Regulatory bottlenecks in the expansion of wireless Internet in India

School of Electrical Engineering

Thesis submitted for examination for the degree of Master of Science in Technology.

Espoo 9.7.2018

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Abstract of the master's thesis

Author	
Title	Regulatory bottlenecks in the expansion of wireless Internet in India
Degree programme	
Major	Network Economics — **Code of major**
Supervisor	Prof. Heikki Hämmäinen
Advisor	M.Sc. (Tech.) Jaume Benseny
Date	9.7.2018 — **Number of pages** 34+2 — **Language** English

Abstract

The Indian telecommunication market is the second largest in the world and is growing rapidly. It is evident from national reports[1] published by the TRAI that the urban markets are getting saturated and that there is a lot of potential and demand in rural areas. Given this situation, the thesis analyses four hypotheses as regulatory bottlenecks in the expansion of wireless Internet in India: (i) Licensed spectrum is scarce (ii) Low spectrum holdings is a bottleneck for the diffusion of wireless network across the country (iii) Market concentration of an operator is a bottleneck for the expansion of wireless network across the country (iv) The regulator is not providing sufficient incentives for the growth of community networks.

To address the hypotheses, we analyze the availability and utilization of licensed and unlicensed spectrum. To estimate the scarcity of licensed spectrum, we calculate the spectrum availability per subscriber(Hz). To examine the utilization of unlicensed spectrum, we perform case studies on community network projects.

The thesis aims to conclude the following results through the aforementioned analysis and study: (i) Licensed spectrum is scarce. (ii) Competition among the operators has a higher impact on the market penetration. (iii) Community network operators is a bottom-up approach but might not initially solve the problems caused by the spectrum scarcity in the expansion of wireless Internet in India. (iv) Policy recommendations for efficient use of spectrum allocation and especially to increase the utilization of unlicensed spectrum.

Keywords licensed spectrum scarcity; community network operators, regulatory recommendations

[1] The Indian Telecom Services Performance Indicators [8]

Preface

The research work for this master thesis has been carried out at the department of Communication and Networking of Aalto University, Finland. The work was supported by the EC H2020 RIFE (architectuRe for an Internet For Everybody) project Grant No. 644663. The first part of the thesis results has been published at the CTTE conference, Denmark, 2017. The abstract which includes the second part of the thesis results has been accepted at the 29th European Regional Conference of the International Telecommunications Society(ITS2018), Italy.

Firstly, I would like to express my gratitude to Professor Heikki Hämmäinen for his patience, support, guidance and encouragement in this project. It has been a great pleasure, honor and privilege to work in the Network Economics research team. I would also like to sincerely thank my advisor Jaume, who helped me in framing the right foundation of the thesis until the end and continuously supported my thesis work through insightful discussions. I would like to thank both of them for taking time to provide valuable comments to improve the quality of the thesis. I am very grateful to the Network Economics research team members for their friendship and inspiration.I would also like to thank my friends who motivated me throughout this.

Finally, this thesis would have not been possible without the encouraging support, blessings, and love of my parents, my sisters, and my dog, Foster.

Otaniemi, 5.7.2018

Bhavya Omkarappa

Contents

List of Acronyms

AHSS	Advanced High Strength Steel
3G	Third Generation
BSNL	Bharat Sanchar Nigam Limited
CP	Consultation paper
DEF	Digital Empowerment Foundation
DOT	Department of Telecommunication
ERP	Enterprise resource planning
GHz	Gigahertz
HHI	Herfindahl-Hirschman Index
Hz	Hertz
ICT	Information and Communication Technologies
IIT	Indian Institute of Technology
ISOC	Internet Society
ISPAI	Internet Service Provider's Association of India
ITU	International Telecommunications Union
LR	Licensing and Regulation
LSA	Local Service Area
LSA_m	Local service area ($m \in \{A, B, C, Metro\}$)
Mbps	Megabits per Second
MHz	Megahertz
MNO	Mobile network operator
MNO_z	Mobile network operator ($z = 1...10$)
MTNL	Mahanagar Telephone Nigam Limited
MTP	Media Transfer Protocol
mW	Milli watt
negHHI	negated Herfindahl-Hirschman Index
NOFN	National Optical Fibre Network
NTG	New Technology Group
Osh	Operator Spectrum holdings
RF	Radio frequency

RFID	Radio-frequency identification
RMSE	Root Mean Square Error
${s_{\text{i}}}^2$	Market share of MNO in n-th telecom circle
SCAFA	Standing Advisory Committee on Radio Frequency Allocation
SE	Standard Error
SH	Spectrum holdings
SIM	Subscriber Identity Module
SWOT	Strength Weakness Opportunity Threat
TC_n	n-th telecom circle ($n = 1...22$)
TRAI	Telecommunication Regulatory Authority of India
Tstat	Test Statistic
TVWS	TV White Spaces
W.Avg	Weighted Average
WANI	Wi-Fi Access Network Interface
W4C	Wireless for Communities
WiFi	Wireless Fidelity
WLAN	Wireless Local Area Network
WMN	Wireless Mesh Networking technology
WRC	World Radiocommunications Conference
WPC	The Wireless Planning and Coordination

List of Figures

List of Tables

1 Introduction

1.1 Motivation

Mobile broadband services are experiencing a rapid growth around the world. In India, the demand for licensed spectrum is rising rapidly, given that it has more than 800 million subscribers and an average of 10 operators in the mobile market. The projection of wireless subscribers by the end of 2020 is 9,684 million. The country is taking several measures to bridge the gap of digital divide[2] and to provide Internet throughout the country including under served regions of India. But the available licensed spectrum might not fulfill this demand alone due to the fact that it is a limited resource and its assignment to mobile operators is highly regulated. In fact, India represents one-sixth of the world population but the share of WiFi hotspots is less than 1/1000 [8]. In comparison to other countries, France is five times smaller than India but has 13 million WiFi hotspots and India has 31,000 hotspots (2017) [35]. As we recognize the contingency, it is important to identify the bottlenecks towards it. The thesis examines the extent of the scarcity of licensed spectrum and also analyses the economic value and the opportunities towards exploitation of unlicensed spectrum which can assist in overcoming the above challenges.

1.2 Research Question

The aim of our research is to examine the role of regulatory bodies in the top down approach such as in the licensed spectrum and also the bottom up approach such as in the unlicensed spectrum. The research question we address in this thesis is:
What are the main regulatory bottlenecks for wireless expansion in India?

The below hypotheses are identified to analyze the main bottlenecks in the diffusion of mobile Internet and proliferation of broadband services.

Hypothesis 1 : Licensed spectrum is scarce
Hypothesis 2 : Low spectrum holdings of operators
Hypothesis 3 : Inadequate market concentration
Hypothesis 4 : Lack of regulatory incentives for community networks

Hypotheses 1,2,3 are categorized with the usage of licensed spectrum and Hypothesis 4 with the usage of unlicensed spectrum. Regulatory recommendations are then made to overcome the challenges faced.

1.3 Scope of Research

The research focuses on analyzing the penetration of mobile Internet which is dependent on variables such as market concentration, spectrum holdings of the operator, etc. We estimate the availability of licensed spectrum per subscriber to derive the scarcity which is quantifiable. The scope of this research is limited to the data

[2] Social and economic inequality w.r.t access, use or impact of ICT in the country [37]

available publicly. A study of community network projects are performed. A majority of them are supported by DEF (Digital Empowerment Foundation). Previous researches have been performed on variables affecting diffusion of mobile Internet in developed and emerging countries [19] [27] [48]. Research on community network operators are performed in various other countries [23]. The concept of community network projects is still flourishing in India and hence there has been less research performed. Therefore, it is in the scope of the research to estimate the extent of licensed spectrum scarcity that the operators are facing and also to perform study on community network projects in India. The research also investigates the role of regulatory bodies in the project public Wifi pilot[3] which increases the proliferation of broadband services. A few recommendations are then presented which we believe will be useful to increase the diffusion of wireless Internet in urban and under served regions in India.

1.4 Country Selection

We have selected India for our study because Indian telecom sector has witnessed remarkable growth in the last decade. It has also emerged as one of the fastest growing telecom markets in the world. A very brief SWOT (strengths, weaknesses, opportunities,threats) analysis is performed below which motivates this study.

Strengths:

- High customer potential due to large growth in mobile subscriber base and subscriber additions
- High competition in the market between the operators in the supply chain, which will benefit the market
- Good market for startups and community network projects

Weaknesses:

- Slow pace of the reform process and hence late adoption of new technology compared to other cities in developing and developed countries
- The sector requires players with huge financial resources since the licensed spectrum itself is very expensive to buy
- Limited spectrum availability
- Low satisfaction rate with the growing subscriber demands
- Poor telecommunication infrastructure that causes a large number of calls to be disconnected prematurely.
- Most competitive market.
- The country's regulatory framework has been highlighted for corruption due to the past cases of mismanagement of spectrum affecting international investors relationship or confidence.

[3] It is an initiative taken by Indian regulator to provide an open architecture based WiFi Access Network Interface (WANI) where any entity, profit or non-profit organization is able to set up a paid public-WiFi access point through which WiFi services are provided.

Opportunities:

- Expansion of the Internet to rural areas
- Increasing the quality of service provided to the customers
- Having a fair price in the market
- Good opportunities for telecom manufacturing companies
- Good opportunity to flourish value added services

Threats:

- Huge price war

1.5 Methods

Firstly, a comprehensive literature review has been performed which highlights previous studies on regulation, licensed spectrum availability and the consultation papers to the TRAI with respect to the public WiFi pilot. An overview of the Indian broadband policy and regulatory processes is presented by discussing the role of regulation in spectrum management. We also discuss the Indian telecom regulator and its objectives in order to learn more about its role in the further study of this research. In order to understand the differences between licensed and unlicensed spectrum, a brief comparison is made between 3G and WiFi technology. Furthermore, we have performed a basic statistical study of the Indian telecom market which provides an inherent summary on the division of telecom circles and its classification to the local service areas. This serves as a base helps to understand the latter part of the quantitative study on spectrum availability and utilization. In the last part of the literature review, we have introduced the concept of community network projects by gathering different definitions of it from the earlier studies.

Secondly, to address hypotheses 1-3 we analyze the availability and utilization of licensed spectrum. The scarcity of licensed spectrum is estimated using 'spectrum per subscriber' (Hz). It is calculated across the telecom circles and then compared with the data available on the national level. Since the concentration of markets in each telecom circle varies, we have considered 'weighted average'as a metric for the evaluation of variables like HHI (Herfindahl-Hirschman Index), which determines the competition between mobile operators. We have performed a regression analysis to study the diffusion of mobile Internet across telecom circles and local service areas. Market penetration is taken into account as a dependent variable. We derive a regression model to indicate the degree to which the market conditions such as number of operators, competition, subscriber density, population density, and operator spectrum holdings (spectrum capacity) affect mobile network penetration. Through this, we interpret the bottleneck for the diffusion of mobile Internet across the country. The tools we have used for the analysis are 'R' and 'MATLAB'.

