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# OPPORTUNITY COST FOR THE DIGITAL DIVIDEND BANDWIDTH: APPLICATION AND COMPARISON WITH LTE AUCTIONS OUTCOMES

*WORKING PAPER*

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## **Abstract**

Radio spectrum represents a scarce resource assigned to operators by national regulatory authorities through auctions, beauty contests or other mechanisms, aimed at introducing sufficient incentives for an optimal use of such a resource. A prerequisite for designing efficient assignment methods is that regulatory agencies, which typically rely on incomplete and asymmetric information, clearly identify the expected value of the spectrum, to be used to set auction bases, prices in beauty contests and administered incentive prices. Those considerations are particularly actual since the transition to digital television transmission opened the space for reallocating parts of the spectrum, to increase its efficiency.

The paper aims at refining a techno-analytical approach to estimate the value of spectrum portions, with a methodology based on opportunity-cost evaluation and at comparing the results with the outcomes of the recent LTE spectrum auctions. Research results could be used by regulatory agencies and by operators to better shape their approach to spectrum valuation.

**Key words:** Spectrum management; Digital Dividend; LTE; Opportunity cost; Investment

**JEL classification:** L51, L96

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## **1 Introduction**

Radio spectrum represents a scarce resource assigned to telecom operators by national regulatory authorities through auctions, beauty contests or other mechanisms, aimed at introducing sufficient incentives for an optimal use of such a resource.

A prerequisite for designing efficient assignment methods is that regulatory agencies, which typically rely on incomplete and asymmetric information, build a clear view on the expected value of the spectrum, to be used to set auction bases, prices in beauty contests and administered incentive prices.

Those considerations are particularly actual since the transition to digital television transmission opened the space for reallocating parts of the spectrum to increase its efficiency and NRAs are in the process of assigning those parts, mainly through bidding mechanisms.

The paper aims at refining a techno-analytical approach to estimate the value of spectrum portions, with a methodology based on opportunity-cost evaluation and at comparing the results with the outcomes of the recent LTE spectrum auctions.

Research results are designed to be used by regulatory agencies to better shape their approach to spectrum valuation and by telecom operators to benchmark the outcome of their investment valuations when entering a bidding process.

The paper is organized as follows: in Section 2, the opportunity cost calculation in the telecommunication industry, the previous literature on the transition from 3G to LTE technology and some forecasting modeling techniques are reviewed. In Section 3, the analytical approach is described. In Sections 4 the estimates and results of the evaluation of the opportunity cost of spectrum for LTE uses are presented and benchmarked with auctions, in order to calculate the MHz per population value. Section 5 concludes.

## **2 Literature review**

### **2.1. Opportunity cost**

The all-digital evolution of the EU TV broadcasting system has sparked a lively debate on the allocation and economic value of the spectrum. This technological shift improves transmission capacity and spectrum efficiency, building the case for freeing valuable frequencies and reallocating unused space [1]. In order to maximize the economic benefits that might derive from this portion of spectrum, it is therefore important that the mechanism of allocating and assigning this public resource be efficient, exploiting the full potential of an asset which can be dedicated to several different and high-value uses. In general, market mechanisms (auctions and trading) increase overall efficiency since the value of the spectrum is determined by market interaction [2].

Even if the goals of efficient spectrum allocation cannot be met by a single solution, market mechanisms (auctions, trading) are considered the most efficient strategy to allocate spectrum resources [3]. Nevertheless, whenever these mechanisms cannot be implemented, or when for some specific spectrum uses (i.e. defense, aviation, radio etc...) they are assumed to generate an inefficient allocation of this primary resource, then other regulatory solutions could be adopted as a second best intervention.

Among them, the use of spectrum fee, reflecting the underlying cost of the spectrum, is a potential and valuable regulatory tool to adopt [1].

Irrespective of the different mechanism used for assigning a specific spectrum portion, regulators need to be fully aware of the potential spectrum value to correctly design the assignment instrument and should periodically evaluate the ex-post effects of new spectrum availability on the market.

The methods used to assign the spectrum up to the '90s were focused mainly on technical efficiency and service assurance and designed around centralized, strict mechanisms that weren't able to ensure economic efficiency. Since then, different systems have been introduced to improve the efficiency and thus the economic use of spectrum: frequency trading, auctions and AIP (Administered Incentive Pricing) [2].

As generally acknowledged, market mechanisms are the most efficient way to allocate spectrum resources and are recognized to be the first-best solutions to guarantee efficiency in their use. However, not all the spectrum is actually traded on the market, because of technical legacies, service coordination, safety or security issues, such as the spectrum for maritime services, radio services, defense and broadcasting [2]. Both in cases where market mechanisms could be applied and in those where second-best solutions represent the only viable alternative, a clear methodology to estimate the spectrum value should exist and the calculation of the opportunity cost is a robust option.

In fact, considering the general notion of the opportunity cost of a choice, it represents the value of the best alternative forgone, in a situation in which a choice needs to be made between several mutually exclusive alternatives given limited resources. Assuming the best choice is made, it is the "cost" incurred by not enjoying the benefit that would have been by taking the second best choice available. Thus, the notion of opportunity cost plays a fundamental role in ensuring that resources are being used efficiently [4].

To estimate the spectrum value, the opportunity cost is calculated as the difference in the costs of production inputs which would have to be paid, should a user of the spectrum be impeded to access a marginal unit of the resource. These additional costs depend on the type of application and the technology used, and they are equivalent to the minimum estimated cost for the provision of the service by using the cheapest available alternative [5].

In August 2014, Ofcom launched a revised framework for the definition of the new spectrum pricing in the 900 MHz and 1800 MHz bands, having particular regard to the sums bid in the UK 4G auction [6]. Ofcom states that market mechanisms are important to ensure a more efficient use of the spectrum; nevertheless, regulation continues to play an important role for spectrum resources in managing interference, negotiating international agreements to enable improved spectrum use, securing compliance with international obligations and addressing market failures. According to Ofcom, there is still little direct relevant market evidence of the value of these specific spectrum bands [6]. Moreover, trading and liberalisation alone are not sufficient to promote an efficient management of the spectrum in some specific spectral markets, while in those specific markets methodologies based on opportunity-cost evaluation may have a more relevant role in promoting efficiency [1].

At the same time new spectrum in "valuable" bandwidths was becoming available, the mobile transmission systems evolved from 3G to 4G technology to face users' fast growing needs for high data rates and to ensure better total capacity, quality of service and spectrum efficiency. Therefore, it is crucial to understand the key

milestones of this technological evolution, in order to calculate a proper opportunity cost and estimate the spectrum value.

## 2.2. Transition from 3G to 4G technology

The wireless industry has experienced a phenomenal growth in recent years, both in terms of subscribers and traffic volumes managed by the network infrastructures. This growth was incentivized and made possible by a significant technology evolution, summarized in Table 1, that provides a comparison of the generations of mobile technologies [7].

**Table 1**  
Comparison of the generations of mobile technologies.

	<b>1G</b>	<b>2G</b>	<b>3G</b>	<b>4G</b>
<b>Start/ Deployment</b>	1970 – 1980	1990 – 2004	2004-2010	Now
<b>Data Bandwidth</b>	2kbps	64kbps	2Mbps	1 Gbps
<b>Technology</b>	Analog Cellular Technology	Digital Cellular Technology	CDMA 2000 UMTS	Wi-Max LTE
<b>Service</b>	Mobile Telephony (Voice )	Digital voice, SMS, High capacity packetized data	Integrated high quality audio, video and data	Dynamic Information access, Wearable devices
<b>Multiplexing</b>	FDMA	TDMA, CDMA	CDMA	CDMA
<b>Switching</b>	Circuit	Circuit, Packet	Packet	All Packet
<b>Core Network</b>	PSTN	PSTN	Packet N/W	Internet

First generation (1G) mobile systems came in the early 1980s and were based on analogue (or semi-analogue) signals [8]. They offered mainly voice services and had a high level of incompatibility among each other. In fact first generations cellular networks had been developed under a number of proprietary, regional and national standards, creating a fragmented global market. In particular, NMT (Nordic Mobile Telephone) was used in Nordic countries, Switzerland, Netherlands, Eastern Europe and Russia, AMPS (Advanced Mobile Phone System) was employed in the USA and TACS (Total Access Communications System) was adopted first in the United Kingdom and then in Italy. Germany, Portugal and South Africa based their networks on C-450, while France employed Radiocom 2000. In Japan different standards were adopted, such as TZ-801, TZ-802, and TZ-803, developed by Nippon Telephone and Telegraph (NTT), NTACS (Narrowband Total Access Communications System) and JTACS (Japanese Total Access Communication System).

