Telecommunications Policy 38 (2014) 236–247

Contents lists available at ScienceDirect

Telecommunications Policy

URL: www.elsevier.com/locate/telpol

Analysis of spectrum auctions in India—An application of the opportunity cost approach to explain large variations in spectrum prices☆

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ARTICLE INFO

Available online 18 February 2014

Keywords:
Indian telecom market
Mobile broadband communication
Network deployment
Opportunity cost of spectrum
Spectrum auctions
Spectrum valuation
Techno-economic analysis

ABSTRACT

The remarkable growth of mobile communication has reinforced the significance of the radio spectrum for mobile network operators. The availability of spectrum varies considerably between different countries due to national regulatory decisions. The focus in this paper is on India where operators have access to a limited amount of spectrum. This paper analyses the value of spectrum by estimating the opportunity cost, which is calculated by the savings that can be achieved by acquiring appropriate amount of spectrum rather than investing in additional base stations. The applied approach combines network deployment, user demand levels, cost, and capacity issues, which are integrated in the application in the opportunity cost approach for spectrum. The opportunity cost of spectrum is compared with prices paid at spectrum auctions. The analysis includes a discussion of drivers that determine the willingness to pay for spectrum. The results show that the opportunity cost of spectrum in relation to auction prices is lower than prices operators paid for 3G spectrum in the metro circles (service areas) while the value derived from the opportunity cost is higher than auction prices in the remaining circles.

1. Introduction

1.1. Spectrum allocation and prices

In October 2011, the Government of India (2011) published a National Telecom Policy that set out to reach broadband speeds of 2 Mbps by 2015 and at least 100 Mbps thereafter. Mobile communications will be instrumental in reaching these targets as the fixed network in India is limited and the deployment of fibre in the access network is minimal.

Access to spectrum varies considerable between different countries. For example, operators in Pakistan and India on average have access to 2×15 MHz, while operators in Germany and Sweden in average control 2×70 MHz. The enhanced role of spectrum turns spectrum allocation and auctions into decisive events for mobile operators (Fig. 1).

The outcome of spectrum auctions varies between countries and spectrum bands. For attractive bands like 800 MHz, operators in Germany paid EUR 1.54 per MHz/pop,[2] while spectrum in the 2.6 GHz band reached considerably lower price

☆ Based on a paper that the authors presented at the regional ITS India Conference 2012, New Delhi, February 22–24, 2012.

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[2] The amount and price of spectrum is presented using the metric "price per MHz normalised with the size of the population" (EUR/MHz/pop).

0308-5961/$ - see front matter
http://dx.doi.org/10.1016/j.telpol.2014.01.002

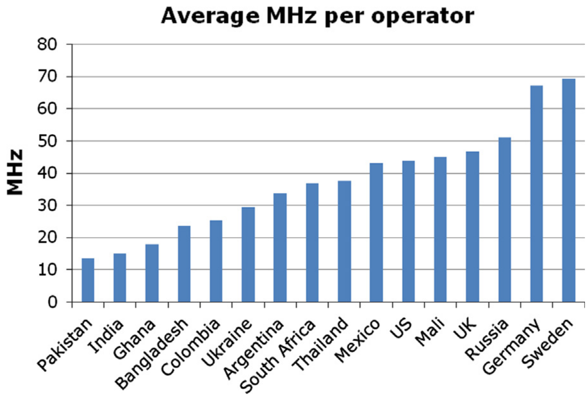

Fig. 1. Average amount of spectrum per operator (downlink). (The numbers presented are based on the total amount of spectrum mobile operators have in the different countries, and then calculated as a market share weighted average.)
Source: NRAs, Cullen-International, operator reports, authors' calculations.

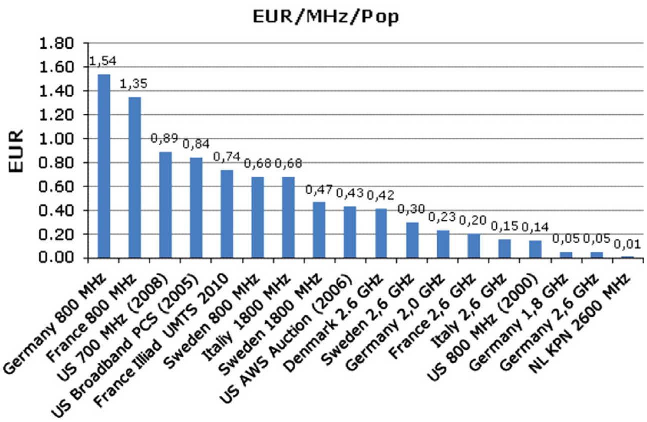

Fig. 2. Prices paid per MHz/pop in auctions in Europe and US.
Source: NRAs, Cullen-International, authors' calculations.

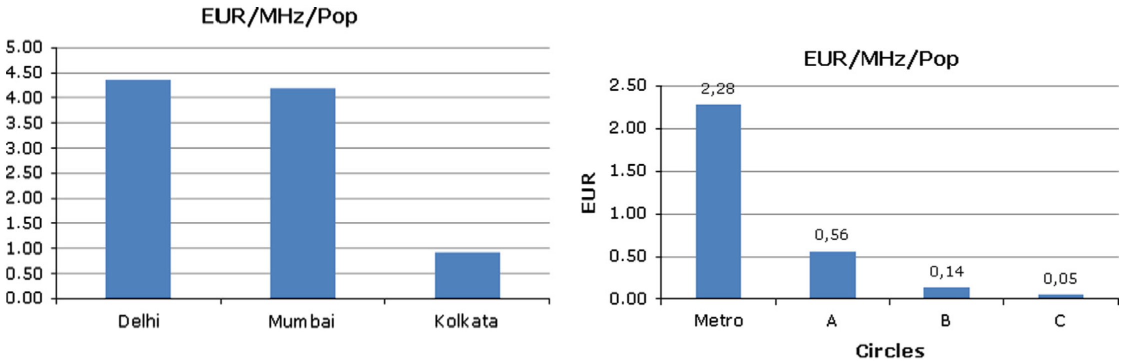

Fig. 3. Prices paid per MHz/Pop for 3G licences 2010 in the four circles in India.
Source: Department of Telecommunications (DoT) India.

levels (see Fig. 2). Interestingly enough, prices paid at the Indian 3G auction in 2010 for the two main Indian cities were not far off from prices paid at the 3G auctions in the UK and Germany in the year 2000.

