

A techno-economic study of non-exclusive sharing of radio spectrum for mobile services and associated policy implications

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Radio spectrum for commercial mobile services continues to be scarce. Countries around the world have recognized the importance of efficient utilization of this scarce resource and have initiated regulatory and policy steps towards flexible approaches to spectrum management, including sharing of licensed spectrum, and releasing unlicensed spectrum for mobile services. While the former is excludable and rival in nature, the second is non-excludable and rival. There are two dimensions along which spectrum use can be categorized. The first relates to whether spectrum is licensed or unlicensed. If the spectrum is licensed whether the spectrum rights are transferred or not; and if transferred whether it is between operators or between operators and non-operators. Second relates to whether exclusive rights have been provided for the assigned spectrum or not. In this paper, we present various advances in the area of non-exclusive use of radio spectrum for commercial services and present two case studies in this area. We also present a techno-economic model that captures various factors that lead to the adoption of this method of spectrum management. Finally we discuss the policy directives needed in India on non-exclusive sharing of licensed spectrum and implications of the same.

Keywords: Licensed Shared Access, Spectrum Access System, spectrum sharing, Government spectrum

1. Introduction

Radio spectrum for commercial mobile services continues to be scarce. Realizing the need for efficient use of radio spectrum due to exponential increase in wireless broadband penetration and associated data usage, countries around the globe are transitioning from the traditional *command and control* mode of spectrum management to *flexible* use [14]. Country regulators and policy makers that define a stringent set of administrative rules for assignment and usage of spectrum have started to adopt flexible use policies. In fact, several new licensing schemes have emerged from regulatory entities and from the industry to enable a more efficient spectrum usage, such as opportunistic usage of TV white spaces (TVWS) [4], light licensing [3], Licensed Shared Access (LSA) [5], and Spectrum Access System (SAS) (FCC, 2012). The need for associated regulatory governance and licensing mechanisms have also been stressed in [9], and [14].

Flexible spectrum management approaches have been advocated by many including the creation of secondary markets for spectrum [1]. Secondary market transactions in spectrum involve trading (involving a transfer of property rights), leasing (involving a transfer of usage but not property rights), and sharing (involving non-exclusive assignment of a spectrum band). The transactions can be carried out either with another network operator or another category of spectrum user such as a Mobile Virtual Network Operator (MVNO - who leases the spectrum and parts of networks from a Mobile Network Operator (MNO) to provide a retail service) or a property owner (example, an airport or an office building) who leases spectrum and sets up a micro-cellular network on the premises to service subscribers of different networks. In [22], the authors indicate that even the major wireless carriers recognize the importance of sharing arrangements and the high costs of clearing new spectrum. He argues that the primary obstacles to denser usage of spectrum in many bands are regulatory, not technological.

An alternative approach for managing spectrum would be to allocate a band or bands of frequencies for unlicensed uses [6]. In 1985 the Federal Communications Commission (FCC) eliminated the process of case by case approval and set forth technical criteria to which new unlicensed devices needed to adhere. The FCC also opened up new spectrum for unlicensed use at 902-928 MHz, 2400 – 2483.5 MHz, and 5725 – 5850 MHz [14]. The release of new bands facilitated the development of the Bluetooth and Wi-Fi devices that have become ubiquitous. These technologies use spread spectrum techniques, originally developed by the military, which provide high immunity to interference noise compared to conventional techniques and allow more devices to operate in a given frequency band, thus promoting more efficient spectrum use. Over the last twenty five years, the FCC has made further bands available for unlicensed use. The 59-64 GHz band, for instance, which facilitates high bandwidth wireless communications between electronic devices over short distances, was made available in 1995. In the US as of the end of 2008, approximately 955 MHz were allocated to unlicensed uses below 6 GHz. There is considerable evidence that the non-exclusive use of unlicensed spectrum has huge economic value. Recent estimates place the value created by current applications of unlicensed spectrum at \$ 16-37 billion a year in the US alone (Milgrom et al 2011).

Spectrum is a congestible resource in the sense that shared use generates externalities due to interference. Hence the Quality of Service (QoS) for a particular user (measured in terms of throughput and/or latency) generally degrades as the number of users sharing the spectrum increases. The high demand for wide-area access to wireless data services combined with open access to lower frequency bands could create excessive congestion in those bands leading to a “tragedy of the commons”. Indeed this is one of the main arguments for granting exclusive-use licenses for spectrum.