Second generation (2G) mobile systems represented the shift to digital transmission and introduced services such as SMS and low speed packet interconnection. They used digital multiple access technology, such as TDMA (time division multiple access) and CDMA (code division multiple access). GSM, PDC and IS-95 (also known as CdmaOne) were the main 2G technologies that became available in the 1990s and, compared with first generation systems, they offered higher spectrum efficiency, better data services, and more advanced roaming. The main element of these systems were the BSS (Base Station Subsystem), in which there were BTS (Base Transceiver Station) and BSC (Base Station Controllers); and the NSS (Network

Switching Subsystem), in which were located the following components: the MSC (Mobile Switching Centre); VLR (Visitor Location Register); HLR (Home Location Register); AC (Authentication Centre) and EIR (Equipment Identity Register) [9].

In order to improve data transmission capacity, 2G technologies evolved towards the so called 2.5 generation. The first major step in the evolution of 2G systems was the introduction of GPRS (General Packet Radio Service), which implemented a packet-switched domain in addition to the circuit-switched domain. GPRS networks evolved into EDGE networks with the introduction of 8PSK modulation. EDGE was a pre-3G technology (also called as 2.75G) that increased the data rate up to 384 kbps. Despite the improvements, the packet transfer on the air-interface still behaved like a circuit switch call, generating inefficiencies. Moreover, the standards for developing the networks were different for various parts of the world, thus it was necessary to develop a network which provided services independently of the technology platform [9].

Multiple bodies interacted in the definition of 3G vision, technologies and standards, being the main ITU (International Telecommunications Union - the United Nations specialized agency for information and communication technologies), IEEE (Institute of Electrical and Electronics Engineers), 3GPP (3rd Generation Partnership Project - a collaboration between groups of telecommunication associations) and the Wimax Forum.

ITU specified 3G technology requirements as part of the International Mobile Telephone 2000 (IMT-2000) project, for which digital networks were expected to provide a minimum speed of 2Mbit/s for stationary or walking users, and 348 kbit/s in a moving vehicle [10].

3GPP has extended the work by defining the UMTS (Universal Terrestrial Mobile System) framework, a mobile system that fulfills the IMT-2000 standard to be used as the technology of reference to enable 3G in GSM-based countries (initially mainly Europe). In contrast, in non-GSM-based countries such as Japan, South Korea and the USA, the 3GPP2 set the standards for CDMA2000, direct evolution of CdmaOne.

Therefore, UMTS and CDMA2000 were adopted as the primary 3G systems, although in 2007 WiMAX, created by the WiMax Forum and based upon the IEEE 802.16e-2005 standard [11], was also recognized by the ITU as an official 3G technology [12]. The main components of 3G systems included BS (Base Station), RNC (Radio Network Controller) and WMSC (Wideband CDMA Mobile Switching Centre).

3G enabled network operators to offer users a wider range of advanced services while achieving greater network capacity through improved spectral efficiency. Services include wide-area wireless voice telephony, video calls and broadband wireless data, all in a mobile environment [9]. 3G technologies use a hybrid system of circuit switching and packet switching [13]: a circuit-switched voice network for phone calls, and a digital data packet network for access to Internet and email. Used in telephone systems since the beginnings and giving immediately available circuit when connection is established, circuit switching has the downside that it ties up the resource for as long as the connection is kept up, being relatively inefficient.

Despite multiple improvements, such as HSPA (High Speed Packet Access), 3G service cannot fully satisfy users' fast growing needs for high data rates [14] and cannot seamlessly integrate the existing wireless technologies (e.g., GSM, GPRS, IMT-2000 and Bluetooth). Nowadays, users expect a dynamic and continuous stream of new applications, capabilities and services that are available across a range of devices using a single subscription and a single identity [15]. To achieve these objectives, together

with higher Quality of Service (QoS), higher spectrum efficiency and better interference protection, the development of telecommunication systems was a necessary step further.

Therefore, in 2008 ITU issued IMT-Advanced requirements for 4G systems to face the new technological needs. According to the framework, a 4G system has to be based on an All-Internet Protocol (IP) packet switched network and it must reach speeds of up to 100Mbps for a moving user and 1Gbps for a stationary user. So far, these speeds are only reachable with wireless LANs [13], as shown in figure 1. Thanks to higher speed data, the 4G technology is able to support new services such as high-quality video chat, video conferencing and online gaming [16].

The fundamental difference between the GSM/3G and All-IP systems is that the functionality of the RNC and BSC are now distributed among the BTSs and a set of servers and gateways. 4G technologies no longer utilize circuit switching even for voice and video calls and all Information is packet switched to enhance efficiency [13]. In fact, with packet switching, network resources are only used when there is information to be sent across, improving the efficiency of the system.

In December 2010, ITU recognized LTE and WiMax as 4G technologies, since they provide a substantial level of improvement in performance and capabilities with respect to the initial third generation systems. However, none of these technologies are actually compliant to the specifications set forth by the 4G requirements [17].

In March 2011 with its Release 10, 3GPP has standardized LTE-Advanced to meet the IMT-Advanced requirements for 4G [18]. Also, WiMAX Forum and IEEE are evolving WiMAX through IEEE 802.16m or WiMAX-m to satisfy 4G requirements. Currently, 4G has been deployed or is in the technology roadmap of the majority of worldwide mobile operators [14].

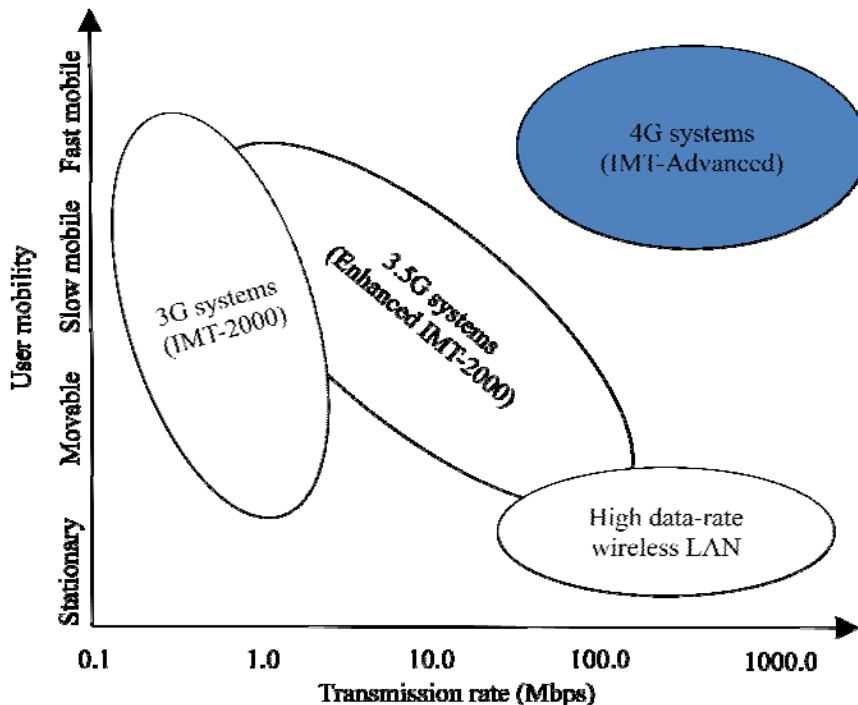


Fig. 1. 3G and 4G mobile communication systems [19].

However, even if multiple operators have obtained the necessary spectrum and technology patents for the 4G upgrade, many industry examples show that in practice the upgrades happen at different times ( [16], [20] ). In South Korea, for example,

Korean Telecom took the lead to deploy the world's first 4G network using WiMAX technology in 2006, whereas SK Telecom started to upgrade using more mature LTE technology in 2011. In US, Sprint deployed the first 4G WiMAX network in late 2008, while Verizon waited until the end of 2010 to deploy his 4G LTE network, and AT&T developed his 4G LTE network at the end of 2011 [16]. In China, being China Mobile and China Unicom the two dominant cellular operators, China Mobile has decided to first deploy 4G LTE network during 2012-2013 [20].