Prices paid at the 3G auction in India in 2010 varied significantly between the different circles. The Indian market is divided into 23 circles (service areas), divided into metro, A, B, and C circles, structured according to the economic level. The average prices in the circles were in the range of over EUR 2.00 per MHz/pop in the metro circles, with prices in Delhi and Mumbai topping EUR 4.00 per MHz/pop, down to EUR 0.05 per MHz/pop in the C circles (see Fig. 3).

In this paper, an analysis of the opportunity cost of spectrum is conducted in order to examine if this approach can explain different price levels at auctions. Altogether, access to spectrum is a critical resource for the development of electronic communications in India, which is reinforced by the ongoing diffusion of smartphones providing easy access to the Internet. It is therefore important to analyse the value of spectrum and relate it to the outcomes of spectrum auctions.

1.2. *Paper objective and research questions*

The objective of this paper is to estimate the opportunity cost of spectrum and analyse the differences between prices paid at spectrum auctions suitable for mobile broadband communication. The analysis takes the outcome of the 3G spectrum auction in India (2010), comprising 10 circles, as a point of departure for the valuation. The prices that operators pay for spectrum at auctions are seen as their willingness to pay for spectrum.

This paper explores potential gaps between the opportunity cost of spectrum and auction prices. The estimated opportunity cost of spectrum is based on a comparison between different network deployment options using different amounts of spectrum. It is complemented with an assessment of the intrinsic properties of spectrum, which altogether determine the conditions for network deployment. Hence, the research question for the paper is:

What do estimates of opportunity cost of spectrum imply for the paid levels for spectrum at auctions?

Given that a number of factors determine the final price operators pay for spectrum, the aim with this paper is to make a contribution to the ongoing discussion of spectrum strategies for operators, which has relevance for the industry as well as for regulators and academia. Key goals of the analysis are as follows:

- To identify factors for competitive advantage in relation to spectrum and impact on production cost depending upon the amount of spectrum.
- To identify factors that determine the willingness to pay for spectrum.
- To explore potential deviation of estimated opportunity cost and the willingness to pay for spectrum.

2. Related work

2.1. *Spectrum value and valuation*

Industry, operators, consultants, academia, regulators, and governments are all interested in the area of valuation of spectrum. Plum Consulting (2011) presents a review of the value of spectrum licences, model values based on expected revenues and costs for a hypothetical operator. The Australian government (ACMA, 2009) has applied an opportunity cost modelling, which it defines as the highest value alternative forgone, but underscores that the opportunity cost pricing differs according to circumstances. Doyle (2007) states that it is necessary to take into account the opportunity cost values associated with alternative uses and across different frequency bands used by different users. Yeo (2009) estimates spectrum values based on calculations from auction data and with an analysis of observed bidding behaviour through an econometric model.

Ard-Paru (2010) captures the value of spectrum commons in Thailand through a cost–benefit analysis, in combination with an engineering valuation used as an indicator for the regulator to decide whether or not to licence spectrum.

ITU (2012) presents an approach to valuation of spectrum in order to facilitate spectrum regulators' determination of reasonable expectations for market-based revenues for the spectrum in beauty contest or administrative distribution processes, and for spectrum auctions to determine reserve prices.

However, Doyle (2007) underscores that it is challenging to calculate opportunity cost values of spectrum and that any such calculation will generate a wide range of estimates. This paper uses the opportunity cost approach in order to estimate the value of spectrum as it builds on the fundamental idea of capturing the value of the alternative use, expressed as what has to be forgone when one alternative is chosen over another (Buchanan, 2008).

2.2. *Coverage, capacity, and cost*

Capacity in mobile networks can be increased by replacing existing radio equipment with more efficient technology, by deploying new base stations, or by adding more radio equipment to existing base station sites using additional spectrum. The basic relation between network costs, capacity, bandwidth, and service area is derived by Zander (1997). For a specific amount of spectrum and for a specific radio access technology, the following relation holds for capacity-limited systems: '*the deployment of N times more capacity requires N times more base stations*'.

Operators that are unable to obtain additional spectrum are forced to deploy more base stations, which require more investments compared to competitors who can add more spectrum and reuse existing base stations sites (see Fig. 4). Although Zander's study does not address the issue of spectrum valuation as such, it does describe basic relationships that can be used to compare different network deployment options. For example, if a mobile operator with a 3G network at 2.1 GHz wants to expand its capacity, one option is to build a denser network using the 2.1 GHz band. Another option is to

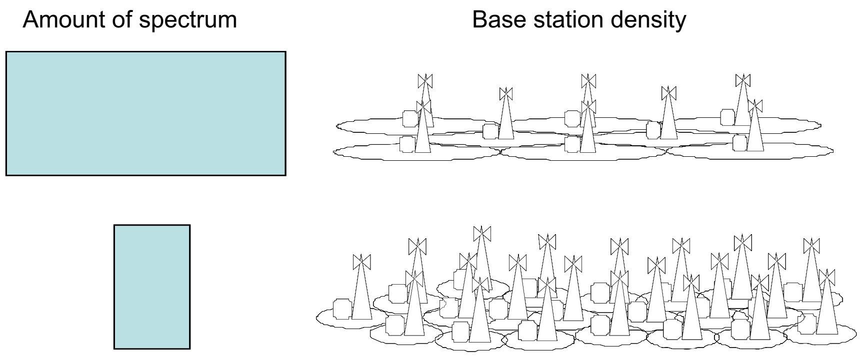

Fig. 4. Capacity can be provided by a large number of sites or with large amount of spectrum.
Source: Markendahl (2011).