In this paper, we present various advances in the area of non-exclusive use of radio spectrum for commercial services and present a techno-economic model that captures various factors that lead to the adoption of this method of spectrum management.

In the next section we present the taxonomy of radio spectrum use. In section 3 we elaborate on various methods of sharing licensed spectrum and its economic implications. In section 4 we present our techno-economic model of spectrum management. In the penultimate section we present the India case and conclude with future research directions.

2. Taxonomy of spectrum usage

While licensed spectrum is excludable and rival in nature, unlicensed spectrum is non-excludable and rival. Many researchers have studied economic models of sharing licensed spectrum [1]. In a recent work [11], researchers provided framework for multi-tier shared spectrum operation in wireless networks, where multiple entities dynamically acquire, manage and sell shared spectrum. Technologies for shared access and the associated standardization activities have also progressed towards possible large scale deployments.

There are two dimensions along which spectrum use can be categorized. The first relates to whether spectrum is licensed or unlicensed. If the spectrum is licensed whether the spectrum rights are transferred or not; and if transferred whether it is between operators or between operators and non-operators. Second relates to whether exclusive rights have been provided for the assigned spectrum or not. The complete taxonomy of spectrum usage arrangements is given in Table 1.

Table 1. Taxonomy of spectrum usage

	Licensed Spectrum			Unlicensed Spectrum
	<i>Spectrum rights not transferred</i>		<i>Spectrum rights transferred</i>	
	<i>Between operators</i>	<i>Between operators and other entities</i>		
Exclusive use	Intra and inter circle roaming	Spectrum leasing, Mobile Virtual Network Operators (MVNOs)	Trading, acquisitions	NA
Non-exclusive use	Spectrum sharing and pooling	License Shared Access, Spectrum Access System, TV White Space	NA	Wi-Fi, Long Term Evolution (LTE)-Unlicensed

Following are the different possibilities of spectrum usage based on exclusive use:

- 1) Exclusive use, rights not transferred between operators: Use cases relates to this classification are of two types as practiced in India:
 - a) Intra Circle Roaming (ICR): In this, operators make arrangements to share spectrum within the Licensed Service Area (LSA) (also called as telecom circles), mainly to provide expanded coverage. For example, operator A might share spectrum in a specific geographical area (say X) with operator B both of whom have spectrum and the associated license in the LSA, so that the area X is served by operator B. Operator A need not invest in the Radio Access Network (RAN) infrastructure to provide coverage in area X. This is normally done to avoid duplicate RAN infrastructure in semi-rural and rural areas of the LSA. The complete guidelines for ICR were released by the Department of Telecommunications in 2008.
 - b) Inter Circle Roaming: In this, operators make arrangements to share spectrum across the Licensed Service Area (LSA). For example, operator A might share spectrum in a specific LSA (say X) with operator B. Operator B may not have spectrum in that specific band in LSA X. This is normally done since each operator may not have spectrum in a specific band across all LSAs. By using these sharing arrangements, operators can provide pan-country services even though they may not have spectrum in specific LSAs.
- 2) Exclusive use, rights not transferred between operators and other entities: This category refers to leasing of spectrum to a non-operator, typically referred to as Mobile Virtual Network Operator (MVNO) for a defined duration. TRAI [20] has released its recommendations on the entry of MVNOs in the country. The recommendations have been forwarded to the Telecom Commission of the Department of Telecommunications (DoT) for review.
- 3) Exclusive use, rights transferred between operators: This involves outright purchase of spectrum by one spectrum holding mobile operator from another, normally referred to as spectrum trading. The main benefits of such a transaction could be to move spectrum from an under/un-used state to much valued used state. Though the same could be achieved through intra and inter circle roaming arrangements, the property rights are not transferred in the roaming case. However, in spectrum trading, the property rights and associated obligations are transferred from the seller to buyer. TRAI issued recommendations and subsequently issued working guidelines on spectrum trading in 2014 [18].

In the following section, we will discuss in depth the case of non-exclusive spectrum use which is the topic of this paper.

3. Licensed Spectrum Sharing

3.1. Non-exclusive sharing of licensed spectrum between mobile operators

In this case licensed spectrum is shared or pooled between mobile operators, mainly to enhance capacity of the RAN. Since the trunking efficiency of spectrum increases with larger spectrum holdings as pointed out in [14],

pooling of spectrum especially in spectrum congested dense areas is likely to give operators increased capacity. Further, spectrum sharing enables operators to operate their RAN on larger spectrum blocks thus improving spectral efficiencies through higher order technologies such as 3G, and 4G. TRAI came out with recommendations on spectrum sharing between operators and issued guidelines in 2014 [19].