This can be partially explained by an economic analysis of 4G network upgrade. The analysis shows that when an operator is the first to move and upgrade 3G to 4G, it increases its market share and revenue, but it also takes more risk because of the higher upgrade costs [14].

Market share is increased because a portion of existing 3G users have an incentive to switch to the new service. In fact, 4G technology offers to users several benefits, such as a better QoS, higher network speed and new applications. In addition, innovators and early-adopters switch as soon as the new service is introduced, because of their technology interest [21].

Higher revenue, instead, is reached even with the same number of users. In fact, the revenue an operator obtains by charging users can be proportional to the network value, which is higher when upgrading to 4G technology because of more efficient and frequent communication [14]. Since the data rate in the 4G service is between 5 and 10 times faster than the one in the 3G service, user can utilize their devices for new applications, such as high-quality video chat and online gaming, generating more mobile traffic [16].

On the cost side, operators' upgrade decisions are affected by two key factors: the 4G upgrade cost and the user switching cost [14]. The 4G upgrade cost decreases over time as 4G technology matures. The switching cost is made by the amount an operator has to bare to migrate a 3G user to the 4G service, which depends on user willingness to upgrade [22]. Users face different switching costs if the upgrade to the news service happens within the same operator or between two different operators. In the first case, 3G users need to update their device to use the 4G service and to learn how to use it. In the second case, users either wait till their 3G contract expires, or pay for the penalty to terminate the contract immediately, adding an extra cost on top of the mobile device update [14]. Thus, the switching cost for the user will be higher when the upgrade to the new service happens between two different operators.

Therefore, when operators have to decide to upgrade to 4G technology, there is a trade-off between the increased market share (and revenue) and the decreasing upgrade cost. Depending if one or more operators have the possibility to upgrade to 4G at the same time, the timing operators decide to upgrade differs.

In fact, when only a dominant operator has the possibility to upgrade to 4G, the operator obtains higher market share and revenue, but cannot benefit from the cost depreciation of 4G technology. Therefore, if the upgrade cost is relatively low, the operator upgrades at the earliest available time; otherwise it postpones the upgrade [14].

In contrast, when two or more operators have the possibility to upgrade, by upgrading early an operator captures a large market share and revenue, which can compensate the higher upgrade cost. The other operator, instead, postpones its upgrade to incur a reduced upgrade cost and to take advantage of the network effect in the 4G market. Thus, in order to fully obtain the advantages of earlier or later upgrades, operators will avoid upgrading at the same time [14].



Since, the penetration of the new mobile technology in the market goes through phases of gradual diffusion that typically assume an S-shaped curve [21], it is interesting to understand if spectrum management policies can affect the adoption curve and the growth rate of the technology diffusion. An econometric analysis shows that technology standardization, mandatory spectrum band and spectrum auctions had different impacts on the diffusion of 3G technology.

The presence of technology standardization supported countries reaching the peak adoption rate [23]. In fact, mandating a single technology standard has a positive impact since it generates economies of scale for operators and equipment manufacturers, which may set lower prices than in the case of multiple technologies. In addition, standardization avoids consumers from waiting to see which technology will dominate, thus increasing the network effect. However, technology standardization can foster premature adoption of inferior technology and can reduce technological competition, thus slowing innovation [23].

Limiting 3G to a single frequency band promoted faster roll out, but in the long run can slow down the growth. In fact, mandating specific spectrum band enhances global roaming and ensures economies of scale, yet forces operators to go through the spectrum award process to introduce new technology, even though they might be capable of reusing their existing spectrum [23].

Using auctions rather than other methods to allocate spectrum has helped countries to reach peak adoption rate faster. In fact, countries which conducted 3G auction were the first to reach the inflection point. According to the analysis, this can be explained because operators facing high debt resulting from the auction process opted for fast rollout, hoping for prompt user response [23].

Nevertheless, in order to understand the impact of 4G on operators' economics and investment decisions, forecasting the growth in the number of subscribers and in the traffic brought on mobile networks is a key driver.

### **2.3. Mobile data traffic forecasting methodologies**

Mobile data traffic has grown sensibly around the world as large and smart small screen devices have took up and it will continue its growth trajectory in the next decade, challenging mobile operators from commercial, operational and strategic sides.

The ability to accurately forecast data consumption is critical to keep competitive advantages in the fast changing environment. A systematic bottom-up approach based on the analysis of technological trends and user behavior is useful to create improved forecasts accuracy [24]. There are relevant examples of data providers and network equipment vendors that developed methodologies to forecast the mobile traffic growth; the main examples are represented by IDATE, Cisco and Ericsson, whose methodologies are summarized in the following paragraphs.

#### *2.3.1. IDATE mobile traffic forecast*

In 2005, the Institut de l'Audiovisuel et des Télécommunications en Europe (IDATE), an experienced research company on the digital economy, has developed a 10-year forecast model used by the UMTS Forum in several reports ( [25], [26] ).

In 2011, key trends and assumptions were reviewed, in order to be aligned with the new market scenario. In particular, mobile voice was overtaken by mobile data at

the end of 2009, which became the number one service category at the beginning of 2010 in terms of traffic generated on mobile networks [26].

The forecast model is structured with a three-step approach:

- Step 1 is aimed at identifying the main technology trends that can impact device characteristics and mobile access networks. Some major emerging services that might be available by the 2010-2020 decade are considered in line with the technology improvements and with existing facts and possible trends in terms of consumer adoption [25].
- Step 2 has the purpose of building three possible market scenarios, in order to deal with uncertainty and to enable sensitivity. Geopolitical, social, economical and technological key variables are identified and used as assumptions for the different scenarios that could affect mobile forecast [25]. Table 2 provides the three scenarios developed in 2005 and the changes adopted after the revision in 2011.

**Table 2**

IDATE 2005 and 2010 scenarios for mobile forecast, 2011.

	2005 scenarios	2010 scenarios
<b>Scenario 1</b>	Low price, voice-dominated growth	Low price, limited data services adoption
<b>Scenario 2</b>	Balanced, broad-based growth	Balanced, broad-based growth (50 bn devices in 2020)
<b>Scenario 3</b>	Pervasive data-driven growth	No change to this scenario

- Step 3 selects the most plausible scenario and develops a market model for the evolution of 3G and LTE services, taking into account the various categories of devices that use mobile networks, including smartphones, dongles and M2M devices. Scenario 2 has been selected as the most plausible base for mobile forecast for the years 2010-2020 [26].

The results are used to helpbuilding a vision on mobile network evolution to create data for the CEPT/ITU-R spectrum requirements calculation process [25].

### 2.3.2. Cisco Visual Networking Index

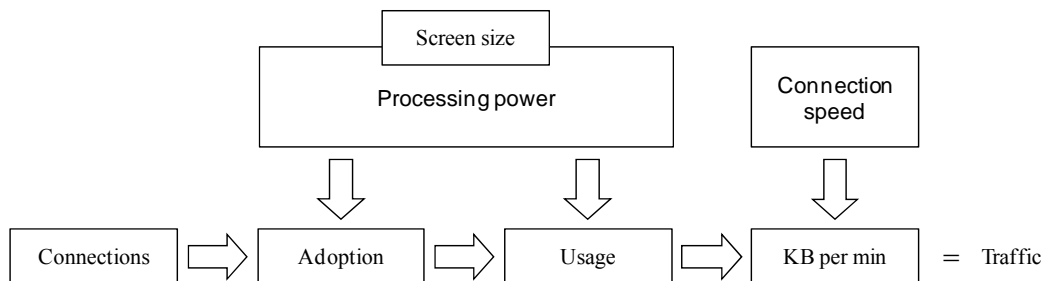
Each year, Cisco releases its updated Visual Networking Index (VNI) survey which includes data on the expected evolution of mobile traffic. Cisco VNI combines analyst assessments and direct, automated data collection to forecast mobile data growth. The Cisco VNI Global Mobile Data Traffic Forecast also relies in part upon data published by external sources such as Informa Telecoms and Media, Strategy Analytics, Infonetics, Ovum, Gartner, IDC, Dell’Oro, Synergy, ACG Research, Nielsen, comScore, Arbitron Mobile, Maravedis and the ITU [27].