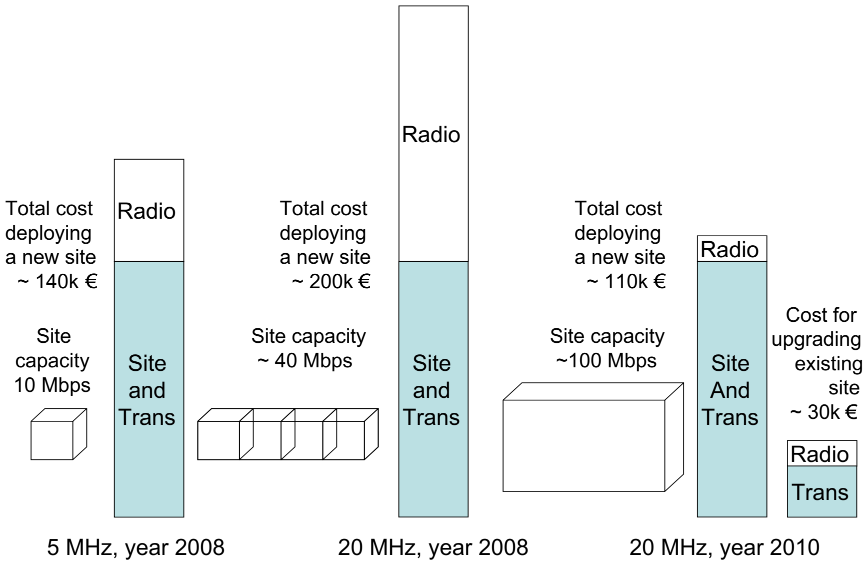

Fig. 5. Comparison of site capacity and deployment costs (the calculation is based on assumptions of three sector sites and cell average spectral efficiency of 0.7 bps/Hz (using HSPA year 2008) and 1.7 bps per Hz (using LTE year 2010)) and illustration of cost reduction by reuse of existing sites.
Source: Authors' calculations (Markendahl, 2011).

acquire new frequencies in the 1.8 GHz or 2.6 GHz band and reuse existing sites. This is feasible since these bands have similar propagation characteristics. Analysis of network deployment and sharing strategy cases for operators with different amounts of spectrum and set numbers of base stations are presented in Markendahl, Mölleryd, Mäkitalo, and Werding (2009) and Markendahl (2011).

2.3. Cost structure modelling and analysis

For macrocellular network deployment, the main components in the cost structure of the Radio Access Network (RAN) are the base station sites, the radio equipment, and transmission. It is, however, not the cost of radio equipment that is the dominant component in the cost structure. The largest costs are associated with base station sites, including costs for towers, masts, non-telecom equipment, power, installation, and site leases (Johansson, 2007).

When 3G and HSPA systems were deployed, the costs for the radio equipment (and the capacity) were comparable with the site costs. The fierce competition among equipment manufactures in combination with technological advancement has depressed prices for network equipment during the last decade, improving the cost-capacity ratio significantly. This enables operators to replace existing radio equipment with new equipment (LTE) for approximately EUR 10K per base station. This can be compared to typical costs of EUR 100K in Europe for deployment of a new site and EUR 20–30K for upgrading an existing site with fibre connection (Markendahl, 2011) (see Fig. 5 for a comparison of site capacity and costs). The most recent base station equipment supports three sectors, bandwidths up to 20 MHz, and multi-standard solutions, e.g., GSM, WCDMA, and LTE.[3]

The main driver for network costs is the amount of new sites that need to be deployed. Hence, this is a key aspect when alternative deployment options are investigated. The capacity is related to the amount of radio equipment. Additional spectrum means that operators can reuse existing sites and hence capitalise on existing infrastructure investments.

3. Methodology

The analysis is carried out through a bottom-up approach which takes specific operator and network conditions into consideration. In this section, the overall approach is outlined, and the different steps for calculating the opportunity cost are described. It is also complemented with a description of completed interviews on network deployment strategies.

3.1. The overall approach

The estimation of the opportunity cost of spectrum is based on an analysis of network capacity and cost for different network deployment options that use different amounts of spectrum. The cost comparison is the basis of the opportunity cost of spectrum and is represented by the cost savings facilitated by additional spectrum bands compared to building out existing networks that provide the same capacity as the network with additional spectrum. This approach builds on Nera and Smith (1996), Sweet, Viehoff, Linardatosc, and Kalouptsidis (2002), and Marks, Viehoff, Saadat, and Webb (1996), Marks, Pearson, Williamson, Hansell, and Burns (2009) and has been explored in a number of papers (Mölleryd, Markendahl, & Mäkitalo, 2010; Mölleryd, Markendahl, Mäkitalo, &Werding, 2010; Mölleryd & Markendahl, 2011). The analysis consists of the following steps:

1. Selection of the network deployment and spectrum allocation cases to compare.
2. Analysis of the deployment cases including user demand, capacity, and cost structure.
3. Comparison of network costs for the options resulting in the opportunity cost.