To address hypotheses 4, we perform different case studies on community network projects in India. We believe community network projects establishes a bottom-up perspective in the expansion of the wireless Internet in India. Community network operators usually set up the network for the communities' welfare and build up the infrastructure with the support of the community, other nonprofit/profit organizations to offer wireless access [37]. Establishment of these networks is inexpensive and is relevant to the local needs of that community. We summarize the challenges faced by them and the factors hindering their growth in the rural regions of India. The project 'public WiFi pilot' is extensively studied to understand the role of the regulator and its impact on closing the gap of digital divide in the country.

Lastly, we present some regulatory recommendations to overcome the scarcity of the licensed spectrum by having efficient policies and regulating the market concentration of operators. The primary need of regulatory bodies to promote community network projects is also suggested.

1.6 Structure of Thesis

The structure of the thesis is represented in Figure 1. Chapter 2 introduces background to the thesis. It introduces the regulatory bodies, the comparison between licensed and unlicensed spectrum. An overview of the Indian telecom market is provided with market assessment of the mobile network operators and the existing study of the community network operators in India. Chapter 3 analyses the licensed spectrum scarcity and also the effect of different variables on mobile network penetration. Chapter 4 studies the availability and utilization of unlicensed spectrum. Chapter 5 provides the results obtained in the previous chapters and recommends regulatory actions as a conclusion.

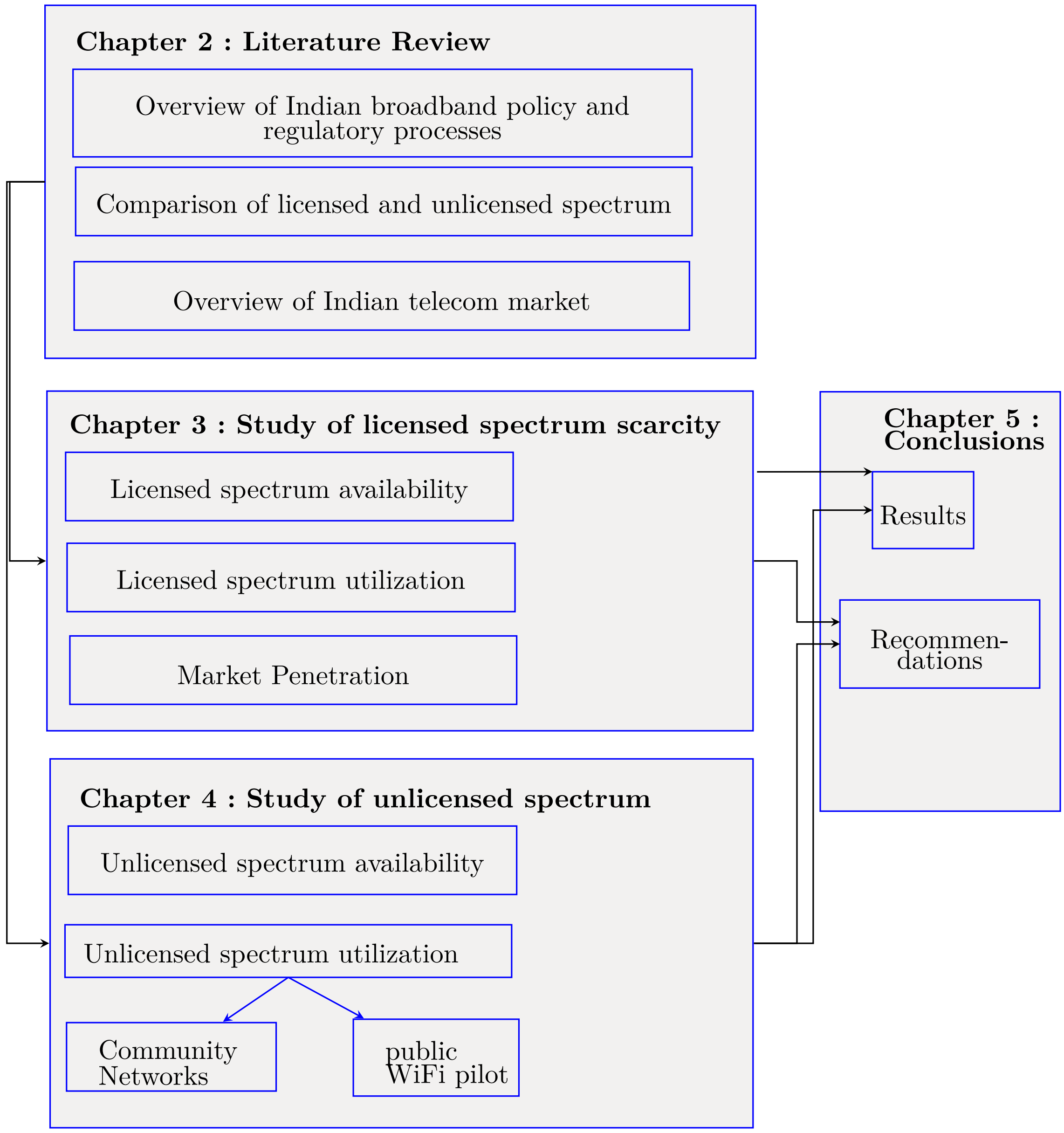

Figure 1: Structure of thesis

2 Literature Review

2.1 Overview of Indian Broadband Policy and Regulatory Processes

2.1.1 Role of Regulation in Spectrum Management

Usage of radio spectrum has been highly regulated to prevent interference among users particular for defense and security reasons. Regulation of spectrum is required not only for efficient usage of the spectrum itself but also to maintain a healthy competition between the operators in the market. The regulations for the usage and management of the radio frequency spectrum is agreed upon by the ITU at the World Radio communications conferences (WRCs) [39]. Telecommunications policy and regulatory reform in India has undergone numerous changes, especially with licensing [21]. In 1996, Eli Noam predicted that TV regulation will become telecom regulation [?] and states that TV spectrum became scarce because the government allocated the frequencies inefficiently. In the first place, they believed that the spectrum was scarce and that regulation was needed but it turned out to be quite the opposite.

2.1.2 Indian Telecom Regulator and its Objectives

The Indian telecom regulatory framework is shown in the Figure 2, in which it is classified under Indian government bodies and independent bodies.

1. The Wireless Planning and Coordination (WPC) wing of the Ministry of Communications was created in 1952 and is the National Radio Regulatory Authority. It is responsible for the radio frequency spectrum management, which includes licensing and it caters to the needs of all wireless users which includes both government, and private users in the country. It is divided into:

   - Licensing and Regulation (LR)
   - New Technology Group (NTG)
   - Standing Advisory Committee on Radio frequency allocation (SCAFA)

   SCAFA is the entity that makes the recommendations which relate to all the radio frequency allocations, the allocation plan and recommendations on the various issues related to the International Telecom Union (ITU).

2. Department of Telecommunications (DoT) is responsible for granting licenses and takes care of the frequency management of telecom.

3. Group on Telecom and IT handles the adhoc issues of the telecom industry.

4. Telecommunication Regulatory Authority of India (TRAI) acts as a sole independent regulator of the business of telecommunication in the country. The main objective is to encourage growth in the telecommunications sector in India by forming a transparent and fair policy environment that also supports healthy competition in the telecom market.

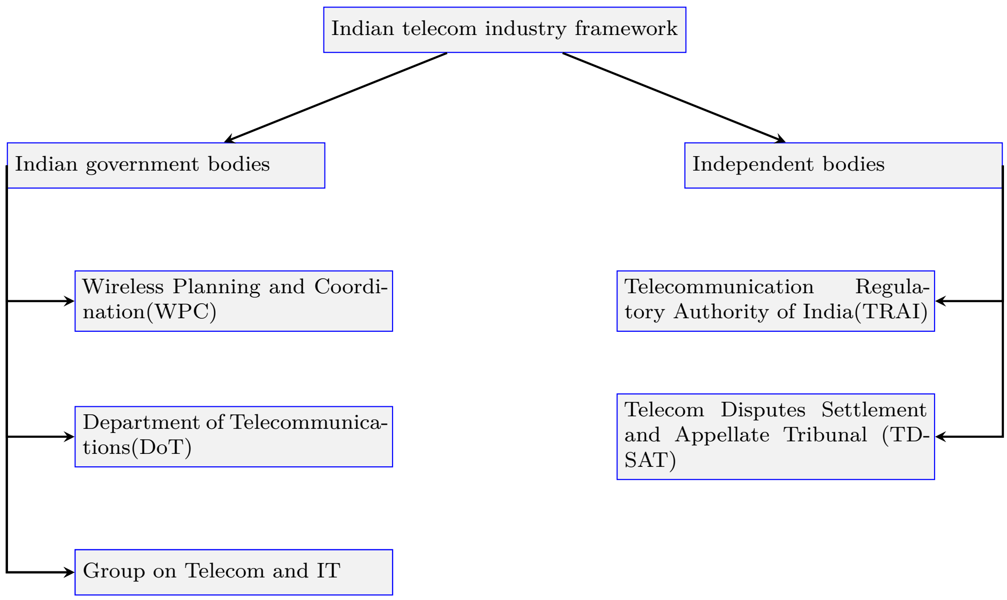

Figure 2: Framework of Indian Telecommunication Industry

5. Telecom Disputes Settlement and Appellate Tribunal (TDSAT) takes care of disputes and disposal of appeals.

2.2 Comparison between Licensed and Unlicensed spectrum

2.2.1 Comparison between Wireless Internet Access: 3G vs. WiFi

Table 1 compares 3G and WiFi technologies which operate in the licensed and unlicensed spectrum, respectively. The technical comparison of both technologies is kept out of the scope and hence not covered in the following table.