The Cisco VNI methodology relies on a 6-steps approach to forecast mobile traffic [28]:

- Using external sources, the model calculates the number and growth of mobile connections.
- The model estimates each user sub-segment (i.e. smartphones, mobile PCs, tablets, M2M) by applying adoption rates through different assumptions.
- Minutes of usage (MoU) are estimated for each application category.

- A representative bit rate is established by estimating regional and country average broadband speeds and assuming that they growth at the same speed. To calculate local bitrates, country specific values such as average broadband speed, digital screen real estate and average device computing power are considered.
- The penultimate step in the methodology is to multiply the bitrates, MoU, and users together to get an average PB per month
- The last step consists in a traffic migration assessment, which is made by subtracting the portion of mobile data traffic that has migrated from the fixed network from the fixed forecast.

Overtime, the methodology has evolved to link assumptions more closely with fundamental factors, to use data sources unique to Cisco, and to provide a high degree of application, segment, geographic, and device specificity [27]. Figure 2 shows a sketch of the forecast methodology to calculate average traffic adopted by Cisco.



**Fig. 2.** Sketch of Cisco forecast methodology [28].

Cisco updates its VNI Global Mobile Data Traffic Forecast every year in order to increase the linkage between the main assumptions and fundamental factors such as available connection speed, pricing of connections and devices, computational processing power, screen size, resolution, and device battery life. The update focuses on the relationship of mobile connection speeds and the KB-per-minute assumptions in the forecast model. Proprietary data from the Cisco Global Internet Speed Test (GIST) application are used as a baseline for current-year smartphone connection speeds for each country [27].

### 2.3.3. Ericsson Mobility Report

Ericsson performs mobile forecasts several times per year to support internal decisions, strategic planning and market communication [29]. Even if a step-by-step methodology has not been fully released, it is possible to extract some Information about the main assumptions.

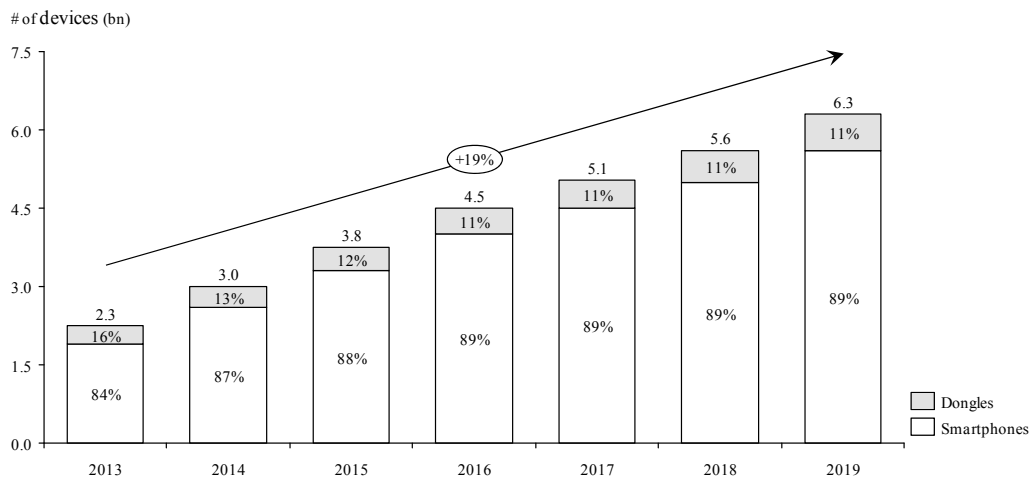
- Historical data from external sources, such as NRAs and operators reports, are used as baseline to forecast subscription and traffic growth, and then validated with Ericsson's internal data, including extensive measurements in customer networks.
- Macroeconomic trends, user trends<sup>1</sup>, market maturity, technology development expectations and industry analyst reports, together with

<sup>1</sup> Researched by Ericsson ConsumerLab

internal assumptions and analysis, are used to forecast the future development of mobile networks [29].

- As underlying data changes, historical data are revised.

The model provides a 5-year forecast of mobile subscriptions, mobile traffic and mobile application traffic, both at worldwide and regional level. Mobile subscriptions include all mobile technologies, such as smartphones and dongles, excluding M2M devices. Figure 3 provides an insight about Ericsson mobile subscriptions forecast for years 2013-2019.



**Fig. 3.** Ericsson mobile subscriptions forecast, 2013-2019<sup>2</sup> [29].

Mobile traffic refers to aggregated traffic in mobile access networks and does not include DVB-H, Wi-Fi and Mobile WiMax traffic, while voice traffic does not include VoIP [29]. It is calculated by multiplying the number of subscriptions for each device category for the respective average monthly traffic.

To have a deep and up-to-date knowledge of the traffic characteristics of different devices and applications, traffic measurements are performed in over 100 networks in the major regions of the world. In addition, to discover different traffic patterns, Ericsson made detailed measurements in a selected number of commercial WCDMA/HSPA and LTE networks [29].

#### 2.3.4. Forecasting methodologies comparison

There are two main common drivers between the methodologies used by IDATE, Cisco and Ericsson. First, all the three methodologies use a bottom-up approach to forecast mobile traffic growth and use as baseline historical data from external sources. In fact, variables such as population, mobile subscribers, number of devices and minutes of usage, available on NRAs statistics and operators reports, are established to give an initial structure to the models. Second, the analysis of the main geopolitical, socio-economical, technological and behavioral trends is widely used to estimate growth rates and mobile networks future trajectory.

However, since the methodologies rely in part upon data published by external sources and in part on internal assumptions, the growth rates are expected to be slightly

<sup>2</sup> Percentages are the results of calculations based on Ericsson Mobility Report June 2014 data.

different when comparing the results. IDATE methodology, for example, is the only one that builds three different scenarios to understand the possible outcomes of the trends and then selects the one which is considered more suitable. Also, while Cisco and IDATE include M2M devices in the number of mobile connections, Ericsson exclude them. Similarly, Ericsson does not include DVB-H, Wi-Fi, Mobile WiMax traffic while Cisco does.

Thus, when comparing the results, it is very important to carefully understand the main assumptions and limitations behind the methodologies, in particular those regarding device categories and technologies considered.

### **3 Spectrum value calculation methodology**

The methodology is based on the evolution of a techno-economical model for evaluating the opportunity-cost of the spectrum, whose results are then empirically tested [1]. The model is designed to take into consideration the most recent technical developments in mobile technology, such as LTE, multiple channel bandwidths, MIMO (2x2, 4x4) antenna configurations and relies on evolved bottom-up market forecasting to estimate the demand of traffic in the network in the period of evaluation.

Bidirectional services include all those applications which require devices to be communicating in two directions. This may mean communication between user devices and network nodes (e.g. mobile phones, WiMax, PMR, etc.) or between two similar devices (e.g. fixed radio links). The marginal value of the spectrum for these services is calculated based on the assumption that the value should be positive only within densely inhabited areas, where network nodes are used at their maximum capacity, because in lower density areas it is quite likely that re-use of frequencies is optimally arranged, so as not to require the use of the entire allocated bandwidth. In this situation, the marginal opportunity cost of one additional spectrum unit might well be negligible. This assumption is made in order to have the possibility to examine the spectrum's marginal value without being bound to transmission and propagation issues, which would greatly limit the applicability of the study's results.

A crucial factor in the determination of the exact marginal opportunity cost is the analysis of the capacity needed to cover the area under examination. This information is estimated through a dedicated market forecasting sub-model that based on a systematic bottom-up approach, which considers actual mobile subscribers, mobile broadband subscribers and mobile traffic, applies specific growth rates until 2020. The market forecasting provides also total traffic in a given area.

For services concerned with supplying circuit capacity, the unit of measurement applied is the Erlang (a non-dimensional unit used in telecommunications as a statistical measurement of traffic volumes). Services concerned with supplying packet transmission capacity are measured in Mbit/s. The volume managed by each single node is calculated directly.

The marginal opportunity cost calculation is based on a comparison between two network configurations: the first is what can be obtained with the bandwidth currently available, while the second presents the situation which could be obtained by increasing or decreasing the bandwidth by one marginal (basic) unit.

Generally, what happens is that to supply a predetermined capacity by using less bandwidth, it is necessary to increase the number of transmission nodes, decreasing their coverage radius. Increasing the number of nodes has an impact on the operator's cost structure, both in terms of investment (purchase of equipment and set-up) and in terms of maintenance and management (the network's complexity grows at a quasi-exponential rate as the number of nodes increases).