As explained in [14], the access licensees in India have blocks of spectrum distributed as follows:

- i) Liberalized spectrum that has been allocated through auction (especially post 2008), that is technology and service agnostic;
- ii) Administratively assigned spectrum that is technology and service specific, especially restricted to offering 2G services.

The important features and caveats in the recommendations are given below:

- i. Spectrum sharing is allowed between two access licensees, both having access spectrum in the same band, in an LSA for their simultaneous use, using a common RAN.
 - a. This does not allow cross band sharing, especially those having only higher frequency bands to use lower frequency bands for coverage purposes; or those who have only lower frequency bands to use higher frequency bands for micro coverage for capacity augmentation.
 - b. Shared RAN is likely to promote efficient use of existing RAN infrastructure thus providing economies of scale and maximal utilization of existing RAN infrastructure.
- ii. Though spectrum sharing using a common RAN between two access licensees may be implemented only in part of LSA, the whole LSA will be considered for administrative purposes, especially for calculating the Spectrum Usage Charges (SUC) based on Annual Gross Revenue (AGR) of the operators.
 - a. The above clause is mainly due to the impracticality of monitoring only those RANs that are shared in an LSA. This is likely to reduce the sharing possibilities in larger LSA, due possibly to higher SUCs. The metro LSAs are likely to see more sharing implementations due to their limited geographical areas.
- iii. Though the access licensees may share only part of the spectrum holding, for the calculation of SUC which is a percentage of AGR, the entire spectrum holding in a particular band in the entire LSA. The SUC rate post-sharing will be increased by 0.5% of AGR. 50% of the spectrum held by the other access licensee in the shared band shall be counted as the additional spectrum being held by the licensee. This recalculated holding shall be used for the verification of whether the spectrum holding by the licensee is within 25% of total spectrum assigned in that LSA and 50% in a band.
 - a. This is likely to deter two licensees who have larger spectrum blocks to share due to possible violation of spectrum caps.
- iv. If any one or both the licensees sharing their spectrum, have administratively assigned spectrum in that band, then, after sharing, they will be permitted to provide only those services which can be provided through the administratively held spectrum.
 - a. The licensees still have larger block of administratively assigned spectrum especially in 1800 MHz which makes it uneconomical to share in that band.
 - b. Even if the access licensees migrate their administratively assigned spectrum to liberalized spectrum by paying a one-time fee, due to its non-contiguous assignment pattern, it is unlikely to offer any capacity augmentation through sharing arrangements.

3.2. Non-exclusive sharing of licensed spectrum between mobile operators and other entities

In most of the countries including India and USA, a large quantity of spectrum, including that allocated for commercial mobile communications is reserved for government use, especially for defence. Due to spectrum scarcity, many countries have taken the approach of loosening their command-and-control approach to spectrum management and allowing flexible use of government spectrum [14]. Moreover, a number of niche applications require specific bands of spectrum in certain locations at certain times. An example is the allocation of 2.3 GHz (Band 40) to the Program Making Special Events (PMSE) licensees that use professional wireless camera links of the broadcasting and TV production companies. This band is not harmonized and allocated for commercial mobile

services in Europe. However this spectrum band is not used by the incumbent holders across space and time continuously. Hence, the case for allowing secondary access to this spectrum band for mobile services. A tiered approach (i.e. secondary and tertiary) using opportunistic access mechanism is used for to enable sharing of spectrum between new operators and the incumbent holders [22]. It should be noted that in this case, the property rights are still with the incumbent. Whenever the primary user needs access to the spectrum block, it should be let free by the secondary or tertiary users. We list below some use cases of this mode of spectrum sharing being piloted in Europe and the USA.

3.3. Case study: Licensed Shared Access (LSA) in Europe

European Commission released ECC Report 205 on Licensed Shared Access (LSA) in February 2014 [5]. LSA is a complementary spectrum management tool that facilitates the introduction of new users in a frequency band while maintaining incumbents' existing services on the same band. LSA ensures a certain level of guarantee in terms of spectrum access and protection against harmful interference for both the incumbents and LSA licensees [16].