3G	WiFi
The business and the service model for 3G is more advanced and has an existing structure.	The business and the service model for WiFi is much less advanced since the commercialization of these services is still in the initial stages.
The basic business model is that the operators or the players own the infrastructure including the spectrum bought and then they sell services using this	The basic business model is that of the equipment suppliers who supply to end users or the consumers.
3G provides wide coverage with narrow bandwidth.	WiFi provide less coverage with higher bandwidth
Supports call handover which is handled by the base stations	Private hotspots are used for WiFi technology
3G follows top-down approach to provide Internet access. while the spectrum distribution is centralized	WiFi follows end user-centric approach to deliver internet access, while the spectrum distribution is decentralised
Voice services are the inherent features of 3G and then data services were provided	WiFi has emerged out of a data communications industry. Voice services are not the intrinsic feature of WiFi
3G operates in the licensed spectrum	WiFi operates in the unlicensed spectrum in the 2.4 GHz band
An operator/player has very high entry costs to acquire spectrum and build infrastructure to provide wireless services	Since the spectrum is shared, and the infrastructure is quite inexpensive to deploy and needs a backhaul network, the entry costs for a player is comparatively much lower
Radio communications are more secure and private. Interference is avoided.	public WiFi is less secure compared to 3G but private WiFi is secure.
Mobile technologies were evolved to support high-speed handovers between base stations	WiFi technology was not designed to support high-speed handovers
The service is sold to both residential and business customers on a subscription basis	The service is free to customers who belong to a closed user community, like employees of a company, students at a university, or travelers at the airport
	The power constraints limit the range of WiFi base stations

Table 1: Comparison of 3G and WiFi technology [30]

2.3 Overview of Indian telecom market structure

2.3.1 Analysis of mobile data market

India is divided into 22 telecom circles which are grouped into four different local service areas(LSA). The classification is done based on population density, subscriber base and also revenue potential. Table 2 provides some of the analysis done and is grouped under the telecom local service areas.

Variables \ LSA	**METRO**	**A**	**B**	**C**
No. of telecom circles	3	5	8	6
No. of subscribers (millions)	107.5	377.8	430.7	162.2
Population density (population/km^2)	18137.26	1440.27	1221.04	392.12
Subscriber density (subscriber/km^2)	36612.19	1646.43	1552.27	556.43
Mobidensity (%)	240	100	75	60
Penetration	2.29	1.01	0.88	0.70
W.Avg Operators	8.6	9.1	8.9	8.3

Table 2: Different variables across local service areas

Figure 3 shows that the population density and the subscriber density decreases across the LSAs being Metro, A, B and C. The subscriber density is greater than population density for many reasons. Each person can hold multiple mobile service connections (SIM cards), inactive subscriptions. Dual SIM variants i.e., mobile phones which can accommodate more than one SIM is very common in India. This already accounts for two subscriptions for one person. It is important to understand that the market penetration (subscribers/population) can be distorted because of this.

Mobile Operators: India has 11 operators operating in different telecom circles. No telecom circle has all the 11 operators operating. The least number of operators in a telecom circle is 7 and the maximum number of operators in a telecom circle is 10.

Cellular Subscriptions: A cellular subscription is defined by TRAI as an active IMSI (SIM Card) registered with an account. From Figure 4, local service area B has the highest cellular subscriber base and Metro has the least cellular subscriber base. The mobile penetration decreases from Metro to telecom circles A, B and C. It is highest in the Metro service region and the lowest in telecom service area C as shown in figure 2.

Due to the possibility of one person holding multiple subscriptions, mobidensity[4] is calculated. From Figure 5, it is seen that the mobidensity decreases across the local service areas Metro, A, B and C. This does not imply the percentage of people holding a subscription but gives us a picture of the reality of subscriptions in the local service areas.

[4]Mobidensity is defined as mobile cellular subscribers per hundred inhabitants which is calculated by dividing the number of subscribers by the estimated population, and multiplied by 100.

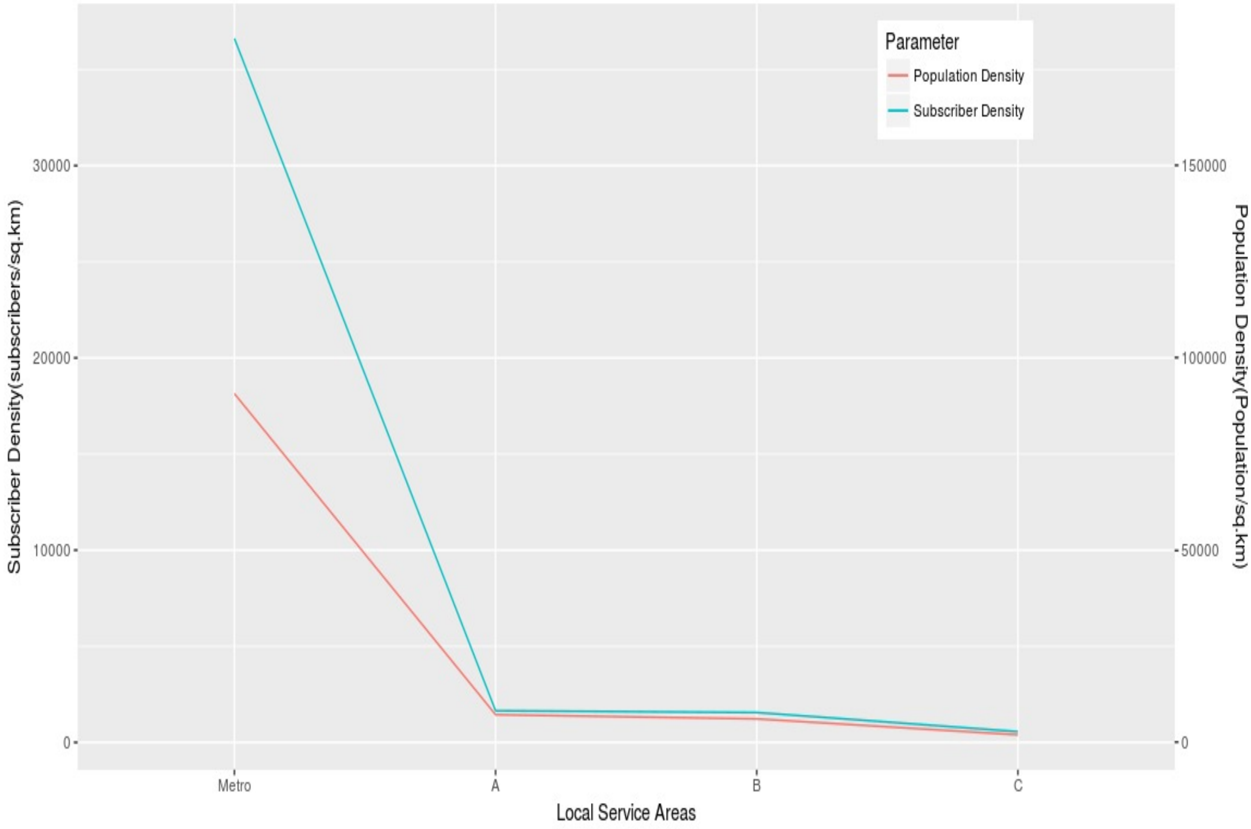

Figure 3: Comparison of population density and subscriber density across the service areas

2.3.2 Analysis of Wi-Fi Market

The Telecom Regulatory Authority of India (TRAI) understands the importance of public WiFi networks and have initiated support to a project called 'public WiFi pilot'. The motivation of this project comes from the success of TV regulation in India. The objectives of this pilot is to provide an open architecture based WiFi Access Network Interface (WANI). The consultation paper, it indicates that the government is supporting small entrepreneurs and private entities in the community to sell WiFi network services for public use [6]. The consultation paper (CP) "Consultation on Proliferation of Broadband through Public WiFi Networks" with regard to this pilot addresses the possible challenges such as the interoperability between different providers of the WiFi services and delicensing additional unlicensed bands which is required when WiFi service usage increases [6]. The success of this pilot depends on the area of deployment. If it becomes a profit model, then there are possibilities of small entrepreneurs setting up their WiFi networks in urban areas where there are already good network services provided by the mobile-network operators. This means that the operators providing WiFi services can compete with the mobile network operators and WiFi could become a competing technology instead of a complementary service.

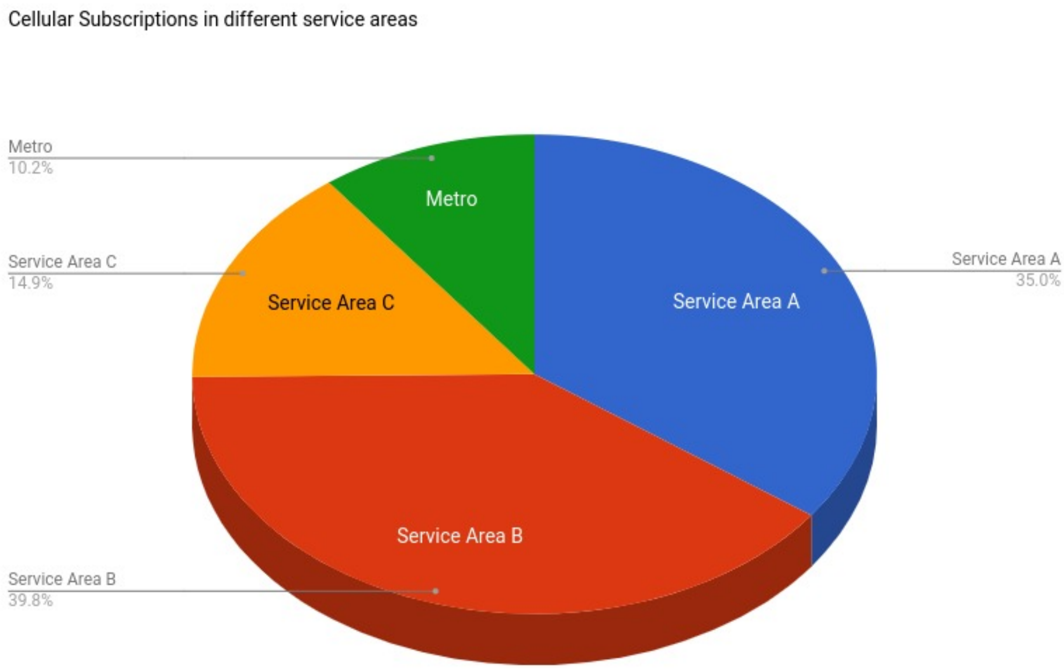

Figure 4: Cellular subscriptions in different service areas

Another set of bottom up approach which is very common in small communities throughout the world are community networks. The definition of community networks is wide and might differ slightly among academic, technical, government, and regulatory perspectives. For example, Baig, Freitag, Roca, and Navarro (2015) defined these networks as 'crowdsourced networks'. They are supposed to be open and free, built by the members of the community, and is usually managed as a common resource. Ellin-Koren (2006) defines community networks as architectures that are distributed in which users implement a decentralized network through the decentralization of the hardware supporting the network. The European Commission (EC) defines it as a 'community broadband model' which is a private initiative by the local residents of the community. It is a bottom up approach using unlicensed spectrum instead of the traditional top-down approach which uses licensed spectrum and involves mobile network operators [46].