The selection of the network deployment and spectrum allocation cases is based on the existing infrastructure and spectrum bands controlled by the operators. If the additional spectrum is not acquired, then a denser network is required to be deployed as the existing spectrum bands are used. A denser network is an option in areas where the capacity is limited, while the capacity of the existing network may be sufficient in some areas, for example rural areas. This highlights an important aspect of the approach, which is the prerequisite to carry out an in-depth analysis of coverage and capacity in both rural and urban areas. In the analysis of the opportunity cost of spectrum in India, a sensitivity analysis is carried out including three different network deployment options regarding the cell radius.

The strategies for network deployment and spectrum portfolio management are vital parts of the overall operator business strategy, which varies from operator to operator depending upon regulatory and market conditions as well as operators' market position. Hence, it is important to understand different forms of 'operator thinking' that influence the selection of network deployment strategies. Input for this understanding has been acquired through discussions and interviews with mobile operators in India and Sweden, with telecom regulatory authorities, and with vendors of mobile communication systems. We summarise the data collection and completed interviews relevant for this paper in Section 3.3.

We would like to highlight that the approach taken in this paper is a high system-level analysis that provides an estimate of capacity and cost performance. It can be used for network or frequency planning, e.g., taking into account distribution of voice, data, and signalling channels or the physical location of sites. We consider an average site density, implying that sites could be physically moved, which of course is not the case in real life.

3.2. The steps resulting in the opportunity cost

The traffic load expressed as capacity per area unit (Mbps/km^2) is based on user density and the data usage per subscriber. This is based on the user demand expressed as data volume per month (GB/month) and an approximation on how the usage is spread out over the day. For example, a usage of 5 GB per month spread out over 8 h/day is equal to a continuous demand of 0.05 Mbps per user.[4] This implies that different numbers of busy hours can be used for the dimensioning.

By calculating the demand of all users within an area, an estimate is obtained of the total area demand (Mbps/km^2). This is compared with the capacity per area unit provided by the base stations. The capacity of the sites is calculated according to the following equation:

$$\text{Site capacity} = \text{bandwidth(MHz)} * \text{spectral efficiency(bps/Hz)} * \text{number of cells/sectors per site}$$

[3] An example (NSN): http://www.nokiasiemensnetworks.com/portfolio/products/mobile-broadband/single-ran-advanced/flexi-multiradio-10-base-station.

[4] The estimate of 0.05 Mbps per user is based on a usage of 5 GB per month and is calculated as follows: $5 \times 1024 \times 1024 \times 8 = 4{,}194{,}304{,}000/30 = (1{,}398{,}101{,}333/24/3600) * 24/8 = 49$ kbps $= 0.05$ Mbps per user.

With an LTE system and a reuse factor of 1— i.e., all the frequencies can be used in all cells (or sectors)—translating that into 20 MHz and an average spectral efficiency of 1.7 bps/Hz, the capacity for a three sector site is 100 Mbps.

The structure of the cost modelling follows the description in Section 2.3. The total investment to deploy a mobile network is calculated by taking the capital expenditures (capex) for electronics and civil works per site, multiplied by the total number of sites. The total cost per site for the active equipment (electronics, radio) is currently around EUR 10K. However, the cost for civil works, which is in addition to electronics if the operator is not able to reuse existing sites, is dependent upon cost for material and labour, implying that the capex is determined by national cost levels.

The basis for estimating the opportunity cost of spectrum is to analyse the substitution between spectrum and base stations (sites), and calculating cost savings provided by additional spectrum bands compared to increasing the number of sites. The approach for this analysis takes as its starting point operators' current spectrum holdings and the geographical coverage of their respective networks. It is followed by an estimation of the number of sites in different circles and the range of the cell radius. This in combination with assumptions on the average spectral efficiency gives the basis for calculating network capacity for the different deployment options providing a similar amount of capacity per km^2.

3.3. Interviews

During a trip to India in February 2012, a number of meetings were organised in order to capture an understanding of the Indian telecom market. We met representatives of three major mobile operators: Bharti Airtel, Idea Cellular, and Reliance Communications, as well as of the largest independent tower company, GTL Infrastructure. We also had meetings with telecom manufacturers, telecom analysts, and advisors at the Ministry of Communications & IT and the Telecom Regulatory Authority of India (TRAI). In total, we had 14 meetings/interviews about the Indian telecom market. The questions concerned the existing regulatory and business landscape, spectrum policy and spectrum allocation, network deployment, network sharing strategies, and operator and regulator strategies in relation to the development of wireless broadband in India.

In addition to these interviews with actors in the Indian market, useful information about network investments and deployment strategies has been collected from Swedish mobile operators. One set of interviews was made in 2010 with representatives of mobile operators in order to capture the experience of 10 years of network sharing in Sweden. The questions concerned drivers for sharing, how network sharing was started, what kinds of activities had been part of the cooperation (and not), and finally the lessons learned from the cooperation.

4. Spectrum allocation in India

4.1. India—still a growth market

Mobile communications have grown immensely in India since it took off in 2005, reaching almost 900 million mobile subscriptions by the end of 2012.[5] This translates into a mobile penetration of 73%, but with large variations between rural and urban areas. The average revenue per user and month (ARPU) is EUR 2.00–3.00, compared to EUR 15.00–20.00 in Europe.[6] Mobile operators in India on average have access to 2×15 MHz of which 5 MHz is 3G spectrum, but it varies between circles and operators.