LSA in Europe on 2.3 GHz can be called *LSA Region Jump*. In this case, mobile spectrum band is taken to an International Telecommunications Union (ITU) region or regulated area, which has the band licensed for other than mobile use. An example of LSA Region Jump is to use Band 40 of 2.3 GHz that is used in 19 countries including Australia and India, with the help of LSA technology in Europe. The advantage in the LSA Region Jump is that the chipsets, mobile devices, and base stations exist in a different market area already. The investments required to begin deployment are modest compared to specifying a new band, developing a new chipset, and integrating it into the devices. An illustration of LSA Region Jump is given in the following Figure.

On the other hand, this approach will also complement the roll-out of services where Band 40 is currently being used as well. For example, Indian operators who acquired Band 40 in the auction in 2010 at very high prices are unable to roll out networks due to high cost of equipment and handsets in this band. The region jump option, if adopted in Europe, is likely to provide the required scale economies and reduce equipment and handset costs.

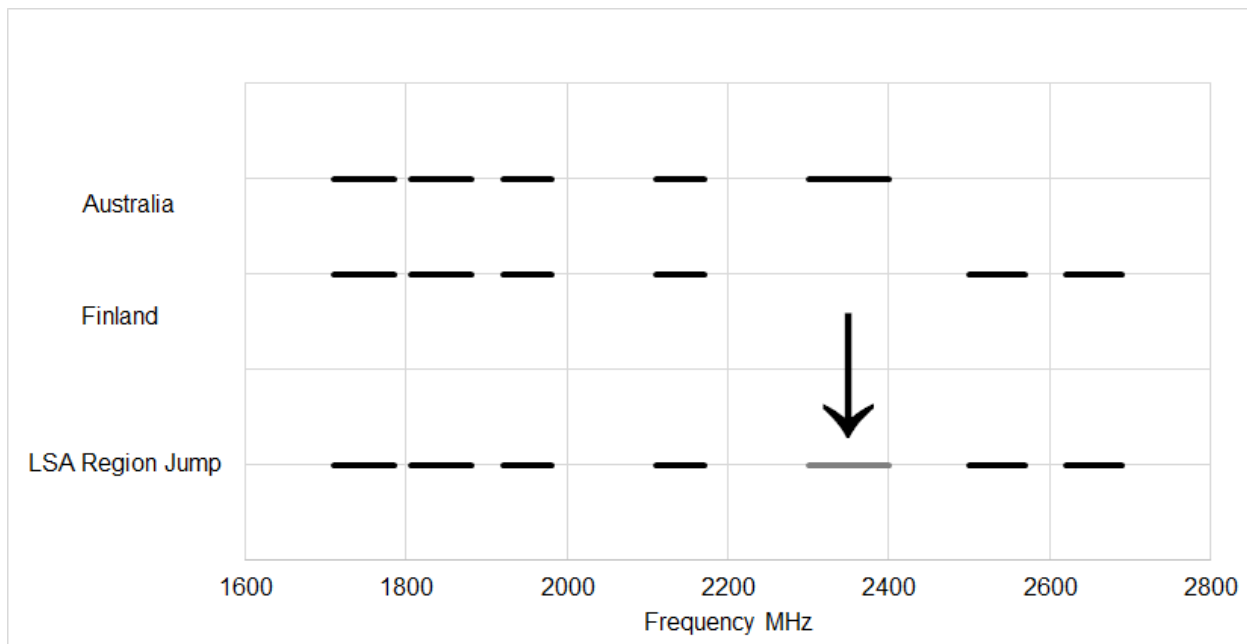


Figure 1. Illustration of LSA Region Jump across countries

In April 2013, Finland was the first country to trial the LSA on 2.3 GHz band, where the incumbents are PMSEs and secondary access is given to mobile operators. It is reported in [7] that The LSA concept can offer a complementary approach to traditional exclusive licensing and license-exempt operations with features that benefit all involved stakeholders.

3.4. Case study: Spectrum Access System (SAS) in the USA

Federal Communications Commission (FCC) in the USA proposed the release of 150 MHz in 3550-3650 MHz (3.5 GHz Band) currently used for military and satellite communication for shared use in 2012 [10]. In line with the recommendations of President's Council of Advisors on Science and Technology (PCAST), Spectrum Access System (SAS) envisions three tiers of service: (i) Incumbent Access, (ii) Priority Access, and (iii) General Authorized Access (GAA). Priority Access and GAA tiers would be licensed for users with automatic authorization to deploy small cell systems similar to installing Wi-Fi access points. SAS deploys a dynamic spectrum database to assign and monitor spectrum use and associated interference, thereby protecting higher level users from the usage by lower level users. A GAA tier would be assigned on an opportunistic and non-interfering basis within designated geographic areas.