Community networks can be used as an alternative approach to the commercial model in which Internet services are sold to end users, but in a typical case, users get together and establish connectivity between themselves. In India, community networks do not yet have a solid space in the society. There are very few projects

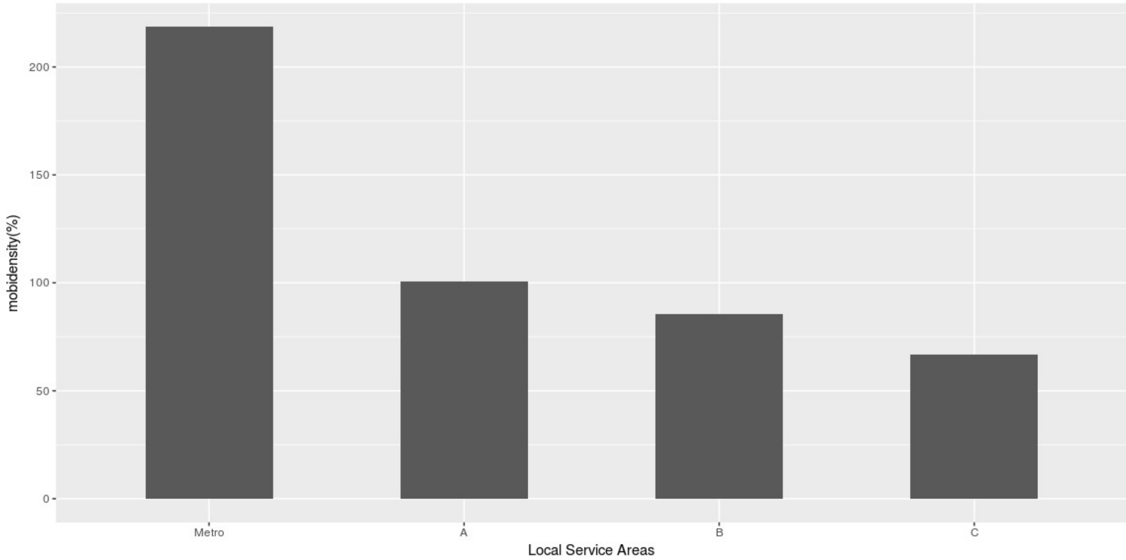

Figure 5: Mobidensity across service areas

which are established yet. The study of these projects is covered in Chapter 4.

3 Study of Licensed Spectrum

3.1 Definition of Spectrum Scarcity

Spectrum scarcity can be defined as the limited spectrum available to the mobile network operators in order to provide the required quality of service to their associated customers. Spectrum scarcity is an estimate of the total available spectrum for a single subscriber. This parameter is calculated by dividing the available spectrum (MHz) by the number of cellular subscribers (in millions), and is termed as spectrum availability per subscriber.

As defined in Hypothesis 1, licensed spectrum is scarce. We know that licensed spectrum is a limited resource. But scarcity is also possible when the operators are not getting sufficient spectrum to provide to their subscribers the required quality of service. We justify through the following analysis.

3.2 Licensed spectrum

3.2.1 Research Method and Data

The data for the following analysis has been gathered from different sources such as the spectrum holdings of the telecom service providers from the Wireless Planning and Coordination (WPC) wing. The data corresponds to the year 2015. The wireless subscriber base has been taken from TRAI reports and is also from the year 2015. The other variables such as population corresponds to the year 2011. Please refer to Table B for the complete data used for the analysis.

We have considered 'weighted average' for the evaluation of different variables for local service areas. The reason is that the market concentration is not equal in the telecom circles. Hence the variables such as HHI Index, spectrum holdings of an operator, and the spectrum holdings per subscriber is weighted by the number of subscribers in that particular local service area. The tools we have used for the analysis are `R` and `MATLAB`.

The equations for the calculation are as follows.

$$s_i^2 = \frac{No.\ of\ subscribers\ of\ MNO_z in\ TC_n}{Total\ no.\ of\ subscribers\ of\ all\ MNO\ in\ the\ TC_n} \tag{1}$$

$$HHI\ in\ TC_n = \sum_{i=1}^{z} s_i^2 \tag{2}$$

$$w.avg\ HHI\ of\ TC_n = HHI\ of\ TC_n * \frac{Total\ no.\ of\ subscribers\ in\ TC_n}{Total\ no.\ of\ subscribers\ in\ LSA_m} \tag{3}$$

$$w.avg\ HHI\ of\ LSA_m = \sum_{i=1}^{n} w.avg\ HHI_i \quad (4)$$

$$SH\ per\ subscriber = \frac{Total\ no.\ of\ SH\ of\ all\ operators\ in\ TC_n}{Total\ no.\ of\ subscribers\ in\ TC_n} \quad (5)$$

where
${s_i}^2$ = market share of MNO in TC_n,
TC_n = n-th telecom circle (n = 1...22),
MNO_z = mobile network operator (z = 1...10),
LSA_m= local service area (m = A, B, C or Metro),
SH = spectrum holdings.

3.2.2 Quantitative Analysis on Licensed Spectrum Availability

The thesis discusses the licensed spectrum scarcity on a country level through the Table 3. From Table 3, it is seen that China and India are the countries with the largest cellular subscribers and that the spectrum available to those countries is relatively small. Hence, when the spectrum per subscriber is calculated, the spectrum each subscriber gets is very small. In India, a subscriber on average relatively gets 0.2Hz spectrum for his/her usage.

Country	**Available spectrum (MHz)**	**Cellular subscribers (in millions)**	**Spectrum per subscriber (Hz)**	**MNO**	**HHI**	**4G speed (Mbps)**
India	221	1127.0	0.2	11	0.14	6.39
USA	608	416.7	1.5	5	0.25	13.95
China	227	1364.9	0.16	3	0.47	21.74
Finland	398	7.3	54.52	3	0.33	24.34
Australia	478	26.5	18.0	3	0.35	32.50
Germany	615	94.4	6.51	3	0.28	20.30
Japan	500	164.2	3.04	3	0.36	22.38

Table 3: Summary of the licensed spectrum for mobile broadband in selected countries [37]

A drawback of Table 3 is that the values are absolute and even though these values provide us a picture of spectrum scarcity, it is quite difficult to prove that the licensed spectrum is scarce with absolute numbers. Since the frequency is reused, it might imply that the spectrum per subscriber calculated in the table above might not be accurate. For this, in the subsequent sections, spectrum per subscriber is calculated at the telecom circle level.

Figure 6 provides an overview of the spectrum holdings of operators per telecom circle, weighted average and the median per local service area (A, B, C, and Metro). The median is estimated with the operator spectrum holdings of all the telecom circles in that respective local service area. Even though there is not much difference between the median and the weighted average, we would like to say that the weighted average is more accurate since the weight of the subscribers per region is taken into consideration.

The operator spectrum holdings across the telecom circles is between 210MHz and 290MHz. From Figure 6, the telecom circles in LSA 'B' has the maximum operator spectrum holdings compared to any other telecom circle. By comparing the operator spectrum holdings per LSA as well, we see that in LSA 'B', the operator have the highest spectrum holdings to serve their customers. The least spectrum holdings per operator in seen in LSA 'A' and in the Metro region. One reason could be that the LSA 'B' has the highest number of telecom circles.

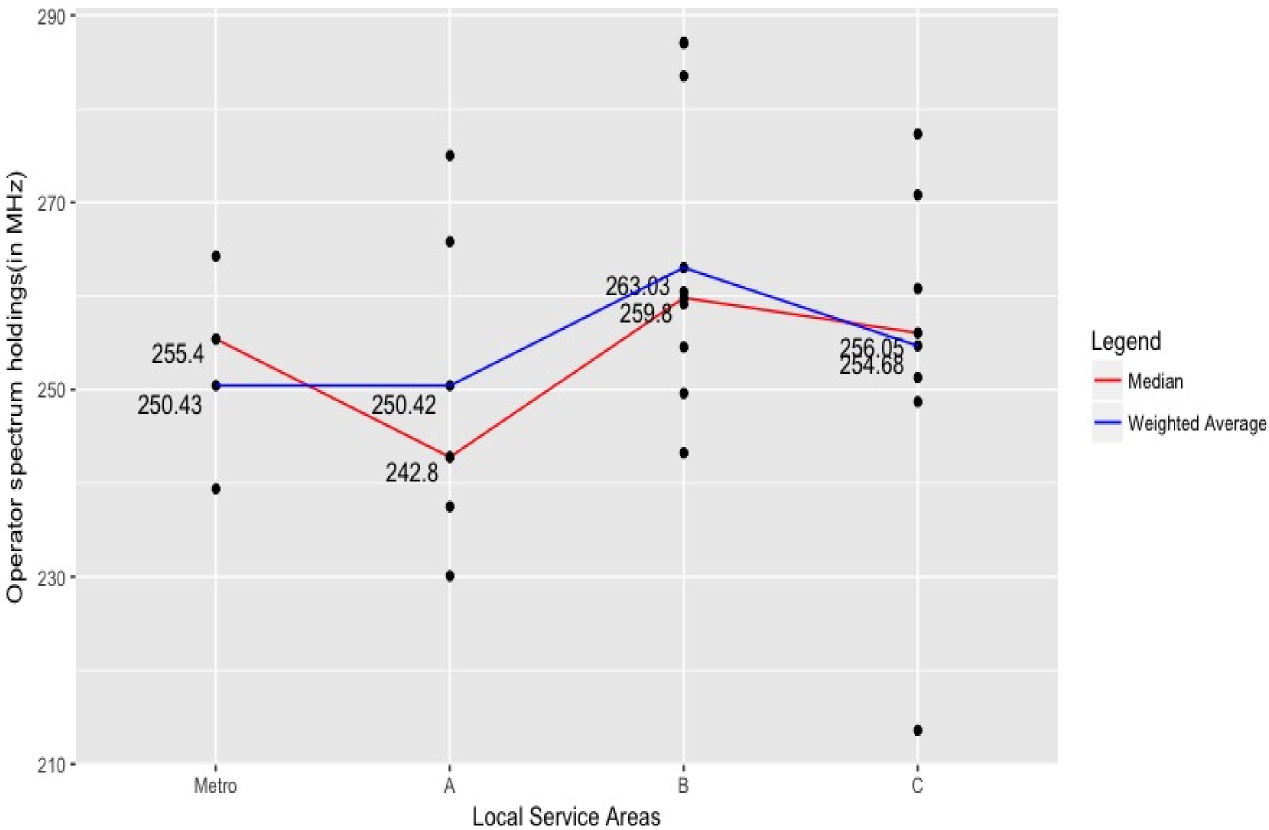

Figure 6: Operator spectrum holdings across local service areas

The parameter 'spectrum availability per subscriber' gives us a broader view of spectrum scarcity. With the current number of subscribers and the amount of spectrum available per operator, which is a cumulative summation of all the bands to serve different services, we see from Figure 7 that the subscribers in the local service area A have the least amount of spectrum per subscriber. Each subscriber in the local service area A gets an average of 3.29Hz of the spectrum. The subscribers in LSA ‘C’ get an average of 9.38Hz of spectrum for their services. The reason could be that the LSA ‘C’ has a lot of telecom circles in the rural area and that the subscriber numbers are low. It is also evident that the spectrum associated to LSA ‘C’ is almost the same as with the other telecom circles that we have seen in the previous graph in Figure 6. Spectrum per subscriber needs to be calculated at the lower most level, i.e., city level because of frequency reuse. The data of the spectrum holdings are available at the telecom circle level in India and is one of the reason for the calculation of spectrum availability per subscriber at the telecom circle level. These figures are an approximation and allow us to understand the extent of spectrum scarcity across the local service areas.