Comparison of the two configurations yields to the yearly cost differential for the operator, which indicates the savings (or extra costs) associated to the availability or loss of an extra unit of bandwidth. This value, divided by the spectrum's marginal unit's width (in MHz), gives the cost differential per megahertz, which can be considered to be the marginal value of 1 MHz of the spectrum.

While this approach allows the model to be applied whilst disregarding propagation issues correlated to morphology and urbanization characteristics of the area under analysis, its main limit is that it sets a negligible value for low-density, non-congested areas.

Nevertheless, this constraint is supported by some NRAs frameworks. The ACMA (Austrian Communication & Media Authority), for example, recognizes that opportunity cost pricing should only be positive where demand exceeds supply, such as in high-density areas. Thus, in low-density areas, which are unlikely to ever be congested, the opportunity cost of spectrum would be negligible [30].

### 3.1. The national mobile bandwidth demand forecast

The first factor in the determination of the marginal opportunity cost is the analysis of the capacity needed to cover the area under examination. In order to derive it, the mobile bandwidth demand (in Mbit/s) for each Country is estimated through a bottom-up starting from the number of subscribers per voice and data services and from their average daily consumption. The methodology, which is synthesized in figure 4, is based on four steps:

- a. Collection of the number of mobile voice and data subscribers in each Country
- b. Segmentation of the mobile broadband subscribers
- c. Estimation of the daily mobile traffic
- d. Rollup

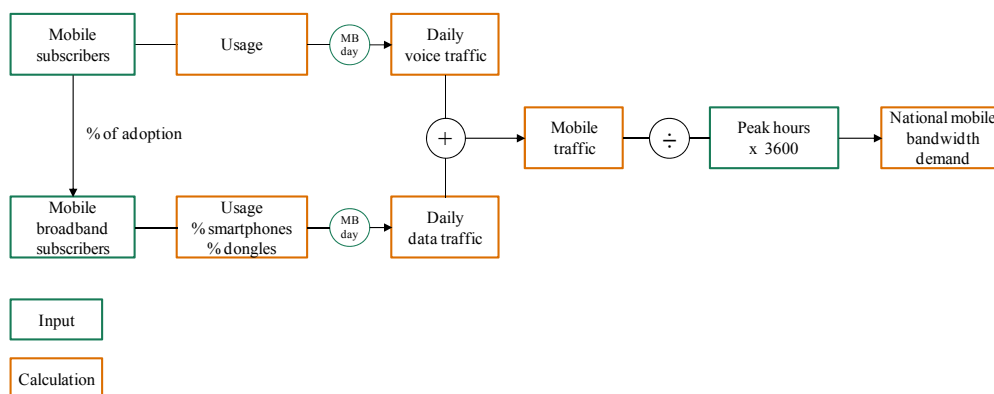


Fig. 4. Forecast methodology

### a. Collection of the number of mobile voice and data subscribers in each Country.

Our forecast begins with the estimation of the number of active mobile voice and data subscribers obtained from a variety of sources, including NRAs, ITU, GSMA and World Bank statistics.

The following tables synthesize the data points relative to 2013 used as the baseline for our projection. In particular, Table 3 summarizes the total number of mobile subscribers per Country, while Table 4 summarizes the mobile broadband subscribers, together with the broadband adoption rate.

**Table 3**  
Mobile subscribers, 2013.

<b>Country</b>	<b>2013 Mobile Subscriptions</b>	<b>Source</b>
Austria	13,272,000	RTR
Belgium	12,313,375	BIPT
Czech Republic	14,047,000	World Bank
Denmark	8,730,000	GSMA Intelligence
Estonia	2,055,234	World Bank
Finland	9,318,000	FICORA
France	75,500,000	ARCEP
Germany	115,959,000	Bundesnetzagentur
Greece	15,861,833	EETT
Hungary	11,540,058	NMHH
Iceland	399,603	PTA
Ireland	5,614,744	ComReg
Italy	96,640,000	AGCOM
Luxembourg	788,371	World Bank
Netherlands	22,097,000	ACM
Norway	5,873,564	World Bank
Poland	54,851,000	Office of Electronic Communications
Portugal	11,990,993	World Bank
Slovak Republic	6,208,412	Telekomunikačný úrad SR
Slovenia	2,237,708	AKOS
Spain	54,896,980	CMT
Sweden	13,992,000	PTS
Switzerland	10,808,000	World Bank
United Kingdom	78,143,682	World Bank
Turkey	69,661,108	BTK
USA	335,650,000	FCC
Brazil	271,099,799	Anatel
India	886,304,245	TRAI
China	1,229,113,000	China Mobile, China Unicom, China Telecom

**Table 4**

Mobile broadband subscribers and adoption rate, 2013.

<b>Country</b>	<b>2013 Mobile Broadband Subscriptions</b>	<b>Source</b>	<b>Adoption rate</b>
Austria	5,337,190	ITU	40%
Belgium	5,103,965	ITU	41%
Czech Republic	4,850,000	ITU	35%
Denmark	6,029,427	ITU	69%
Estonia	996,426	ITU	48%
Finland	6,699,800	ITU	72%
France	36,720,000	ITU	49%
Germany	37,007,000	ITU	32%
Greece	4,013,404	ITU	27%
Hungary	2,619,270	ITU	23%
Iceland	244,716	ITU	69%
Ireland	3,107,147	ITU	55%
Italy	39,542,703	ITU	41%
Luxembourg	427,200	ITU	54%
Netherlands	10,448,040	ITU	55%
Norway	4,319,301	ITU	74%
Poland	22,806,993	ITU	40%
Portugal	3,897,597	ITU	33%
Slovak Republic	2,920,396	ITU	47%
Slovenia	865,796	ITU	38%
Spain	31,492,905	ITU	63%
Sweden	10,172,918	ITU	85%
Switzerland	3,578,970	ITU	33%
United Kingdom	55,048,828	ITU	70%
Turkey	24,173,143	ITU	35%
USA	297,018,000	ITU	88%
Brazil	103,107,569	ITU	38%
India	40,660,000	ITU	5%
China	295,961,000	ITU	24%

#### **b. Segmentation of the mobile broadband subscribers.**

Once the number of mobile broadband subscribers has been collected, it is important to discriminate between the different types of mobile users, because of different consumption levels and behaviors.

The model identifies two device segments: small screen (smartphones) and large screen (including portable modems, USB wireless modems, tablets and mobile PCs featured with a wireless Internet access).

It is assumed that 85% of mobile broadband subscribers is represented by small-screens, while the remaining 15% is represented by large-screens<sup>3</sup>.

<sup>3</sup> Ericsson Mobility Report June 2014, data extrapolated from statistics, excluding machine-to-machine devices.



### c. Estimation of the daily mobile traffic.

The traffic estimation is built identifying (and converting in bit/s) two different sources: the voice traffic, generated by mobile phone calls, and the data traffic, generated by data usage.

- **The traffic generated by voice calls** is obtained from the Minutes of Usage (MoU) data obtained by the NRAs, which are converted into the MB per minute consumption using a simplified equation. It is assumed that 1 second of phone call generates 13 Kbits/s (considering a GSM call), corresponding to 0.00016 MB/s or 0.098 MB per minute.
- **Daily mobile data traffic per subscriber** is calculated by multiplying the percentage of smartphones times the average smartphone traffic per day, plus the percentage of dongles times the average dongles traffic per day. According to recent statistics<sup>4</sup>, in 2013 the global average data usage of a smartphone is 600 MB per month, while the one of a dongle is approximately 3 times higher<sup>5</sup>. However, the average data usage has very different values depending on the region/country. Thus, it is assumed that in EU countries, the average data usage is 20% higher than the average value, while in developing countries (Turkey, Brazil, India, China) it corresponds to the 30% of the average value<sup>6</sup>. In the USA, it is assumed that data traffic is twice the average value [31]. Table 5 lists the average broadband traffic per day according to region/country.

**Table 5**  
Average daily data traffic according to region/country, 2013.

Region/ Country	Smartphones share	Dongles share	Average smartphone traffic (MB per day)	Average dongle traffic (MB per day)	Average data traffic (MB per day)
EU <sup>7</sup>	85%	15%	24	72	31
Turkey	85%	15%	6	18	8
USA	85%	15%	40	120	52
Brazil	85%	15%	6	18	8
India	85%	15%	6	18	8
China	85%	15%	6	18	8

The daily mobile traffic is then calculated by multiplying the number of mobile subscribers (considering only the smartphone segment) by the daily voice traffic, and the number of mobile broadband subscribers by the daily data traffic.