Although 3G licences were auctioned in 2010 and networks have been deployed, the expansion of 3G was initially limited due to the lack of affordable handsets and smartphones. India had about 50–60 million 3G subscribers by end of 2012, representing around 7% of the total base of mobile subscriptions.[7] The limited availability of spectrum created fierce competition in the spectrum auction in 2010, resulting in auction prices significantly higher than reserve prices set by the regulator.[8] The Indian authorities allocated three 3G licences with 5 MHz per licence in most circles. But given that there were around six 2G operators in most circles, operators entered into roaming agreements with holders of 3G licences in order to be able to provide 3G services on a national basis.

In February 2012, the Indian Supreme Court cancelled 122 GSM-licences that had been allocated to 6–7 operators in 22 circles from October 2008 due to irregularities in the allocation decisions. The licences had been issued on a skewed first-come-first-serve basis with prices considerably below market value.[9]

The Telecommunication Regulatory Authority (TRAI) held an auction in October 2012 where it auctioned the spectrum that had been withdrawn by the Supreme Court. But the market response was cautious as final prices were in line with

[5] *Source*: Nirmal Bang Institutional Equities Research. Reports from operators show that they have phased out inactive subscriptions, but the published number is SIM cards, which means that the number of active users could be lower. India had 657 million GSM subscriptions by the end of 2012 according to Cellular Operator Associations of India (CAOI).

[6] *Source*: Bloomberg.

[7] *Source*: Nirmal Bang, Institutional Equities, Bharti Infratel, 7 December 2012. Smartphones cost around INR 10,000 (EUR 145), but operators would like to see smartphones down to INR 3000 (EUR 43) in order for 3G to take off in India.

[8] The mobile operators paid between EUR 0.27 and EUR 4.36 per MHz/pop.

[9] The Supreme Court of India, Civil Original Jurisdiction, Writ Petition (civil) No 423 of 2010, Judgment Supreme court decision, February 2, 2012. The irregularities have been labelled 'the 2G scam' and been extensively covered in the press. See Swamy (2011). The price that the licensees paid was in line with the outcome of the auction for the 4th GSM licence in 2001.

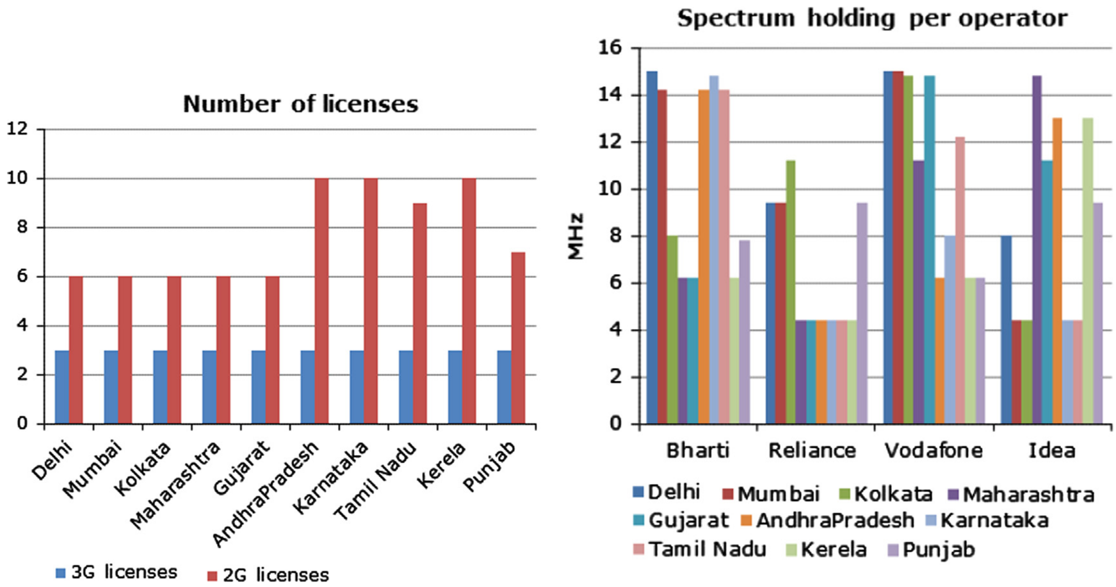

Fig. 6. Licences in 10 circles and spectrum holding for the major operators.
Source: DoT.

reserve prices and no spectrum was allocated in four circles, like Mumbai and Delhi. TRAI's goal was to set reserve prices close to the market value, since spectrum, according to the regulator, 'is a function of the business potential and profitability outlook for the services that are to be offered using the spectrum'.[10]

4.2. Focus on 10 circles

This paper focuses on the 10 largest circles, where the regulator has issued between six and 10 licences for 2G and three 3G licences (Fig. 6). These circles cover 42% of the Indian population.

The spectrum holdings for the four major operators in the 10 largest circles vary between 4 and 15 MHz, with an average of 10 MHz per operator. The total amount of spectrum is 50–70 MHz, which is distributed among a large number of operators (Table 1).

4.3. Estimating the opportunity cost of spectrum

For calculating the capacity of 3G (HSPA) with access to 5 MHz, we apply a spectral efficiency of 1.5 bits per Hz, and three sectors per site, which translates into a capacity of 22.5 Mbps per site.[11] We make an assumption that the usage is 5 GB per month per user and that it is spread out over 8 h/day. This is the equivalent of a continuous demand of 0.05 Mbps per user, which implies that each site can provide services for up to 450 subscribers. In New Delhi, for example, we estimate that the operator has 5673 sites, making it possible to provide mobile broadband services for up to 2.6 million subscribers, representing 12% of the total Delhi market (Table 2).