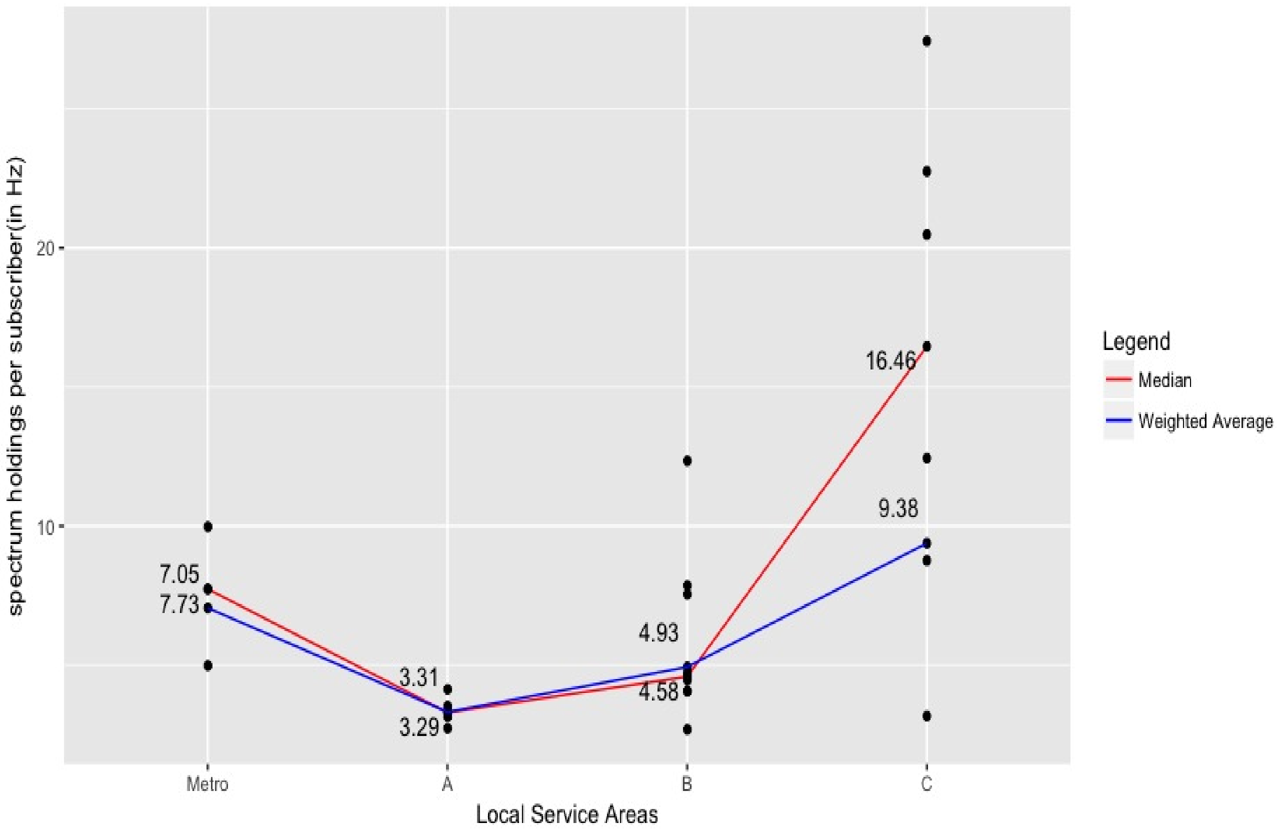

Figure 7: Spectrum holdings per subscriber in different local service area

3.2.3 Quantitative Analysis of Licensed Spectrum Utilization

This subsection deals with the quantitative analysis performed on licensed spectrum utilization in terms of mobile penetration and the competition of mobile network operators among the telecom circles and local service areas.

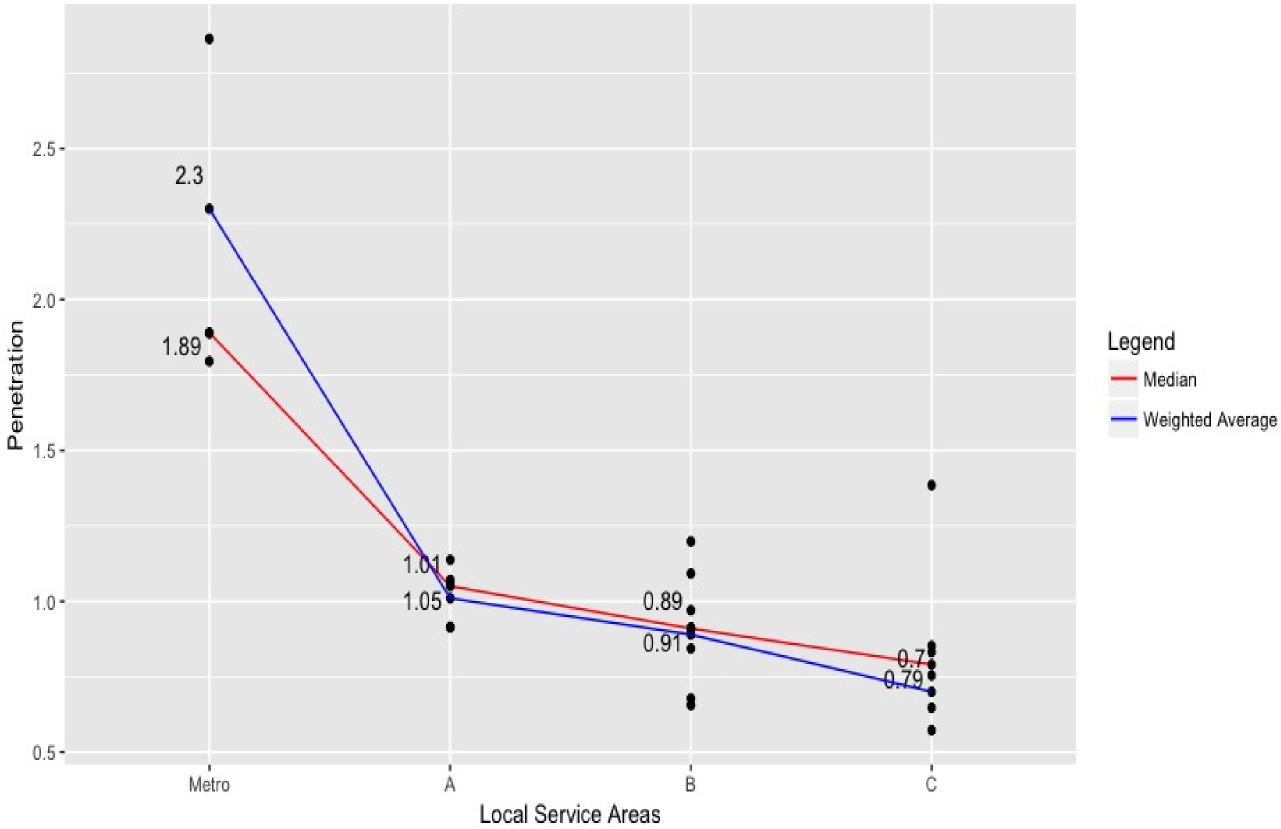

Figure 8: Penetration among telecom circles and LSAs

From Figure 8, it is seen that the mobile penetration is at highest in the metro region and then decreases across the local service areas A, B and C. The low penetration values in local service C is an evidence that there are a lot of opportunities to increase penetration in that service area.

The term 'HHI' means the Herfindahl–Hirschman Index, a commonly accepted measure of market concentration. The HHI takes into account the relative size distribution of the firms in a market. It approaches zero when a market is occupied by a large number of firms of relatively equal size and reaches its maximum of 10,000 points when a market is controlled by a single firm. The HHI increases both as the number of firms in the market decreases and as the disparity in size between those firms increases [2]. The lower HHI index nearing 0 indicates high competition and the higher HHI index indicates low competition. Figure 9 shows that the competition between the mobile network operators is the highest in the metro region and is lower in local service areas A, B, and C. The number of operators does matter to the competition between the network operators to a certain extent but the addition of the number of operators doesn't change the competition in the market after a