As spectrum is moved from command and control or flexible use to a commons, the rights of licensees under the old regime need to be safeguarded. This issue acquires even greater importance in the context of spectrum held by government departments. In this context, the PCAST in the United States has proposed a model of spectrum sharing with a hierarchy of license types [15].

The paper of the President's Council argues that since measurements show that less than 20% of the capacity of prime spectrum (below 3.7 GHz) is used even in the most congested urban areas, there is a need to evolve a new spectrum architecture that enables more efficient use. Today wireless architecture is less commonly being built out for wide area coverage but is being built for higher aggregate capacity over small areas. Spectrum architecture is moving from a macro-cell to a micro-cell approach. This brings high frequency spectrum at par with low frequency spectrum due to the irrelevance of propagation over a large area.

The paper argues that we should move from a narrow-band approach where small swathes of spectrum are licensed to single entities over a large area, to a wide-band approach where wide swathes of spectrum (up to a factor of two in frequency) over localized regions are given to prioritized licensees who share the spectrum in accordance with their place in the pecking order. In order to provide a test case they have recommended that 1000 MHz of Federal spectrum be reallocated for sharing with three categories of licensees (PACT, 2012):

- i. *Federal Primary Access* – users would register their actual deployments in a database and would be guaranteed protection from harmful interference in their deployed areas. Users would have exclusive use of the spectrum when and where they deploy network assets or in locations where, or times when, underutilized capacity can be put to use without causing harmful interference.
- ii. *Secondary Access*: users would be issued short-term priority operating rights in a specified geographic area and would be assured of interference protection from opportunistic use. However they would be required to vacate when a user with Federal Primary access registers a conflicting deployment in the database. There may be multiple levels of secondary access, either because of payments (e.g. Auctions) or because of a public interest benefit.
- iii. *Generalized Authorized Access (GAA)*: users would be allowed opportunistic access to unoccupied spectrum if no Federal Primary or secondary users are registered in the database for a given frequency band, specific geographical area, or time period. GAA users would be obliged to vacate once a conflicting Federal Primary or Secondary Access deployment is registered. GAA devices should have the ability to operate on multiple bands, use dynamic frequency selection, so that there is no dependency on access to a particular frequency. Certain bands could also be subject to a device registration requirement.

4. Techno-economic model of spectrum management

An illustrative model of the trade-offs between unlicensed and licensed spectrum management is given in the Figure below.