In order to exhibit sensitivity on the outcome dependent upon applied cell radius, we conduct a sensitivity analysis by using different cell radii in three different cases, while maintaining the 5 MHz holding unchanged: (1) base case, (2) a dense network, with shorter cell radius increasing the number of sites considerably, and (3) a thin (sparse) network case, with longer cell radius, requiring considerably fewer sites. The following table demonstrates that the sparse network can provide services to 1% of the Delhi market, while the base case can support 12%, and the dense network can provide services for up to 32% (Table 3).

Consequently, the three cases require different amounts of capex for network deployment. We calculate with EUR 25K in capex per site, which gives a broad range of total capex for the three cases—for example, in Delhi, it ranges from EUR 35 m to EUR 394 m (Table 4).[12]

[10] TRAI, Recommendations on Auction of Spectrum, 23 April 2012. Retrieved from http://www.trai.gov.in/WriteReadData/Recommendation/Documents/Finally%20final%20recommendations230412.pdf.

[11] The calculation is as follows: 5 MHz × 1.5 bits per Hz = 7 Mbits × 3 = 22.5 Mbits.

[12] Capex per site varies considerably depending upon whether it is a ground-based site or a roof-top site. Based on reports from Idea Cellular, we have calculated that the average capex per site during FY 2009–2012 was EUR 37,000. The infrastructure company GTL reports that average capex is EUR 39,000 per site (excluding active equipment). Given that passive network sharing has been established, we applied a more conservative estimate which also is based on lower equipment prices.

Table 1
Spectrum holdings in 10 circles in India.
Source: DoT.

Service area:	Delhi Metro	Mumbai Metro	Kolkata Metro	Maharashtra A	Gujarat A	Andhra Pradesh A	Karnataka A	Tamil Nadu A	Kerala B	Punjab B
Pop (m):	22.7	23.1	17.8	89.3	58.7	83.4	59.5	68	34.6	28.6
Spectrum 3G										
Bharti	5	5	0	0	0	5	5	5	0	0
Reliance	5	5	5	0	0	0	0	0	0	5
Vodafone	5	5	5	5	5	0	0	5	0	0
Idea	0	0	0	5	5	5	0	0	5	5
Tata	0	0	0	5	5	0	5	0	5	5
Aircel	0	0	5	0	0	5	5	5	5	5
Stel	0	0	0	0	0	0	0	0	0	0
Total 3G spectrum	15	15	15	15	15	15	15	15	15	20
Spectrum 2G										
Bharti	10	9.2	8	6.2	6.2	9.2	9.8	9.2	6.2	7.8
Vodafone	10	10	9.8	6.2	9.8	6.2	8	7.2	6.2	6.2
Idea	8	4.4	4.4	9.8	6.2	8	4.4	4.4	8	4.4
Reliance	4.4	4.4	6.2	4.4	4.4	4.4	4.4	4.4	4.4	4.4
Aircel	4.4	4.4	4.4	4.4	4.4	4.4	4.4	9.8	4.4	4.4
BSNL	0	0	10	8.2	9.8	6.2	10	9.2	10	6.2
MTNL	12.4	12.4	0	0	0	0	0	0	0	0
Datacom	0	0	0	0	0	4.4	4.4	0	4.4	4.4
TTSL	0	0	0	0	0	4.4	4.4	4.4	4.4	0
Unitech	0	0	0	0	0	4.4	4.4	4.4	4.4	0
Loop	0	0	0	0	0	4.4	4.4	4.4	4.4	0
Total 2G spectrum	49.2	44.8	42.8	39.2	40.8	56	58.6	57.4	56.8	37.8
Total spectrum	64.2	59.8	57.8	54.2	55.8	71	73.6	72.4	71.8	57.8

Alternatively, the increased capacity can be achieved by using additional spectrum. We therefore calculate how much spectrum would be required to provide a similar amount of capacity. The difference in capacity between the base and dense case is equivalent to 6–9 MHz, except for one case where it is 15 MHz. The difference in capex between the dense and base case is divided by the estimated amount of spectrum and the population. The result is the opportunity cost of spectrum expressed as EUR per MHz/pop (Table 5).

The opportunity cost per circle ranges from EUR 0.40 up to EUR 1.25 per MHz/pop. This can be compared to auction prices for 3G, where prices paid in Delhi and Mumbai significantly surpassed the estimated opportunity cost. TRAI held an auction for spectrum in the 1800 MHz-band in October 2012 where it had set reserve prices based on 3G auction prices in 2010, with some adjustments. The auction failed to allocate spectrum in Delhi and Mumbai as operators were not prepared to bid in line with the reserve prices, while in the other circles spectrum was allocated as operators did pay in line with reserve prices (Fig. 7).

TRAI presented an expert valuation in 2011 made by Manjunath, Kumar Raja, Kathuria, and Prasad (2011) that shows values that are over 50% higher in five circles while being around 35% lower in another five, as presented in Fig. 8. Manjunath et al. (2011) apply two valuation methods, the first is a cash flow valuation and the second uses the opportunity cost principle, which implies that this paper uses a similar approach. The cash flow valuation captures the expected net cash flow during 20 years generated by an operator with up to 6.2 MHz spectrum and a market share that is proportional to its spectrum holding in relation to the total amount of available spectrum. The annual cash flow is derived from total revenues (ARPU $\times$ number of subscribers) less costs for licences, spectrum, network, administration, marketing and personnel. The second method applies the opportunity cost principle and analyses the value of incremental spectrum in the 1800 MHz-band, for blocks from 6.2 MHz up to 8 MHz, and assumes that spectrum and base stations sites can be substituted in order to provide mobile communication services to the subscribers. The calculation is performed in a production function based on two input variables: (1) allocated spectrum that provides the required channel capacity and (2) the number of deployed base stations sites; which combines produce sufficient network capacity to serve the subscribers. The estimated value of the incremental spectrum, which is presented in the figure below, is derived from the average of the output from two methods. The cash flow valuation for spectrum up to 8 MHz takes trunking efficiency into consideration. Altogether, this implies that this paper takes a similar approach, but the difference in output can be explained by the fact that different data is used, which confirms Doyle (2007) that states that the opportunity cost principle will generate a wide range of estimates.