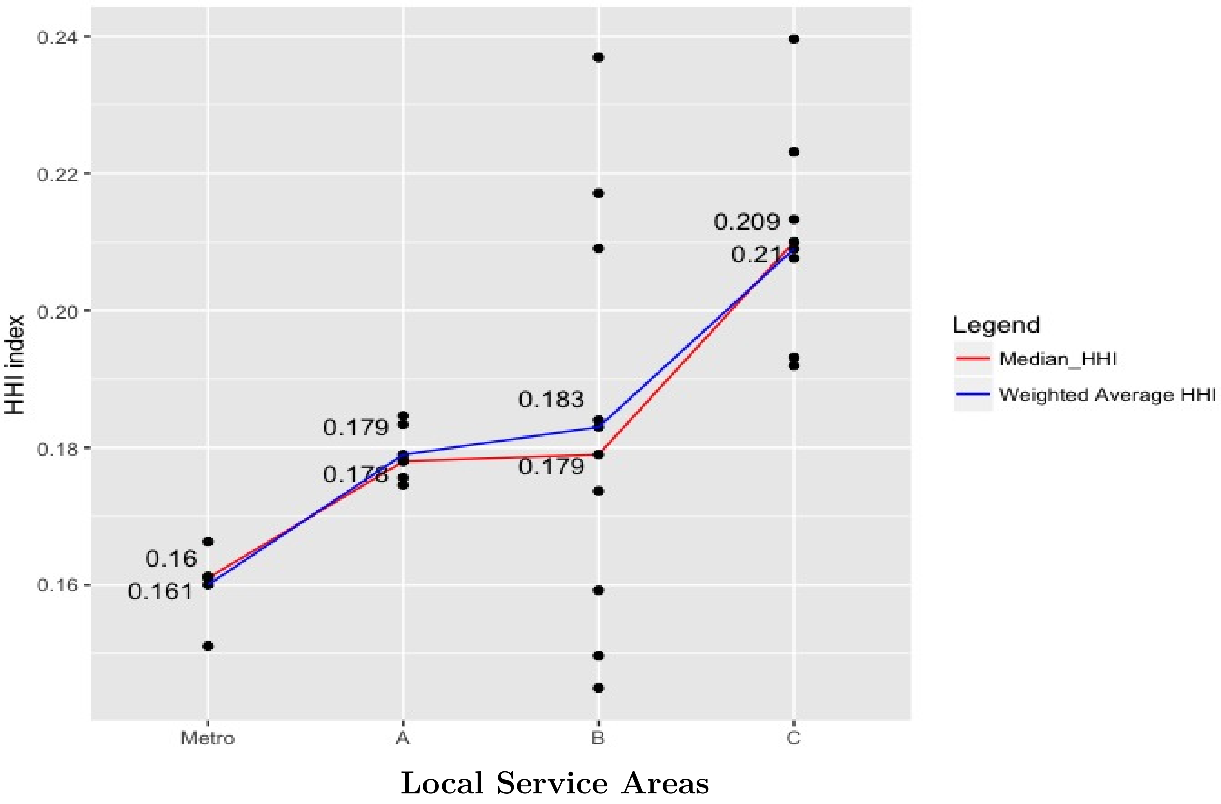

Figure 9: Competition between telecom operators across telecom circles and LSAs

certain number of players. However, the competing operator firm size matters for the increase in the competition. Meaning, two small sized companies will not increase the competition with a player having the highest market size.

3.2.4 Effect of Market Conditions on Mobile Network Penetration

In this subsection, we aim to find a correlation between different variables related to the telecom market which impacts network penetration. We narrow it down to find a correlation between competition in the market and mobile network penetration. The primary goal is to test the hypotheses 2 and 3 which states that competition and low operator spectrum holdings are a bottleneck for the expansion of wireless Internet in India.

Our modeling approach on the effect of network penetration with these independent variables is discussed below. The impact of the independent variables such as the number of network operators, competition between the network operators (HHI), subscriber density, population density, and spectrum holdings by the operator on the network penetration is expected to be positive as described in Table 4, but the degree of impact is of special interest.

Independent Variables	**Expected impact on the penetration**
Number of network operators	Positive
Competition between the network operators (HHI)	Positive
Subscriber density	Positive
Population density	Positive
Operator spectrum holdings	Positive

Table 4: Impact of market variables on network penetration

We present the regression results of the impact due to single independent variables in the below Table 5. It depicts that the operator spectrum holdings has a very low impact directly on the penetration of the network. It shows r-square of 0.0109. This is contradictory to what we thought of initially. It might not be that the penetration increases with the increase of quality of service. People seem to be late adopters of technology in India and this result proves that to increase the penetration, they do not really need the latest technology. However, population density has a positive greater impact on the penetration of the mobile Internet. This is also proved in the previous section. From Figure 8, the penetration is highest in the metro areas, which comprises of telecom circles that has high population density. We have considered negHHI in the above model since HHI is inversely proportional to the competition. From the results, it is so that competition as a single variable also has a negligible impact on the penetration. Because of this, we model the combination of the independent variables states above as follows.

Regression Model	**Estimate**	**SE**	**Tstat**	**Pvalue**	**R-squared**	**RMSE**
Penetration ~1 + negHHI	9.8008	3.5795	2.738	0.012676	0.273	0.453
Penetration ~1 + No.Of Operators	0.084545	0.14555	0.58085	0.56783	0.0166	0.527
Penetration ~1 + Osh	-0.002866	0.0061201	-0.4683	0.64457	0.0109	0.528
Penetration ~1 + subscriberdensity	3.2458e-05	4.9254e-06	6.5899	2.0282e-06	0.685	0.298
Penetration ~1 + populationdensity	5.6209e-05	1.2056e-05	4.6624	2.000014	0.521	0.368

Table 5: Regression results on single independent variables

Regression Model 1 is depicted in Figure 10. The model takes into consideration of all the independent variables we have seen in the above Table 4. It has a higher rsquare of 0.71 due to the linear relationship between subscriber density and penetration holds. Penetration is higher with higher subscriber density. We use coeffiecient pValues to determine which variables need to be retained in the model. A predictor which has a low pValue could be an effective addition to the model, since the changes in the predictor value is directly proportional to the changes in the response variable. In this model, we could probably use subscriber density as the predictor variable, but since it holds a linear relationship with penetration, it is quite obvious that its inclusion will lead to a significant model. However, this model helps us determine the most intricate variables to the impact of penetration in the mobile market, and that is population density, and subscriber density. It can be categorized towards the demand of the spectrum or mobile services in the market. Number of operators and the competition between them also affects the penetration of the mobile Internet and these variables can be categorized towards the supply of the spectrum or to the mobile services.

Regression model 2 is another following model which better explains the network penetration in terms of supply variables such as competition and the number of Operators. It is intuitive that with competition, there is innovation in the market. Model 2 has a low value of R-square, but is still a significant model if the slope coefficients and the coefficient pValues of the predictor variables are considered. It is seen that the HHI factor which determines the competition has a positive slope co-efficient of approximately 11 and a lower pValue of 0.012201. This shows the benefits of competition in the outcome of the mobile market. Results prove that competition acts as a positive catalyst in the increase of the network penetration. This could also have significant implication on moving away from the competition into having a single network operator which can been directed by the government might actually harm the penetration and make the damage potentially irreversible.

Linear regression Model 1:
Penetration ~1 + NumberOfOperators + negHHI + subscriberdensity + Osh+ populationdensity

Estimated Coefficients:

	Estimate	SE	tStat	pValue
(Intercept)	1.6219	1.2585	1.2888	0.21581
populationdensity	-0.00013741	3.3374e-05	-4.1174	0.00080658
subscriberdensity	9.5802e-05	1.6763e-05	5.7152	3.1903e-05
NumberOfOperators1	-0.0039594	0.07477	-0.052955	0.95842
OSH	0.00066079	0.0026914	0.24552	0.80917
negHHI	4.1305	2.4007	1.7206	0.10461

Table 6: Regression results of Regression Model 1

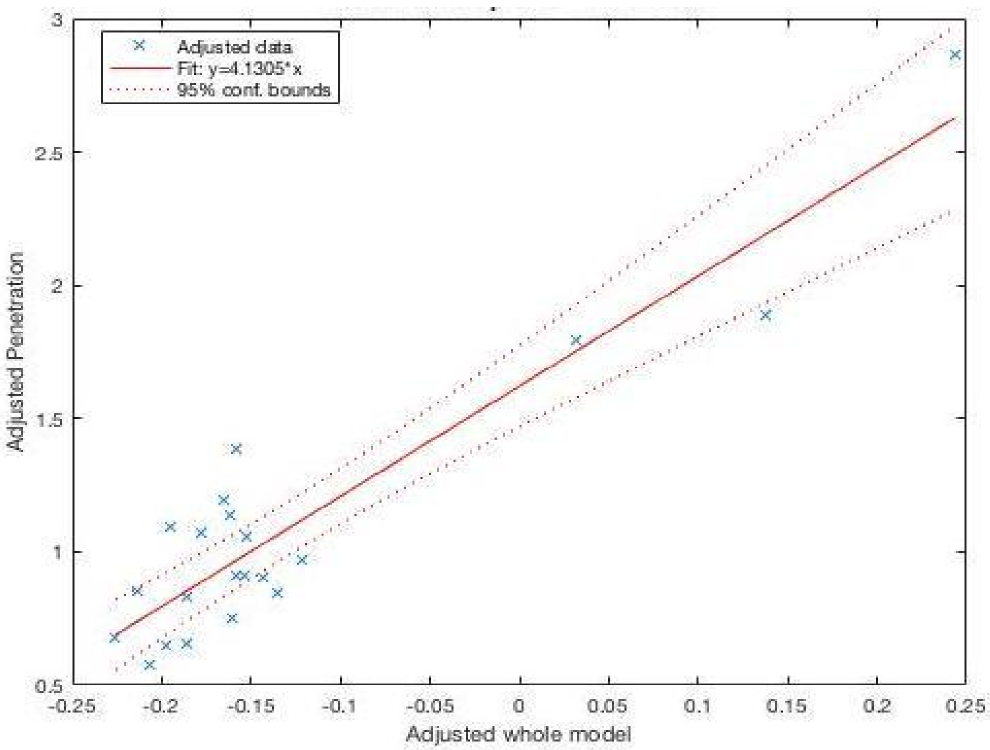

Figure 10: Linear regression model 1

No. of observations: 22, Error degrees of freedom: 16
RMSE: 0.223, R-squared: 0.859, Adjusted R-Squared 0.815
F-statistic vs. constant model: 19.5, p-value = 2.67e-06

Linear regression model 2:
Penetration ~1 + NumberOfOperators + negHHI

The model is represented by Figure 11

Estimated Coefficients:

	Estimate	SE	tStat	pValue
(Intercept)	4.3519	1.8093	2.4052	0.026515
NumberOfOperators	-0.1254	0.14708	-0.85263	0.40449
negHHI	11.649	4.2058	2.7697	0.012201

Table 7: Regression results of Regression Model 2

Number of observations: 22, Error degrees of freedom: 19
Root Mean Squared Error: 0.456
R-squared: 0.299, Adjusted R-Squared 0.226
F-statistic vs. constant model: 4.06, p-value = 0.034

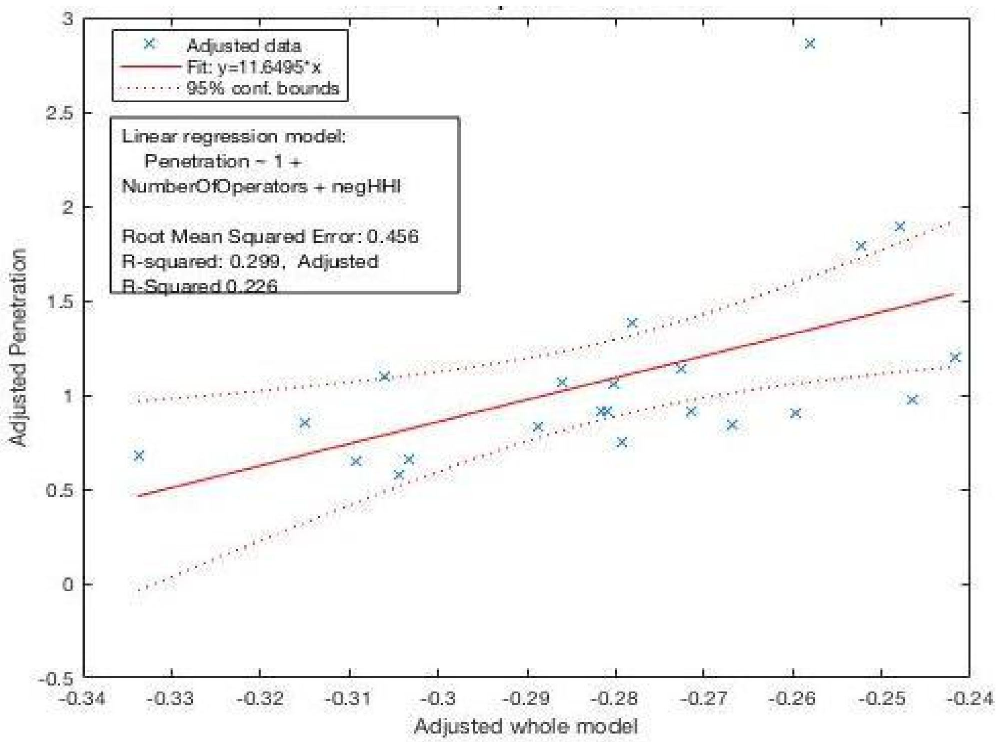

Figure 11: Linear regression model 2

4 Study of Unlicensed Spectrum

The value of the unlicensed spectrum is often underestimated in comparison with that of the licensed spectrum.