<sup>4</sup> Ericsson Mobility Report June 2014 lists monthly data traffic per smartphone equal to 650 MB, monthly data traffic per mobile PC equal to 3,300 MB and monthly data traffic per tablet equal to 1,400 MB. Cisco VNI 2014 reports monthly data traffic per smartphone equal to 539 MB, monthly data traffic per mobile PC equal to 2,450 MB and monthly data traffic per tablet equal to 1,374 MB.

<sup>6</sup> 2G will remain the dominant technology in many lower income countries for a number of years to come, in contrast with the technology shift underway in the developed region (GSMA). To reflect this statement data traffic is discounted to the 30% of the global value.

<sup>7</sup> Values adjusted for Finland, Netherlands, Norway, Portugal, Slovak Republic and UK

**d. Rollup.** Finally, the national mobile bandwidth demand is estimated by dividing the daily mobile traffic (converted in Mbit<sup>8</sup>) by the number of peak hours<sup>9</sup> times 3600.

For the years 2014-2020, specific compound annual growth rates (CAGR) are applied for all the variables involved, except for the daily voice traffic which is assumed to remain constant over time and marginal with respect to the total mobile traffic.

- **Mobile subscribers growth.** Unique subscriber penetration has almost reached the "demographic ceiling" in developed countries, while it is still below the 50% in developing markets [32]. Thus, it is assumed that mobile subscribers growth is tending to stall in EU countries and USA with a CAGR of 2%. In contrast, in developing countries (Turkey, Brazil, India and China) it is assumed to be 4%.

- **Mobile broadband subscribers growth.** Rising smartphone penetration is driving global mobile broadband subscribers growth; however the growth rate presents very different values depending on region and country. Operators are continuously investing in infrastructures and attractively priced propositions foster the growth of mobile broadband connections, offering consumers a viable substitute for a fixed broadband connection [32]. It is assumed that the growth rate is negatively related to the adoption rate, meaning that countries with a low mobile broadband penetration are expected to have higher growth rates. However, as the adoption rate increase, it is assumed that the growth will slow reaching the saturation level. Thus, every year the growth rate is calculated for each country depending on the previous year adoption rate. Table 6 provides the estimations for the mobile broadband subscribers' growth rate according to the adoption rate.

**Table 6**  
Mobile broadband subscribers growth rate.

<b>Adoption rate</b>	<b>Mobile broadband growth rate</b>
5%	80%
10%	64%
15%	51%
20%	41%
25%	33%
30%	26%
35%	21%
40%	17%
45%	13%
50%	11%
55%	9%
60%	7%
65%	5%
70%	4%
75%	4%
80%	3%

<sup>8</sup> 1 MB = 8 Mbit.

<sup>9</sup> It is assumed a number of 8 peak hours per day.

85%	2%
90%	2%
95%	1%
100%	0%

- **Mobile data traffic growth.** Mobile data traffic is expected to have an extraordinary growth thanks to the advancement of devices, which are able to operate on increasingly ubiquitous higher speed networks (both 3G and 4G) and are allowing users to adopt an ever growing range of new services and applications [32]. Therefore, data traffic it is assumed to have a 50% CAGR from 2013 to 2020.

Table 7 lists the variables, the average CAGRs estimated using the model and the respective benchmarks.

**Table 7**  
Average CAGRs for the selected countries and global benchmarks.

Variable	Current Model	GSMA <sup>10</sup>	Ericsson <sup>11</sup>	CISCO <sup>12</sup>
Mobile subscribers CAGR	3.5%	4.2%	4.2%	4.3%
Mobile broadband CAGR	15%	15%	19%	17%
Mobile data traffic CAGR	50%	54%	45%	61%
Coverage	Detailed view on specific Countries - generalizable	Worldwide-aggregated view	Worldwide-aggregated view	Worldwide-aggregated view
Timeframe	2013-2020	2013-2020	2013-2019	2013-2018

It is interesting to compare the existing evaluations by GSMA, Ericsson and CISCO reports with that deriving from the application of the proposed model. The small discrepancy in the obtained values is mainly due to two factors.

First, the proposed model has been applied to 24 EU countries, the USA and 4 developing countries (Turkey, Brazil, India and China) while the other evaluations are on a worldwide base. This explains the difference between the mobile subscribers CAGRs. In fact, by considering only a selection of countries, the lower growth rate of European countries and the USA affects the average.

Second, the different timeframes considered partially explains the lower mobile broadband subscribers CAGR of the proposed model. In fact, it is expected that year after year the growth rate is going to decrease as the broadband connections saturation level increases. The discrepancy between the mobile data traffic CAGR is due to different assumptions in the evolution of mobile traffic. The estimated values are compatible with the benchmarks and international trends.

### 3.2. The network configurations

<sup>10</sup> GSMA The Mobile Economy 2014

<sup>11</sup> Ericsson Mobility Report June 2014

<sup>12</sup> CISCO VNI 2014

The marginal opportunity cost calculation is based on a comparison between two network configurations. Once the national bandwidth demand is forecasted, it is possible to estimate the network configurations. In fact, the first network is obtained with the bandwidth currently available, while the second presents the situation which could be obtained by increasing or decreasing the bandwidth by one marginal (elementary) unit. What happens is that to supply a predetermined capacity by using less bandwidth, it is necessary to increase the number of transmission nodes, decreasing their coverage radius.

In particular, the model calculates the number of nodes in a network by relying on two drivers: the number of sectors and the number of available elementary units. Figure 5 shows the methodology to estimate the network configurations.

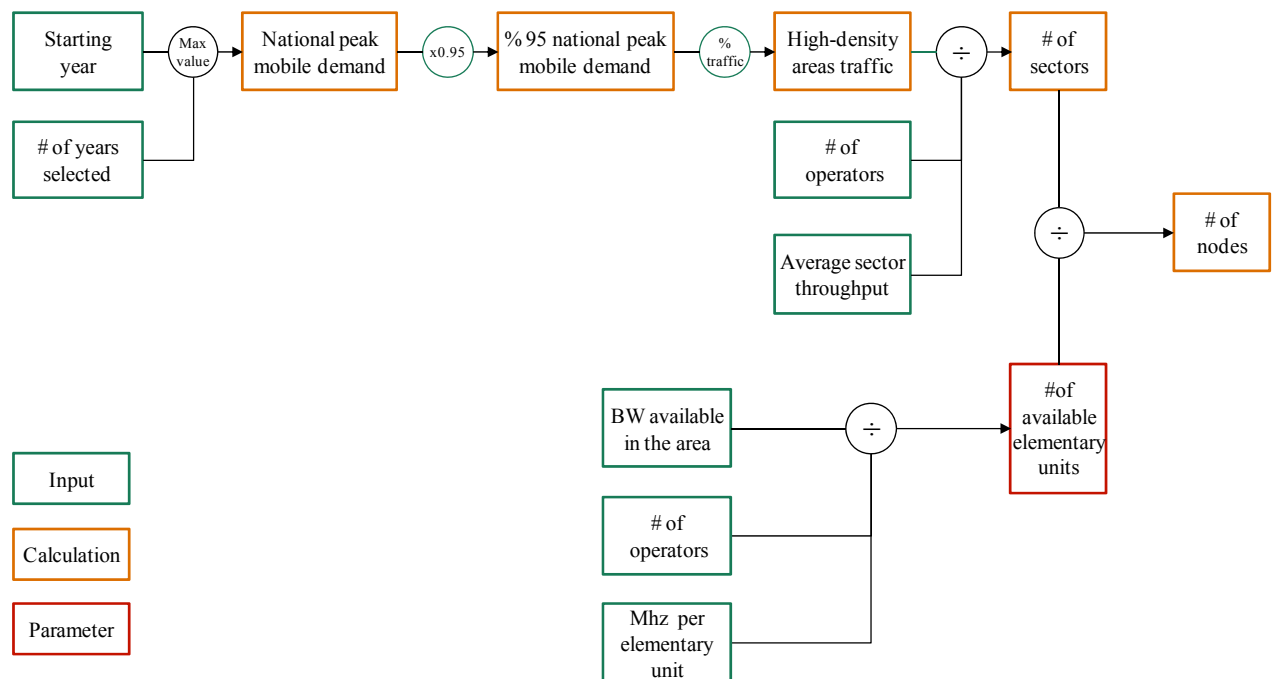


Fig. 5. Network configurations estimate methodology.