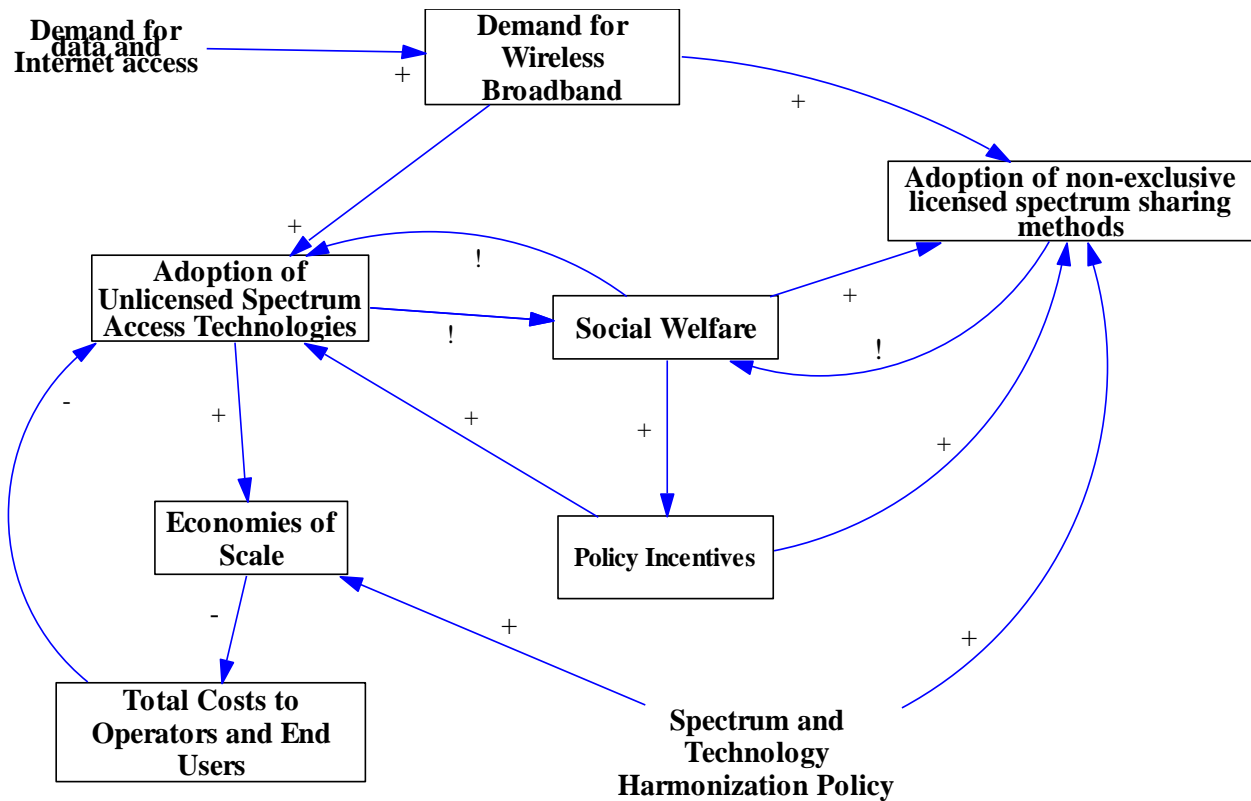


Figure 2. The techno-economic model of unlicensed and licensed spectrum management

The causal diagram illustrates the relationship between different variables of interest. The relationship is positive (or negative) if a change in the causal factor produces a change in the same (or opposite) direction in growth. The “!” refers to ambivalent relationship that needs to be tested. A closed sequence of causal links represents a causal loop.

There are two exogenous variables namely *demand for data and Internet access* and *spectrum and technology harmonization policy of the government*. The demand has a positive influence on the adoption of both the methods, namely (i) unlicensed spectrum technologies; and (ii) non-exclusive access to licensed spectrum. However, the success of either or both depends on the net social welfare generated. The social welfare has a reinforcing effect on the adoption of either of these methods. The successful adoption of one method influences the other through social welfare that is generated. Social welfare also has positive relationship with the policy incentives developed by the government to nurture the two methods. The adoption of unlicensed method also develops the associated equipment and devices and yields economies of scale effects; thus having an effect on price which further influences adoption. The harmonization policies have a positive association with the adoption of the two methods.

5. Case Study of India

India in certain ways is unique with respect to licensed spectrum management. There are, on average, 10 operators in each Licensed Service Area in India. Typically, an operator holds miniscule 2×10 MHz across all the 800, 900, 1800, and 2100 MHz commercial frequency bands. Out of the globally harmonized 2×60 MHz in 2100 MHz (Band I) for 3G services, only 20 MHz has been released by the government so far. Each of the 4 operators has 2×5 MHz. In the 1800 MHz band, only about 2×40 MHz has been assigned to mobile operators out of the total available block of 2×75 MHz. The following Table gives summary of telecom data in India:

Table 2. Telecom Data of India

Mobile subscriber base (in Million)/ Mobile density per 100 population	930.20/ 74.55
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Landline subscriber base (in Million)/ Landline density per 100 population	27.41/ 2.20
Number of Internet Subscribers (in Million): Wired/ Wireless	18.70/235.70
Number of Broadband subscribers (in Million) (Wireline/ Wireless)	15.13 / 60.60
Average spectrum holding per operator in a Licensed Service Area (in MHz) (Note: The country is divided in to 22 non-overlapping LSAs)	2 x 10 MHz
Average number of operators in each LSA	10
Market HHI	0.18
Spectrum HHI ¹	0.13

On the other hand, India has the second largest mobile subscriber base in the world. There are about 900 million mobile users of which 233 million access Internet using mobiles and 75 million subscribers have a 3G subscription. The scarcity of spectrum does indeed result in poor quality of connectivity. Due to spectrum scarcity, the operators pay huge sums for the auctioned spectrum, resulting a possible “winner’s curse”. India witnessed a high price of about \$6 / MHz / population in some regions for 2100 MHz band compared to about \$0.30 in the U.S. [14].