4.1 Research Method

To study the potential of community networks to narrow the digital divide in the country, different case studies are performed. Through this we understand the typical challenges faced by them and the factors hindering their growth. The role of the regulator is highlighted by studying the project ‘public WiFi pilot’.

4.2 Availability of Unlicensed Spectrum

According to Wireless planning and coordination (WPC) wing of the “Department of Telecommunications" (DOT) of the Government of India, the following bands are free for use by low power devices [4].

- 26.957 MHz to 27.383 MHz (citizen band)
- 335 MHz (for remote control of cranes)
- 865 MHz to 867 MHz
- 2.4 GHz to 2.4835 GHz
- 5.825 GHz to 5.875 GHz

Table 8 gives the the unlicensed frequency ranges and the applications that can work at those frequencies.

4.3 Qualitative Analysis of Unlicensed Spectrum Utilization

Since unlicensed spectrum is unregulated and decentralised, there are new innovative technologies which have emerged for the usage of unlicensed spectrum [11]. The most common ones are WiFi, Bluetooth, Zigbee, and RFID. In this section, we study different community network projects on the utilisation of the unlicensed spectrum, and the Indian government’s initiative called the ‘public WiFi pilot’.

4.3.1 Study of Community Networks

This section discusses the impact of unlicensed spectrum on rural broadband. Communities in rural India lack infrastructure and suffer without the benefits of ICTs (Information and Communication Technologies). There is a huge gap, and as a solution for the digital divide, there are a few communities who have come forward and have built wireless systems that use the unlicensed spectrum and provide services to connect the people from their respective communities to the rest of the world. This also provides value by initiating and facilitating services like e-commerce, e-learning, and telephony services.

Unlicensed frequency ranges in India	**Application/Specifications**
50 - 200 kHz	Very low power devices
13553 - 13567 kHz	Very low power radio frequency devices, indoor only
26.957 - 27.283 MHz	Low power wireless equipment (max. effective radiated power of 5 W)
335 MHz	Low power wireless equipment for the remote control of cranes
402 - 405 MHz	Medical RF wireless devices (max. radiated power of 25 mW) with channel emission bandwidth within 300 kHz
865 - 867 MHz	Low power wireless device (max. transmitter power of 1 - 4 W effective radiated power) with 200 kHz carrier bandwidth
865 - 867 MHz	Radio frequency identification devices (RFID) (MTP of 1 - 4 W ERP) with 200 kHz carrier band width
2400 - 2483.5 MHz	Low power wireless equipment (e.g. WiFi) (max. transmitter output power of 1 - 4 W ERP) with spectrum spread of 10 MHz or higher
5150 - 5350 MHz	Low-power equipment for wireless access systems (max. mean effective isotropic radiated power of 200 mW and max. mean effective isotropic radiated power density of 10 mW/MHz in any 1 MHz bandwidth) indoor only
5725 - 5825 MHz	Low power equipment for wireless access systems (MMEIRP of 200 mW and MMEIRP density of 10 mW/MHz in any 1 MHz bandwidth) indoor only
5825 - 5875 MHz	Low power equipment (MTOP of 1 - 4 W ERPower) with spectrum spread of 10 MHz or higher

Table 8: Unlicensed frequency bands in India and its application [11]

Community network operators usually set up the network for the community's welfare and usually build up the infrastructure with the support of the community, other nonprofit or profit organizations to offer wireless access. It is less expensive and relevant to the local needs of that community [37].

Throughout the world, community networks have adopted a bottom-up approach in providing Internet access to the local community using unlicensed spectrum throughout the world. Different case studies of community network projects which are implemented in India in different local service areas are explained in the Table 9. The table does cover the important community network projects. Even though these community network projects share a similar aim, they use different technologies, and there are different entities supporting it.

Case Studies

Community networks are usually set up by the local people in the community who serve Internet to the local people of that community. They work together, combining the available resources and expanding the networks when it is possible. These networks are usually very small ranging from 100 meters to 1000 sq.km such as the Wireless for Communities (W4C) phase 2-3 and the Airjaldi project respectively. These networks are usually owned by the members of the community along with some governing bodies such as Digital Empowerment Foundation (DEF), ISOC etc. The main community network projects are from DEF, W4C. This program aims to provide affordable, ubiquitous, and democratically controlled Internet access in rural regions of India. The W4C project durations are very short, for example, Phase 1 to 7 have lasted for one year each. However, these projects are implemented in different rural regions in India covering all the local service areas (A, B and C but not Metro region). These projects are often built on wireless mesh networking technology (WMN). It comprises of point-to-point nodes and hotspots. Data traffic is transferred through these nodes to reach the node that is connected to the backhaul of the network. Some of the mobile network operators like BSNL and Airtel are transit providers to some of these networks. For project W4C Phase 6, BSNL which is a state-owned transit provider, and Airtel, which is another private telecommunication service provider have provided 4Mbps of bandwidth. This allows access to specific services which are relevant and needful to that community. The use case scenarios of these projects have been mostly related to education, health centers, banking, and government.

Another important community network project implemented in India is AirJaldi. It started as a social nonprofit organization in Dharamshala, Himachal Pradesh providing affordable wireless broadband connectivity to remote areas. Microsoft and Ford have funded this project through grants. It uses the National Optic Fibre Network (NOFN) project for the optical fiber network and also uses TV white-space technology. Currently, there are more than 2000 computers connected to the mesh network. At a coverage area of these networks are quite huge compared to the projects of W4C around 1000 sq.km. These projects provide Internet access to schools, educational institutions and offer WiFi services to the villagers and businesses.

Another project named Gram Marg which uses TCWS (TV White-space) bands for the backhaul connectivity is still in the testing phase. The implementing entity is Indian Institute of Technology (IIT) Bombay in collaboration with Tata Teleservices. Until now, they have conducted tests in 13 villages in Maharashtra [46].

Challenges

The challenges faced by community networks include various levels of policy, regulatory challenges, spectrum management and regulations, availability of the spectrum, licensing processes, support from the transit providers which is minimal and decreases the growth of community networks in India. Some of the challenges are listed below :

1. Since most of these projects are implemented in rural regions where illiteracy is high and hence the community fails to understand the role of the Internet in day-to-day life.
2. The community is unaware of the technical details on how to build a network.
3. The community is unaware of the legal and the regulatory frameworks involved in setting up a community network.
4. The telecom operators are not interested in investing in the infrastructure in very rural regions. This is due to high investment and low returns.
5. The community network operators were also unaware of maintaining the tower height when built, for example, a tower needs a clearance from the Standing advisory committee on Radio Frequency Allocation (SCAFA) which is a part of DoT (Department of Telecommunications). But a community network operator who does not have an ISP license, needs to use the tallest structure to set up a tower.
6. The community does not have enough money to pool in for community network projects due to high poverty in the country.
7. Less support w.r.t funding from the panchayaths[5] of that village or the government.
8. The community networks receive less funding from a few international organizations.
9. Very challenging to maintain and manage the network.
10. The sustainability of these networks are completely dependent on other local non profit organizations for funding or international organisations.

    Above are some of the challenges that arise and is really high and complicated. When highly motivated people are involved in bringing up the network, it becomes easy to manage. But this comes again at a higher cost. The networks are easily managed until and unless the funding entity supports the project, but becomes very difficult without the support of these funding entities.

[5] The smallest administrative area in India for villages

Projects names	Project Duration	Deployment regions in India	Telecom Circle	Implementing / Funding entity	Transit Provider	Technologies employed	Coverage Size	Usecase Scenarios
W4C Phase 1	2010-2011	Chanderi in Madhya Pradesh	B	NGO (DEF) / ISOC		Wireless mesh setup (one relay station, 5 point to point nodes)	20-30kms wide	Schools, government
W4C Phase 2	2011-2012	Baran in Rajasthan	C			25 hotspots (3 point to point nodes with base station)	10km wide	NGO's, Schools
		Tilonia in Rajasthan	B					School
W4C Phase 3	2012-2013	Giriridh in Jharkhand	C	NGO (DEF), Local community partner (Nav,Jagtri,Yuva Mandal) / ISOC		Tower for wireless network has been set up and wireless mesh network has been deployed. 5 point to point nodes with a base station		Government, banking, local markets
		Mandla in Madhya Pradesh	B	NGO (DEF)/ ISOC		5 point to point nodes have been established with wireless mesh network		Government
		Nangaon in North Tripura	C			5 nodes have been established		Government
W4C Phase 5	2015-2016	Shivpuri, Baran, Guna	B			Mesh network was set up		intranet connectivity to 3 communities
W4C 6	2016-2017	Narayanpet in Mahbubnagar district of Telangana	C		BSNL (state owned)/ 4Mbps			schools, health centers
		Tham in Koderma district of Jharkhand	A		Airtel (private owed) / 4 Mbps			Government, schools
W4C Phase7 (Zero Connect)	2017-2018	Little Rann of Kutch, Manish Rann, Kharagodah Rann, Patadi and Surendrangar in Gujurat	A			Connected vans via unlicensed spectrum, to lend Internet-enabled devices	100 meters	Schools
AirJaldi	2010	Ranchi Network in Jharkhand	C	close co-operation with NGO/support from the Ford Foundation			1000 sq.km	Services offered to educational institutions, businesses and individuals.
	2016	Harisal in Amravati in Maharashtra	A	Microsoft's Affordable Access Initiatives Grant		NOFN Project & using TV White Spaces Technology (link)		Schools, health center and WiFi services to the villagers.
Gram Marg		Palhgar in Maharashtra	A	IIT Bombay/Tata Teleservices		Using TV White spaces (500-520MHz)		Broadband connectivity to villagers

Table 9: Summary of community wireless network projects in India [37]

5 Conclusion

In this section, we summarize the results from the analysis in the previous chapters and propose regulatory recommendations to the usage of unlicensed frequency bands.