**Number of sectors.** The number of sectors is estimated by dividing the traffic in high-density areas by the number of layers, divided by the average sector throughput, which represents the Mbit/s that can be managed by a single bandwidth unit, in the hypothesis that each sector will only manage one of them.

- To calculate the traffic in high-density areas, the starting year and the time period for the evaluation must be selected. The model allows choosing the starting year until 2016 and a time period for the evaluation of 1, 3 and 5 years.

Once selected, the maximum bandwidth demand value reached among the years is used as baseline for the next calculations and considered as peak demand. Since the peak traffic represent the maximum impulsive consumption measured in the network, it needs to be discounted to the 95% of its value to smooth the peaks and to be more representative of the maximum capacity needed in the network. In fact, peak data rates reflect theoretical rates that very few subscribers will actually experience,

since they do not take into account factors, such as traffic load, fading, attenuation loss and the signal to noise ratio, that have an impact on the subscriber data rate [33].

Then, discounted peak demand is multiplied by the percentage of traffic in high-density areas, which is calculated relying on the OECD and World Bank statistics [34]. Traffic in low-density areas is excluded based on the assumption that the spectrum value should be positive only within densely inhabited areas, where network nodes are used at their maximum capacity, because in lower density areas it is quite likely that re-use of frequencies is optimally arranged, so as not to require the use of the entire allocated bandwidth.

- The number of layers equal to the number of operators active in the area and it is assumed that operators equally share the total bandwidth available in the area. Small local players, with a market share below 3%, were excluded.
- The average sector throughput represents the Mbit/s that can be managed by a single bandwidth unit, in the hypothesis that each sector will only manage one of them. Depending on the technology under examination, it takes different values as shown in table 8. Notably, LTE provides a significant improvement in average sector throughput capacity across all channel bandwidths, when compared to the other 3GPP technologies, by leveraging 2X2 MIMO (Multiple-input and multiple-output) antenna technology and OFDM (Orthogonal Frequency-Division Multiplexing) encoding, which assigns each subscriber an individual sub-carrier so that each sector is not impacted by more subscribers [33].

**Table 8**

Comparison of the average sector throughput capacity of HSPA, HSPA+ and LTE technologies [33].

Technology	Carrier Bandwidth (MHz)	Average Sector Throughput (Mbit/s)				3GPP Release
		DL 1x1	DL 2x2	DL 4x4	UL No MIMO	
HSPA	5	2.25			1.3	Rel. 6
HSPA+	5		3.7		1.45	Rel. 7/8
LTE	5		7.85	12	3.17	Rel. 8
LTE	10		16.7	25	6.35	Rel. 8
LTE	20		33.4	50.1	12.7	Rel. 8

**Number of available elementary units.** The number of available elementary units is calculated by dividing the total available bandwidth in the area by the number of layers in the area, divided by the MHz per elementary unit.

- Total available bandwidth in the area is estimated through external sources, in particular the EFIS (ECO Frequency Information System) database and NRAs reports [35]. EFIS is the main spectrum database in EU, since the European Commission Decision of 16 May 2007 (2007/344/EC) and the Decision of the European Parliament and of the Council of 7 March 2002 (676/2002/EC) on harmonized availability of information regarding spectrum use within the Community decided to use it for publication and

access to spectrum information. Bandwidth has been analyzed in the 700, 800, 900, 1700/1800, 1900, 2100, 2300 and 2600 MHz bands because these frequencies are those recommended by the European Commission and considered suitable by the CEPT (European Conference of Postal and Telecommunications Administrations) for UMTS and LTE spectrum allocation [36], [37], [38].

- As previously stated, the number of layers is equal to the number of operators active in the area and it is assumed that operators equally share the total bandwidth available in the area. Small local players, with a market share below 3%, were excluded.
- The MHz per elementary unit represents the channel bandwidth, which is the range of signal bandwidths allowed by a communication channel without significant loss of energy. According to 3GPP Release 8, LTE technology defines a number of channel bandwidths of 1.4, 3, 5, 10, 15 and 20MHz [39].

Once determined the two drivers, it is possible to calculate the number of nodes in a network by dividing the number of sectors by the number of available elementary units. The first network is obtained with the bandwidth currently available, while the second presents the situation which could be obtained by increasing or decreasing the bandwidth by one marginal (elementary) unit. In fact, to supply a predetermined capacity by using less bandwidth, it is necessary to increase the number of transmission nodes, decreasing their coverage radius.

### **3.3. The costing system**

Increasing or decreasing the number of nodes has an impact on the operator's cost structure, both in terms of investment (purchase of equipment and set-up) and in terms of maintenance and management (the network's complexity grows at a quasi-exponential rate as the number of nodes increases).

The complexity of a technology or transmitting element cost is a consequence of each technology's specificity, as each technological system requires notably different configurations and devices. Also, there are difficulties implied in determining depreciation periods and in calculating discount rates. Technology costs are defined as the costs an operator must sustain to purchase and operate an array of devices capable of supplying the required service. Those costs are usually computed for a set of transmitting elements. A transmitting element is a collection of active and passive devices, interconnections, power sources and structures, placed in the same geographical location, which compose the smallest constituent of a transmission network. Depending on the application, it may be called node, cell, etc.

The factors determining the cost of a node can generally be divided in:

- Logistics and material costs, including antennae, filters, internal and external transmission devices, support, synchronization and management devices, cables and power supply protection elements (UPS, generator, electric panels, etc...).
- Costs related to the installation, which may be on the ground (with the building of a mast or other suitable infrastructure), or on a building, by anchoring metal elements over pre-existing concrete structures.

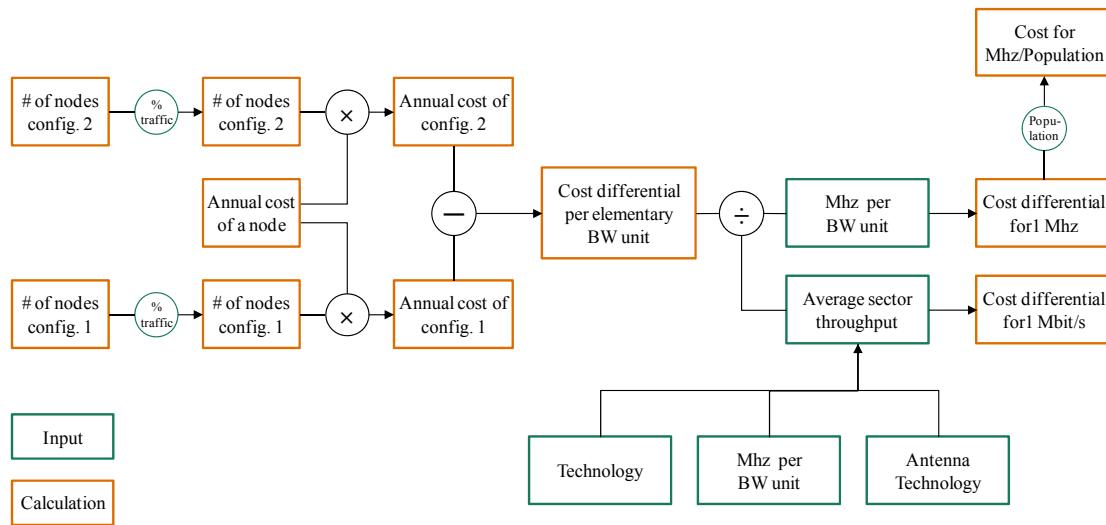
- Costs related to the interconnection to the operator's backbone network
- Maintenance and operational costs.

### 3.4. The opportunity cost

Comparison of the two configurations, estimated by multiplying the number of nodes in the network configuration by the annual cost of a node, yields to the yearly cost differential for the operator, which indicates the savings (or extra costs) associated to the availability or loss of an extra unit of bandwidth.