Following Table illustrates the amount of licensed spectrum currently available and in pipeline across countries. In India, the allocation for mobile services is less than half of that in the rest of other countries, with the exception of China. However, most of the countries including China have initiated the process of vacating some of the spectrum held by incumbents such as government and public utilities as shown under the column “P”. For example, in addition to the 360 MHz shown in the table, unpaired Digital Dividend band 703-803 MHz may also be made available in China for mobile services once the country deploys Digital TV. Hence in about 2-3 years, most of the countries would have allocated 600-700 MHz of spectrum while India is only planning to release 30 MHz for commercial mobile services. The small amount of spectrum is assigned to a very large number of operators in India, with the result that each operator gets roughly one-fifth to one-sixth compared to rest of the world. The spectrum fragmentation is clearly seen in the spectrum Herfindahl–Hirschman Index (HHI which is a measure of spectrum fragmentation): India: 0.13; USA: 0.28; Europe: 0.25; Australia: 0.26; Brazil: 0.21; China: 0.45 (higher value indicates lesser fragmentation).

Table 3. Currently available (CA) and in Pipeline (P) licensed spectrum allocation across countries

Band	USA		Europe		Australia		Brazil		China		India	
	CA	P	CA	P	CA	P	CA	P	CA	P	CA	P
700 MHz	70					90						
800 MHz	64		60	0-60	40		65		20		23	
900 MHz			70		50		20		52		36	

¹Spectrum HHI refers to Herfindahl-Hirschman Index (HHI) of the spectrum holdings by the various operators. It is computed as $HHI = \sum_{i=1}^n f_i^2$ where f_i refers to fraction of spectrum holding by operator in that service area and n refers to the total number of operators with spectrum holding in that service area. Spectrum blocks in different frequencies are added up to compute the total spectrum in an LSA. The HHI can range from 0 to 1; where 1 indicates that all spectrum is held by one operator and a value closer to 0 indicates excessive fragmentation of spectrum across different operators.

1800 MHz		15	120-150	0-20	150		150		90	60	86	
1900 MHz	130	10	15-35		20		20		35	20		
2100 MHz	130	30	120		120		110		30	90	40	30
2300 MHz	20				98						40	
2600 MHz	194		150-190	0-50		140	175			190	40	
Total	608	55	540-615	0-60	478	230	554	0	227	360	265	30

Due to spectrum scarcity the operators pay huge sums for the auctioned spectrum, resulting a possible “winner’s curse”. India witnessed a high price of about \$6 / MHz / population in some regions for 2100 MHz band compared to about \$0.30 in the U.S. [14].

The main reason for this tiny amount assigned to operators is due to holding of the major portion of the rest of the spectrum blocks both in 1800 and 2100 MHz by the Ministry of Defense (MoD). There have been many initiatives to release spectrum from MoD for commercial mobile services recently. The Department of Telecommunications (DoT) in India, through the state owned operator(s) is building a fiber optic network in select places in the country to replace the 2100 MHz wireless network. This project has not progressed as planned.

One of the promising alternatives to improve availability of spectrum to meet the demand is to deploy *spectrum sharing* to supplement operators’ existing spectrum from the government spectrum holding in commercial frequency bands. In [17] the authors have indicated that spectrum sharing and creating an active secondary spectrum market is needed to overcome the spectrum scarcity problems in India.

While the sharing of blocks in 1800 MHz can supplement the 4G-LTE offerings of the operators, sharing of 2100 MHz can augment spectrum holding for WCDMA services. The assignment method could be a suitably designed auction of the shared spectrum blocks in each of the 22 telecommunication service areas of the country. The revenue accruing out of the auction could be directly used to build alternative networks for MoD so that the blocks can finally be vacated for commercial mobile services, similar to the “incentive auctions” of the digital dividend spectrum being proposed in the U.S.