4.4. Discussion of the analysis

This paper has underscored that spectrum allocation is a critical issue for mobile operators in India, as it is strategically important to get access to spectrum in order to maintain competitiveness and to be able to prepare for emerging mobile

Table 2
Capacity estimates.
Source: Authors' calculations.

Capacity base case	Delhi	Mumbai	Kolkata	Maharashtra	Gujarat	Andhra Pradesh	Karnataka	Tamil Nadu	Kerala	Punjab
Cell radius	0.25	0.25	0.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Number of sites	5673	2918	1671	21,748	13,869	19,459	13,582	9201	2750	3563
Capacity (Mbps)	127,650	65,656	37,607	489,330	312,050	437,830	305,597	207,033	61,864	80,169
Capacity (Mbps/km^2)	114.6	114.6	28.7	3.2	3.2	3.2	3.2	3.2	3.2	3.2
Capacity number of users (m)	2.69	1.35	0.77	10.08	6.43	9.02	6.30	4.26	1.27	1.65
Share of population	12%	6%	4%	11%	11%	11%	11%	6%	4%	6%

Table 3
Sensitivity analysis: cell radius, number of sites and share of the population.
Source: Authors calculations.

Cell radius km	Delhi	Mumbai	Kolkata	Maharashtra	Gujarat	Andhra Pradesh	Karnataka	Tamil Nadu	Kerala	Punjab
Base case	0.25	0.25	0.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Dense case	0.15	0.15	0.25	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Thin case	0.50	0.50	1.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Number of sites										
Base case	5673	2918	1671	21,748	13,869	19,459	13,582	9201	2750	3563
Dense case	15,759	8106	6686	48,933	31,205	43,783	30,560	20,703	6186	8017
Thin case	1418	730	418	12,233	7801	10,946	7640	5176	1547	2004
Support share of pop										
Base case	12%	6%	4%	11%	11%	11%	11%	6%	4%	6%
Dense case	33%	16%	17%	25%	25%	24%	24%	14%	8%	13%
Thin case	1%	3%	16%	25%	25%	26%	26%	45%	76%	48%

Table 4
Capex in MEUR for the three cases.
Source: Authors' calculations.

	Delhi	Mumbai	Kolkata	Maharashtra	Gujarat	Andhra Pradesh	Karnataka	Tamil Nadu	Kerala	Punjab
Base case	142	73	42	544	347	486	340	230	69	89
Dense case	394	203	167	1223	780	1095	764	518	155	200
Thin case	35	18	10	306	195	274	191	129	39	50
3G spectrum price mEUR	495	485	81	188	161	205	236	219	47	48
Capex per site mEUR	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025

Table 5
Calculation of the opportunity cost of spectrum.
Source: Authors calculations, DoT. The 1800 MHz auction was completed 14 Nov 2012. source DoT.

	Delhi	Mumbai	Kolkata	Maharashtra	Gujarat	Andhra Pradesh	Karnataka	Tamil Nadu	Kerala	Punjab
Population (m)	22.70	23.10	17.80	89.30	58.70	83.40	59.50	68.00	34.60	28.60
Number of sites	5673	2918	1671	21,748	13,869	19,459	13,582	9201	2750	3563
MHz	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Bits/Hz	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Capacity (Mbps)	127,650	65,656	37,607	489,330	312,050	437,830	305,597	207,033	61,864	80,169
Dense case sites	15,759	8106	6686	48,933	31,205	43,783	30,560	20,703	6186	8017
Capacity (Mbps)	354,585	182,378	150,430	1,100,992	702,113	985,118	687,593	465,824	139,194	180,380
Deviation capacity (Mbps)	226,934	116,722	112,822	611,662	390,063	547,288	381,996	258,791	77,330	100,211
Per site (Mbps)	40	40	68	28	28	28	28	28	28	28
Per sector	13	13	23	9	9	9	9	9	9	9
Equivalent to MHz	9	9	15	6	6	6	6	6	6	6
Incremental capex mEUR	252	130	125	680	433	608	424	288	86	111
Opportunity cost EUR/MHz/pop	1.25	0.63	0.47	1.22	1.18	1.17	1.14	0.68	0.40	0.62
3G auction EUR/MHz/pop	4.36	4.20	0.91	0.42	0.55	0.49	0.79	0.64	0.27	0.34
1800 MHz auction			0.76	0.35	0.46	0.41		0.54	0.23	0.28

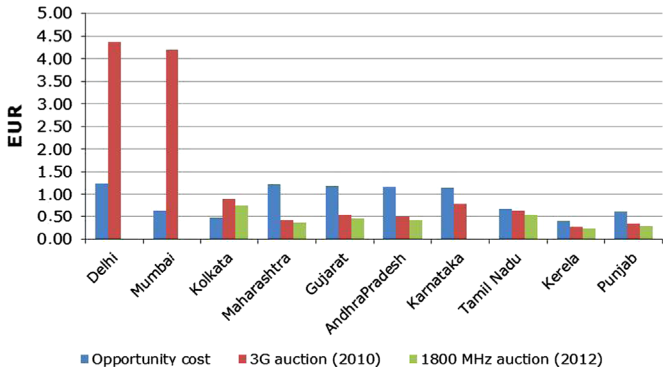

Fig. 7. Opportunity cost compared to auction prices (EUR/MHz/pop).
Source: DoT, authors' calculations.