5.1 Results

Hypothesis 1 : Licensed spectrum is scarce
From Chapter 3, we see that India faces licensed spectrum scarcity compared to other countries which is shown in Table 3. At the local service area level, it is seen that the scarcity of licensed spectrum is higher in telecom circle A compared with telecom circle C. Metro region has a significant amount of spectrum per subscriber even though the competition in that region is the highest compared to any other local service area. It has densely populated cities and the competition is well regulated.
Hypothesis 1 is true.

Hypothesis 2 : Low spectrum holdings of operators
Regression analysis of independent variables and also regression model 1 from Chapter 3, states us that the operator spectrum holdings do not have a significant impact on the model. With the data obtained from Indian telecom market, the operator spectrum holdings across the local service areas is similar. Network expansion then depends on the subscriber base and the investment costs. The frequency is reused and the cumulative spectrum holdings are similar, with these values, it doesn't impact the model as we thought it would. Even though the hypothesis is not proved by data, we would say that low spectrum holdings could be a bottleneck but is not in this case.
Hypothesis 2 is false.

Hypothesis 3 : Inadequate market concentration
From the regression model 2 and its analysis, it is seen that the market concentration does have an impact on the penetration of the mobile Internet in India.
Hypothesis 3 is false

Hypothesis 4 : Lack of regulatory incentives for community networks
From Chapter 4, we see that community networks has the potential to close the digital divide in the country and to expand wireless Internet throughout India. In rural regions, mobile network operators do not invest on infrastructure due to low returns. but community networks act as an alternative approach and it is easy to flourish with less investment. The challenges are discussed in Chapter 4. The success of the community networks depends on a lot of factors like the involvement of the community members, the strategy of the organization and also on the policy environment. Even though the regulations do not directly affect the community networks, it affects them indirectly. From the public WiFi pilot, we have seen that the regulator has a significant role to play in the proliferation of broadband services.
Hypothesis 4 is true

Spectrum scarcity can be managed with efficient methods of spectrum distribution to the operators by the regulator. Maintaining a healthy competition in the market is important to promote the operators business and also to expand mobile Internet in India. The unlicensed spectrum is definitely undervalued. The community network operators face a lot of challenges, but their intention to increase the wireless network in the rural areas is clear and would help in bridging the digital divide. Understanding that regulating unlicensed spectrum is not an option, the government's initiative on public WiFi pilot does not directly address the challenges faced by the community network operators in the rural region currently.

5.2 Proposed Regulatory Recommendations

This section proposes some recommendations to the regulatory bodies since regulation plays a very important role to promote wireless expansion in the country.

Recommendations regarding the unlicensed frequency bands

Requested bands for unlicensing	**Application**	**Current Allocation**	**Regions where exemption is in Place**
433 - 434 MHz	Data telemetry	Low power short range devices	Australia, Singapore, Malaysia, New Zealand
902.5 - 915 MHz	Low power	Additional requirements of cellular telephone systems, train control, mobile train radio systems	US
900 MHz	Low power wireless equipment	Micro cellular low powered telecommunication systems	US
926 - 926.5 MHz	Low power	902.5 - 915 MHz: Low power cordless telephone systems;	US
1880 - 1900 MHz	Low power cordless communication	Micro cellular wireless access systems (fixed/mobile) based on TDD access techniques	Europe
2483 - 2500 MHz	Broadband Access		
5150 - 5350 MHz	Broadband Access	Low power equipments for wireless access systems indoor only	US, UK

Table 10: Delicensing of additional bands [11]

Table 10 shows us some of the requested bands for delicensing by certain industries like the ISPAI (Internet Service Provider's Association of India), DECT Forum, Google, and Microsoft based on studies and practices by other countries.

Recommendations related to Community Network Operators

It is very important for the policy makers and regulatory bodies to understand the benefits of community networks as a bottom up aproach. Below are some of the proposed recommendations.

- Innovative Licensing - Innovative approaches to spectrum management like granting spectrum at a reasonable rate exclusively to the unreserved areas can increase the opportunities for community networks to gain access to the spectrum. Experimental licenses are another set of license to the spectrum which could be provided to the rural regions or the community network operators.

- Increase transparency in the regulatory decisions - The rules and the decisions need to be available to the public in a form that the layman understands. The rules are complicated and hence, communities prevent increasing their knowledge in this area of operation.

- Flexibility in regulation - The Regulatory bodies need to be flexible enough with their operation and ensure that they follow best practices. This could help a lot in terms of spectrum sharing, in offering unlicensed/licensed free spectrum etc.

- Creating public private partnerships - Projects that create public private partnerships needs to be increased.

- Increase in the engagement - The challenges faced by the communities in the rural region are very different and requires more engagement of the government with the rural communities in order to understand the basic problems. Training could be provided to the communities to set up their own network, etc. The community should be taught on how to use Internet in their day to day lives. For example it could be used in agriculture, or e-banking and other services.

- Support from the telecom operators - The regulator must support mobile network operators to invest in their infrastructure in the under reserved regions of India, and to support the upcoming community networks by providing them backhaul network for affordable prices.

5.3 Future Work

Estimation of spectrum availability per subscriber combined with spectral efficiency of a certain technology gives us the bits/sec/Hz. This would provide the data speed for a subscriber which is a good metric to check if there is licensed spectrum scarcity. The future work of the second part of the research in the thesis can be extended to frame business models for the ‘public WiFi pilot’ initiative by the government. This would help us understand if the government is an actor among the other operators or just wants to provide the necessary support to the expansion of Internet in India.

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A Timeline of spectrum auctions in India

Year of auction	**Band which were auctioned**	**Details**
1994	900 MHz	Chennai, Delhi, Kolkata, Mumbai were given the licenses for the operators
1995	Two blocks of 4.4 MHz from the 900MHz band	19 non-metro circles were given operator licenses
1997	4.4 MHz of 900 MHz band	State-owned MTNL was given license
2001	1800 MHz	First time in which spectrum higher than 900 MHz was auctioned in India
2010	3G and 4G	Tata Docomo won and was the first operator to deploy 3G services
2012	2G spectrum in 1800 MHz (GSM) and 800 MHz (CDMA)	2G Scam happened.
2013	50 MHz of airwaves in the 1800 MHz band and 76.25 MHz of spectrum in the 800 MHz band fixed the price of 900 MHz, two times higher than 1800 MHz.	8 circles were given licenses for the operators. No bidders for 1800 MHz and 900 MHz, MTS India was the only bidder in the 800 MHz band
2014	sale 307.2 MHz of 1800 and 46 MHz of 900 MHz-wide spectrum	Vodafone and Bharti were already using 900 MHz frequency and had to renew
2012	1800 MHz frequency	Reliance Jio, the only company to have all-India 4G license entered into voice service and won in 14 circles
2015	Spectrum in the 800 MHz, 900 MHz, 1800 MHz and 2100 MHz bands was auctioned	11% of the spectrum available for auction remained unsold
2016	700 MHz, 850 MHz, 900 MHz, 1800 MHz, 2100 MHz, 2300 MHz, and 2500 MHz	only 40% of the spectrum put up for auction was sold

B Data Collected for Quantitative Analysis

Telecom Circle	LSA	Population (2011)	Subscribers (2015)	Population density	Subscriber density	Penetration	No.of Operators	Osh (MHz) (2016)	HHI	Avg. Spectrum per subscriber (Hz)
Delhi	Metro	16,787,941	48069725	11,320	32413.1045	2.8633	9	239.4	0.16126	4.9802
Kolkata	Metro	14,035,959	26497141	24,306	45884.9665	1.8878	9	264.25	0.1510	9.9727
Mumbai	Metro	18,394,912	33027339	19,652	35284.3909	1.7954	8	255.4	0.1663	7.7329
Andhra Pradesh	A	84,580,777	77424659	308	281.9410	0.9153	9	242.8	0.1846	3.1359
Gujarat	A	61,026,648	65314391	3199	3423.76230	1.0702	10	230.1	0.1782	3.5229
Karnataka	A	61,095,297	64447332	319	336.5021	1.0548	9	265.8	0.1833	4.1242
Maharashtra	A	95,437,966	87183302	759	693.3522	0.9135	9	237.5	0.1745	2.7241
Tamil Nadu	A	73,394,983	83476704	3102	3528.0985	1.1373	9	275	0.1756	3.2943
Haryana	B	25,351,462	22967344	573	519.1135	0.9059	8	283.5	0.1736	12.3436
Kerala	B	33,470,534	36548397	3009	3285.6997	1.0919	9	287.1	0.2090	7.8553
Madhya Pradesh	B	98,172,007	64379812	425	278.7089	0.6557	8	287	0.2170	4.4579
Punjab	B	28,798,788	34514578	9809	11755.8244	1.1984	9	260.45	0.1449	7.5460
Rajasthan	B	68,548,437	62614138	200	182.6858	0.9134	9	254.55	0.1840	4.0653
U.P.(E)	B	99,581,477	96610129	414	401.6469	0.9701	9	259.15	0.1496	2.6824
U.P.(W)	B	71,217,132	60069388	414	349.1958	0.8434	10	243.25	0.1592	4.0494
West Bengal	B	78,231,314	53024580	1160	786.2390	0.6777	9	249.6	0.2369	4.7072
Assam	C	31,205,576	20202346	398	257.66336	0.6473	8	251.3	0.2231	12.4391
Bihar	C	137,087,586	78559101	1520	871.0477	0.5730	9	248.7	0.2076	3.1657
Himachal Pradesh	C	6,864,602	9503853	123	170.29018	1.3844	8	260.8	0.1919	27.4415
J&K	C	12,541,302	10428635	56	46.5664	0.8315	7	213.6	0.2132	20.4820
North East	C	13,956,035	11900702	798	680.4769	0.8527	7	270.8	0.2395	22.7549
Orissa	C	41,974,218	31658619	270	203.6447	0.7542	8	277.3	0.1931	8.7590

Table B1: Data Variables for all telecom circles