered by the existence of externalities associated to services and services that are pure public goods. In addition, market agents may not be willing to change to a more socially efficient spectrum allocation due to several reasons including the existence of uncertain costs but also because current market structure may grant market power to incumbent users, a situation that they are interested to preserve. Regulators must analyze the possibility to enable the re-allocation of spectrum by market forces on a case by case basis.

Annex 1: Proof of propositions

Proof of proposition 1

According to (3) and (4), for a gradual to be superior to a big bang reform, the following must be fulfilled

$$\left(1-\delta\right)H_k+\frac{1}{\sigma}\delta\overline{Pr}\xi_1+\sigma\delta\Pr[\left(1-\delta\right)O_m+\delta O_m]>\left(1-\delta\right)O_m+\delta PrO_m+\delta\frac{1}{\sigma}\overline{Pr}\xi$$

$$\left(1-\delta\right)H_k+\frac{1}{\sigma}\delta\overline{Pr}\xi_1>\left(1-\delta\right)O_m+\delta\frac{1}{\sigma}\overline{Pr}\xi$$

$$\frac{1}{\sigma}\delta\overline{Pr}\left[\xi_1-\xi\right]>\left(1-\delta\right)\left[O_m-H_k\right]$$

Therefore $\sigma<\dfrac{\delta\overline{Pr}\left[\xi_1-\xi\right]}{\left(1-\delta\right)\left[O_m-H_k\right]}$

We know that $O_m>H_k$ and $\xi\le\xi_1\le 0$ and $\delta<1$ therefore all the terms of the expression are positive

But $\sigma>1$ therefore if $\dfrac{\delta\overline{Pr}\left[\xi_1-\xi\right]}{\left(1-\delta\right)\left[O_m-H_k\right]}\le 1$ this condition will never hold and

$$\delta\overline{Pr}\left[\xi_1-\xi\right]\le\left(1-\delta\right)\left[O_m-H_k\right]$$

Proof of proposition 2

According to (7) and (8), for a gradual to be superior to a big bang reform, the following must be fulfilled

$$\left(1-\delta\right)H_k+\delta\overline{Pr}\xi_1+\sigma\delta\delta_0\Pr\left[\left(1-\delta\right)O_m+\delta O_m\right]>\left(1-\delta\right)O_m+\delta PrO_m+\delta\overline{Pr}\xi$$

$$\sigma\delta\delta_0 PrO_m>\left(1-\delta\right)[O_m-H_k]+\delta\overline{Pr}[\xi-\xi_1]+\delta PrO_m$$

$$\delta_0>\frac{\left(1-\delta\right)[O_m-H_k]+\delta\overline{Pr}[\xi-\xi_1]+\delta PrO_m}{\sigma\delta PrO_m}$$

By definition $0<\delta_0<1$

If $\dfrac{\left(1-\delta\right)[O_m-H_k]+\delta\overline{Pr}[\xi-\xi_1]+\delta PrO_m}{\sigma\delta PrO_m}\le 0$ then δ_0 is higher than $\dfrac{\left(1-\delta\right)[O_m-H_k]+\delta\overline{Pr}[\xi-\xi_1]+\delta PrO_m}{\sigma\delta PrO_m}$ and waiting will always be optimal. We know that this may happen because

$\delta Pr\left[\xi-\xi_1\right]<0$ in this case

$$
\begin{aligned}
&\left(1-\delta\right)\left[O_m - H_k\right] + \delta\overline{Pr}\left[\xi - \xi_1\right] + \delta PrO_m \le 0 \\
&\left(1-\delta\right)O_m + \delta PrO_m + \delta\overline{Pr}\xi - \delta\overline{Pr}\,\xi_1 - \left(1-\delta\right)H_k \le 0 \\
&BB \le \left(1-\delta\right)H_k + \delta\overline{Pr}\,\xi_1
\end{aligned}
$$

If $\frac{(1-\delta)[O_m - H_k] + \delta\overline{Pr}[\xi - \xi_1] + \delta PrO_m}{\sigma\delta PrO_m} \ge 1$ then δ_0 is lower than

$\frac{(1-\delta)[O_m - H_k] + \delta\overline{Pr}[\xi - \xi_1] + \delta PrO_m}{\sigma\delta PrO_m}$ and waiting will never be optimal. In this case

$$
\begin{aligned}
&\left(1-\delta\right)[O_m - H_k] + \delta\overline{Pr}[\xi - \xi_1] + \delta PrO_m \ge \sigma\delta PrO_m \\
&\left(1-\delta\right)O_m + \delta\overline{Pr}\xi + \delta PrO_m - \left(1-\delta\right)H_k - \delta\overline{Pr}\xi_1 \ge \sigma\delta PrO_m \\
&BB \ge \left(1-\delta\right)H_k + \delta\overline{Pr}\xi_1 + \sigma\delta PrO_m
\end{aligned}
$$