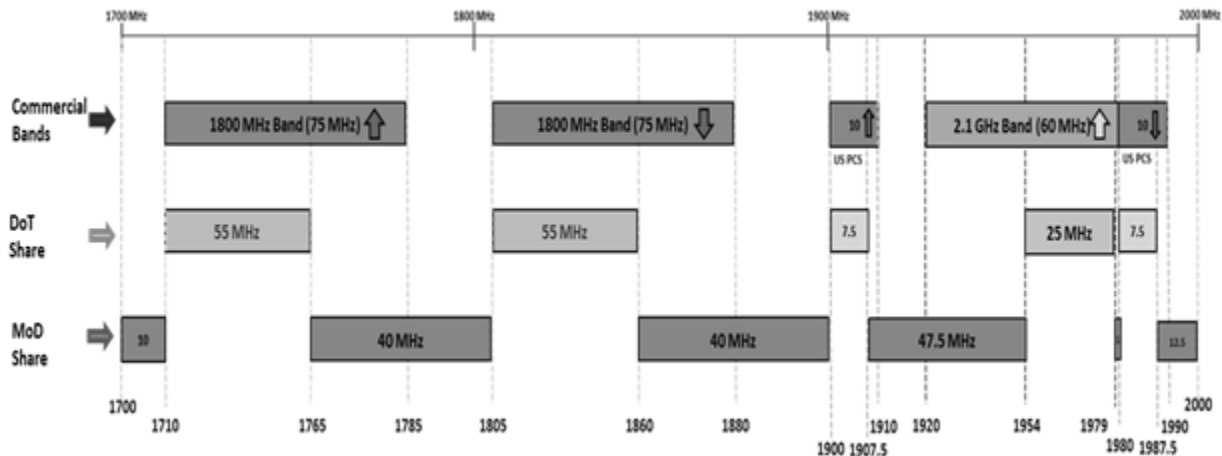


Figure 3. Spectrum allocation between DoT and MoD in India [14]

However, there is a need to convince the MoD and the Government of India (GoI) that LSA will not affect the primacy of the incumbent spectrum holder and alleviate security related concerns. Deployments of LSA in Europe

will certainly provide benchmark for India to evaluate this option seriously to provide much needed spectrum for improving wireless broadband services in the country.

6. Conclusions

The prevailing view amongst policymakers is that the vast majority of economic value from the usage of the spectrum is derived from licensed rather than unlicensed usage. But the value of unlicensed spectrum has always been undervalued. There are many studies that have illustrated the economic value of unlicensed spectrum using data from the United States. They include [21], [8], and [2] on various models including cellular-Wi-Fi offloading, Wi-Fi Internet Service provisioning, Wi-Fi in venues such as hospitals, and residential Wi-Fi. As per the recent work of [12], the sum of consumer and producer surplus effects of the technologies operating in unlicensed spectrum bands in the United States generated a total annual economic value of \$222 billion in 2013, and contributed \$ 6.7 billion to the nation's GDP. In [12] it is also estimated that by 2017, at least, \$547.22 billion in economic value and \$49.78 billion in contribution to the GDP, a significant increase from the 2013 estimate will be contributed by unlicensed spectrum and associated technologies.

There is an extant framework for price competition in markets for congestible resources developed in the operations, economics and transportation literature. In these frameworks, customers request service from Service Provider (SP) firms based on a delivered price that depends on the price paid for the service, announced by the SP, and the congestion cost. The firms then set prices to maximize revenue. The unlicensed spectrum can be viewed as an additional non-exclusive resource made available to each firm. In contrast, prior work on congestible resources has generally assumed that each firm only has access to a resource for exclusive use.

In [13] the authors introduce unlicensed spectrum as an additional resource. Any incumbent service provider as well as new entrants may offer service in the unlicensed band in addition to its licensed band. All customers in a licensed band are served by the associated SP, whereas the customers in the unlicensed spectrum may be served by different SPs.

Two cases are considered: (1) a homogeneous customer population in which all customers weigh the congestion cost and announced price in the same way, i.e., all customers see the same delivered price; and (2) a heterogeneous customer population in which there are two user groups ("high-" and "low-QoS") with different price-congestion trade-offs. In the heterogeneous model, adding unlicensed spectrum could conceivably cause the market to segment; namely, by assigning users desiring higher (lower) QoS to licensed (unlicensed) spectrum.

The main results are as follows [14]:

- i. The social welfare depends on the amount of unlicensed spectrum that is added to the market. Adding an amount of unlicensed spectrum in a particular range, starting from zero, can cause the social welfare to decrease (reminiscent of the Braess paradox)
- ii. In the homogeneous model, consumer surplus is a non-decreasing function of the amount of unlicensed spectrum.
- iii. In the heterogeneous model, both SP profit and consumer surplus can decrease.
- iv. In the heterogeneous model, the customer surplus can be a complicated, non-monotonic function of the amount of unlicensed spectrum added. (There can be many break points between which the customer surplus increases, decreases, or stays the same.)

In [21], the author estimated the value of unlicensed spectrum using a survey based method in case of U.S. consumers. So far no work has been done in this area with reference to India. It is our efforts to model and estimate the value of the unlicensed spectrum for non-exclusive use as an extension of the modeling framework presented in this paper.

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