- The cost differential per elementary bandwidth unit, divided by the spectrum's marginal unit's width (in MHz), gives the cost differential per megahertz, which can be considered to be the marginal value of 1 MHz of the spectrum.
- The cost differential per megahertz, divided by the population in the area, gives the cost for MHz/population.
- The cost differential per elementary bandwidth unit, divided by the average sector throughput (in Mbit/s), gives the cost differential per Mbit/s.

Figure 6 provides the methodology to calculate the cost differentials.



**Fig. 6.** Cost differentials calculation methodology.

## 4 Results and Conclusions

The model has been applied to multiple Countries representative of the main stable and growing economy to simulate the possible values depending on the evaluation period and on the specific technology adopted. The unit adopted for the results presentation and comparison is the €/MHz/population, which represents a ratio

comparable cross Countries and correctly representing the value of the spectrum depending on the population served.

Table 9 summarizes the values obtained simulating the use of a LTE technology using 2x2 antennas, with the evaluation starting in 2013 and with an evaluation period of 5 years.

**Table 9**  
Opportunity-cost model results

<b>Evaluation area</b>	<b>Yearly Estimated Value per MHz/ person (€)</b>
Austria	0.024
Belgium	0.008
Brazil	0.003
Czech Republic	0.0001
Denmark	0.009
Estonia	0.001
Finland	0.011
France	0.009
Germany	0.008
Greece	0.007
India	0.001
Ireland	0.023
Italy	0.009
Luxembourg	0.013
Netherlands	0.011
Norway	0.005
Portugal	0.007
Slovak Republic	0.007
Slovenia	0.003
Spain	0.004
Sweden	0.008
Switzerland	0.012
Turkey	0.005
United Kingdom	0.013
USA	0.016

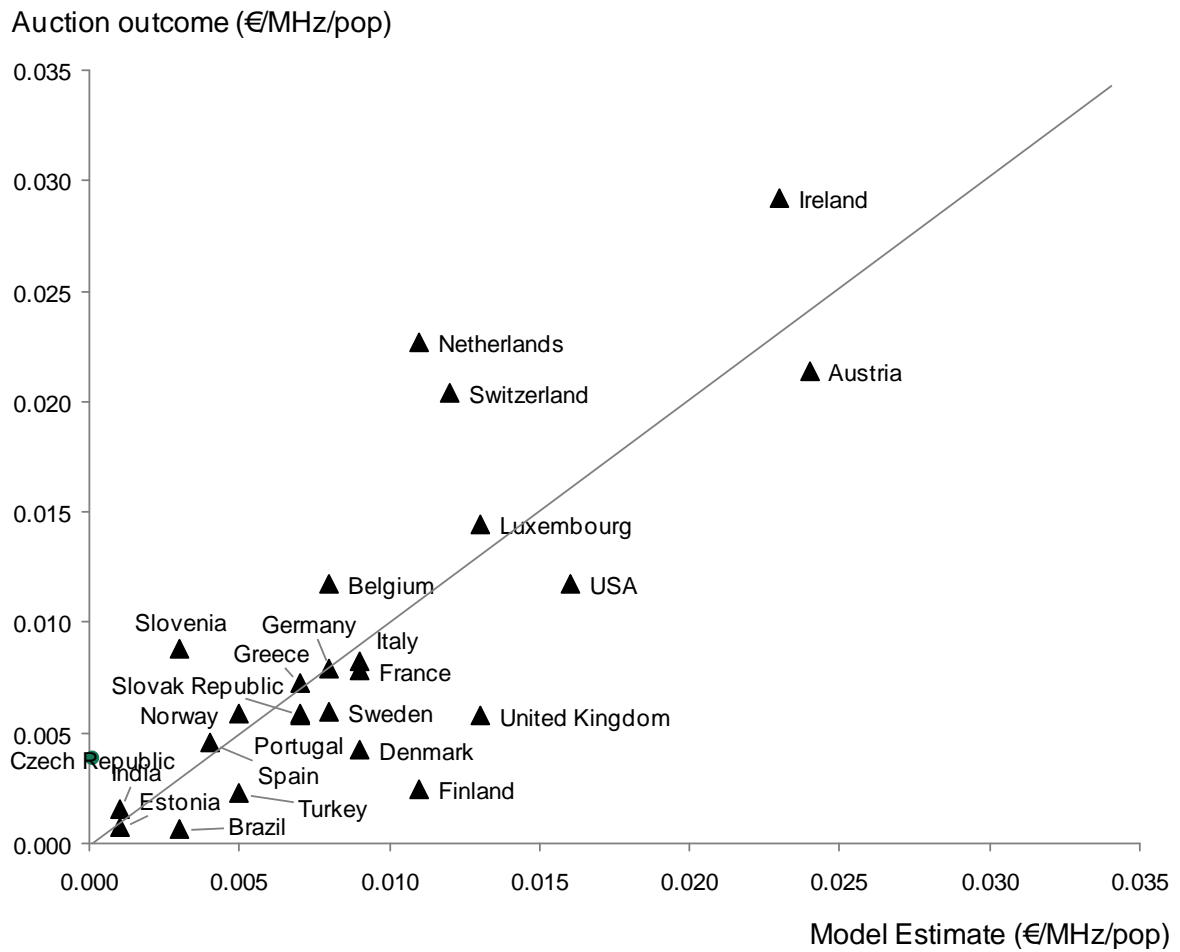
It is interesting to compare the values emerged from 4G auctions run around Europe, US and Asia with those derived by the model. The following table shows the outcomes of mobile auctions completed in recent years in the selected Countries.



**Table 10**  
Auctions outcomes in the analyzed Countries

Country	Frequency (GHz)	Year	MHz auctioned	Auction outcome (€Bn)	Yearly Auction Value per MHz/ person (€)	Yearly Estimated Value per MHz/ person (€)
Austria	0.8-0.9-1.8	2013	280	2.01	0.0427	0.0159
Belgium	0.8	2013	60	0.36	0.0270	0.0295
Brazil	0.45-2.6	2012	134	1.01	0.0026	0.0023
Czech Rep.	0.8-1.8-2.6	2013	198	0.32	0.0101	0.0004
Denmark	0.8	2012	60	0.10	0.0142	0.0030
Estonia	0.8	2013	40	0.01	0.0096	0.0082
Finland	0.8	2013	60	0.11	0.0166	0.0141
France	0.8-2.6	2011	200	3.58	0.0183	0.0061
Germany	0.8-1.8-2.1-2.6	2010	359	4.38	0.0099	0.0077
Greece	0.9-1.8	2011	110	0.38	0.0207	0.0190
India	0.9-1.8	2014	353	9.85	0.0011	0.0006
Ireland	0.8-0.9-1.8	2012	280	0.85	0.0392	0.0325
Italy	0.8-1.8-2.6	2011	240	3.95	0.0163	0.0113
Luxembourg	-	-	-	-	-	0.0225
Netherlands	0.8-1.8-2.1-2.6	2012	574	3.80	0.0233	0.0503
Norway	0.9-0.9-1.8	2013	200	0.22	0.0108	0.0061
Portugal	0.8-0.9-1.8-2.6	2011	299	0.37	0.0078	0.0376
Slovak Rep.	0.8-1.8-2.6	2013	276	0.16	0.0078	0.0282
Slovenia	0.8-1.8-2.1-2.6	2014	465	0.15	0.0103	0.0118
Spain	0.8-0.9-2.6	2011	210	1.65	0.0089	0.0067
Sweden	0.8-1.8	2011	130	0.37	0.0132	0.0153
Switzerland	0.8-1.8-2.1-2.6	2012	575	0.83	0.0121	0.0090
Turkey	2.1	2008	105	0.82	0.0056	0.0057
UK	0.8-2.6	2013	245	2.72	0.0087	0.0245
USA	0.7	2008	62	12.34	0.0661	0.0162
Austria	0.8-0.9-1.8	2013	280	2.01	0.0427	0.0159
Belgium	0.8	2013	60	0.36	0.0270	0.0295
Brazil	0.45-2.6	2012	134	1.01	0.0026	0.0023

The following picture compares the model estimates with the auction results for the Countries under analysis.



**Fig. 7.** Comparison amongst spectrum values from different auctions with the values estimated in the model.

The model appears to have reasonable prediction capabilities, as it appears from the previous graph, (fig.7), where the linear regression on all the values combining auction outcomes with the model estimates is represented by the equation  $y = 0,9743x + 0,0004$ , with a  $R^2 = 0,6204$ .

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