Proof of proposition 3

According to (7) and (8), for a gradual to be superior to a big bang reform, the following must be fulfilled

$$
\begin{aligned}
&\left(1-\delta\right)H_k + \delta\overline{Pr}\xi_1 + \sigma\delta\delta_0\,\mathrm{Pr}\left[\left(1-\delta\right)O_m + \delta O_m\right] > \left(1-\delta\right)O_m + \delta PrO_m + \delta\overline{Pr}\xi \\
&\sigma\delta\delta_0 PrO_m > \left(1-\delta\right)[O_m - H_k] + \delta\overline{Pr}[\xi - \xi_1] + \delta PrO_m \\
&\sigma > \frac{\left(1-\delta\right)[O_m - H_k] + \delta\overline{Pr}[\xi - \xi_1] + \delta PrO_m}{\delta\delta_0 PrO_m}
\end{aligned}
$$

By definition $\sigma > 1$

If $\frac{(1-\delta)[O_m - H_k] + \delta\overline{Pr}[\xi - \xi_1] + \delta PrO_m}{\delta\delta_0 PrO_m} \le 1$ then σ is higher than

$\frac{(1-\delta)[O_m - H_k] + \delta\overline{Pr}[\xi - \xi_1] + \delta PrO_m}{\delta\delta_0 PrO_m}$ and the inequality never holds . In this case

$$
\begin{aligned}
&\left(1-\delta\right)[O_m - H_k] + \delta\overline{Pr}[\xi - \xi_1] + \delta PrO_m \le \delta\delta_0 PrO_m \\
&\left(1-\delta\right)O_m + \delta\overline{Pr}\,\xi + \delta PrO_m - \left(1-\delta\right)H_k - \delta\overline{Pr}\xi_1 \le \delta\delta_0 PrO_m \\
&BB \le \left(1-\delta\right)H_k + \delta\overline{Pr}\xi_1 + \delta\delta_0 PrO_m
\end{aligned}
$$

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Notes

AIP have been implemented in the UK and Canada. https://www.ofcom.org.uk/consultations-and-statements/category-1/aip/update201008

[2] More information about the process of an incentive auction can be found at: https://www.fcc.gov/wireless/auction-1000

[3] Normally there will be a different limit for each type of device, for example, one for transmitters and a different one for receivers.

[4] In some cases the establishment of ex-ante regulation such as the definition of spectrum caps might be required to achieve effective competition. Spectrum caps are limits to the maximum amount of spectrum that a firm is allowed to use to provide a service. In other occasions ex-post measures might be enough.

[5] A complementary explanation is that digital radio receivers are still expensive, and the use of analogue devices is highly extended.

[6] Examples of infrastructure involved in high sunk costs are the deployment of satellite networks or undersea cables.

[7] Profit generated on account of the allocated spectrum.

[8] A list of Federal Spectrum uses elaborated by NTIA (National Telecommunications and Information Administration) can be found at https://www.ntia.doc.gov/files/ntia/publications/spectrum_use_summary_master-07142014.pdf

[9] Roaming is the possibility to continue receiving a service when travelling abroad. Roaming can be enjoyed either because a frequency band is harmonized or because user´s terminal can operate in the different frequency bands used in each country.

[10] This includes reusing infrastructure like telecommunication towers, the electric feeding system, communication devices and also rights of way and site leasing.

[11] There are three types of interference: geographical, out of band and in the band itself. Licenses would establish the maximum interference from the adjacent channel and the maximum out of band interference (Cave and Webb, 2003).

[12] The same radio communication device can work as a transmitter and receiver. For example, a mobile terminal is able to transmit and receive.

[13] Unwanted energy can also be the result of a combination of emissions, e.g. intermodulation products, or inductions upon reception.

[14] For example the use of transmission power control techniques intended to increase mobile phones battery life increases the probability of harmful interference to other systems http://www.erodocdb.dk/docs/doc98/official/pdf/ECCRep138.pdf

[15] Transmission devices send part of the power emitted outside their transmission band. The amount of power sent out of band depends on the features of the transmitter´s output filter. Furthermore, due to the existence of intermodulation products, interferences can be produced on frequencies different to those emitted, due to the emission of a mixture of frequencies taking place in the transmitter. There also exists interference caused by the accumulation of out-of-band signals from multiple nearby transmitters.

[16] When the transmitter of a new service is located at the coverage edge of the existing services the probability of interference increases. Services with similar typical power tend to share the same or nearby sites thus, reducing the possibility of coverage holes.

[17] A receiver can be blocked in the presence of a nearby high power signal. Under such condition the receiver is unable to receive any signal.

[18] The existence of guard bands may be necessary even to expand the allocation of a service to adjacent bands. For example, the expansion of mobile broadband to adjacent frequency bands requires creating a guard band of unused spectrum.

[19] For example, freeing up the so called digital dividend frequencies required to simulcast new and old television channels during a period of time to let people adapt building reception facilities.

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