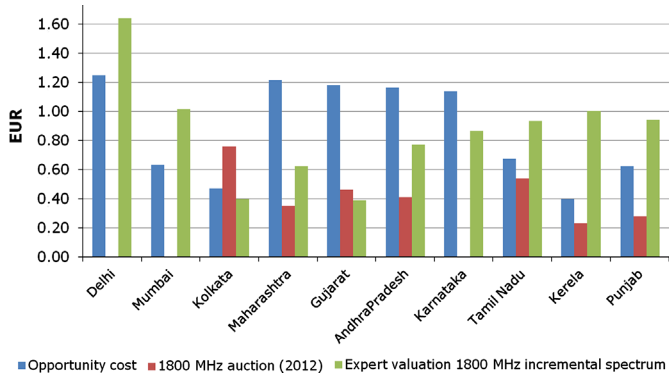

Fig. 8. Comparison of opportunity cost, auction price, and expert valuation.
Source: Authors' calculations, DoT, Manjunath et al. (2011).

broadband development. The aim with this paper has been to analyse the opportunity cost of spectrum and relate it to auction prices with a focus on India. The deviation between the opportunity cost and auction prices, presented in the previous section, can be seen as a valuation gap. The metro circles stand out, with Indian operators having paid from three up to almost seven times more for spectrum than opportunity cost in Mumbai and Delhi, and almost two times more than opportunity cost in Kolkata. However, auction prices for the remaining circles were below the opportunity cost. The ratio between the opportunity cost and auction prices ranges from 0.15 up to 7.

4.4.1. *What does this imply?*

First, circles where operators have paid considerably higher prices for spectrum than the opportunity cost may indicate excess prices. This has been driven by the limited availability of spectrum, creating fierce competition on spectrum as it has been strategically important for operators to be present in these markets. But given that the 1800 MHz auction in October 2012 did not attract bids in line with reserve prices in Mumbai and Delhi, the willingness to pay for spectrum has declined since 2010. Macroeconomic factors and a slower market have contributed to a more cautious approach regarding acquisition of spectrum, indicating that the value has come closer to the opportunity cost. But given that the opportunity cost is higher than auction prices in the remaining circles, this indicates that operators have not overpaid for spectrum, as it is more rational, if possible, to acquire spectrum at a lower price than what it would cost to establish the similar capacity through a densification of sites.

Second, the analysis has underscored that radio spectrum is a vital asset for mobile network operators and with more spectrum—i.e., wider bandwidth—operators can offer higher capacity and data rates and avoid a substitution of sites with spectrum. The limited availability of spectrum for Indian operators creates a bottleneck, since they do not have any alternative spectrum bands to utilise, as operators in other countries do. It is therefore impossible to keep up with demand and be able to expand in the market and provide mobile broadband services without having access to additional spectrum, which influences the willingness to pay for spectrum.

Third, prices on spectrum auctions depend, according to Beard, Ford, Spiwak, and Stern (2011), on allocation decisions, such as rules decided by the regulator (e.g., spectrum caps and reserve prices). This implies that auction prices only partly reflect the underlying value of spectrum. If regulators set very high reserve prices, the outcome of auctions is primarily determined by the financial capability of operators, influencing the competitive situation on the market. The design of auctions and decisions on reserve prices in India is determined by the regulator's spectrum strategy, which prioritises spectrum efficiency and allocation to many operators in combination with potential income for the state. The Indian regulator has only allocated 2×5 MHz for 3G to three operators, making it difficult for an extensive take off for mobile broadband. India has gone through a dramatic process with the previous allocation of 2G spectrum, which has been labelled as the 2G scam (Swamy, 2011), with severe consequences for the individuals involved, and very negative effects for the companies involved, as spectrum licences have been cancelled. Consequently, this had an impact on Indian spectrum strategy and the level of reserve prices set for the 1800 MHz auction.

Fourth, access to capital is essential in order to be able to pay for spectrum, and market position determines the financial conditions for operators. Moreover, research conducted by Bulow, Levin, and Milgrom (2009) underscores that the level of allocated budgets for auction teams appointed by operators influences the outcome of final prices. This implies that the auction prices paid in Mumbai and Delhi for 3G in 2010 was determined by positive expectations from the capital markets and that the operators had decided on generous budgets for the bidding teams.

Fifth, the deviation of the opportunity cost of spectrum and the expert valuation in Fig. 8 indicates that the results may have been generated through different methodologies and parameters, but it underscores the importance of estimating the value of spectrum for the policy discussion on spectrum strategy.

5. Concluding and future work

The combination of an expanding mobile sector that continuously request harmonised and exclusively allocated spectrum with a regulatory spectrum strategy that limits the amount of spectrum available for operators has resulted in high prices for spectrum driven by market forces. But with lower growth and a more uncertain macroeconomic situation, the operators' willingness to pay for spectrum has been negatively impacted. Spectrum valuation is a complex issue relating to a number of factors like corporate strategy, market development, technological issues, financial aspects, and regulatory decisions. The applied approach combines network deployment, spectrum allocation cases, user demand levels, cost, and capacity issues, which are integrated in the methodology that determines the opportunity cost of spectrum. Given that conditions vary between countries, this methodology is dependent on context and national conditions, which makes it relevant to label it as an approach rather than a formal model. A further refinement of the methodology is on the agenda. This paper has shown the significant role spectrum plays on the mobile market and that 5 MHz can support an initial development of mobile broadband in India. But in order to provide sufficient capacity for smartphones as well as dongles with a broad uptake of mobile broadband, more spectrum is required in order for mobile communications to play a key role in achieving broadband targets.

Acknowledgement

This research has been conducted with financial support provided by wireless@KTH.

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