Department of Communications and Networking

Regulation for dynamic spectrum management

Arturo Basaure

Aalto University

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Regulation for dynamic spectrum management

Arturo Basaure

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Abstract

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Abstract

Spectrum management is in the core of Internet access and therefore of vital importance for assuring the most important processes of our society. The increasing demand for new services makes the spectrum scarcer and urges national regulatory authorities (NRAs) to promote a more efficient spectrum usage. In this context, dynamic spectrum access (DSA) technologies and the related dynamic spectrum management (DSM) provide new ways of managing spectrum, by dynamically reassigning the underutilized spectrum (i.e. white spaces).

This thesis employs a combined approach consisting of agent-based modelling and system dynamics to study spectrum management by means of dynamic neo-institutional economics. Thus, this work combines transaction cost and evolutionary economics into the modelling and analysis of the constantly evolving ICT ecosystem.

DSA decreases the costs associated with spectrum transactions and help to clearly define spectrum usage rights, and therefore it provides the basic conditions for the Coasean implications on policy, pushing gradually spectrum management towards a property rights regime.

From the analysed scenarios, this thesis shows that indoor deployment is most promising for DSA technologies. Indoor networks transmitting in higher frequency bands require less coordination for achieving mutual benefits from the performed spectrum transactions. Therefore, this thesis emphasizes that spectrum reforms, allowing spectrum transactions, should focus on higher frequency bands and new indoor network deployments, such as small-cells, 5G, IoT and M2M services. NRAs should facilitate flexibility in spectrum assignment in the higher frequency bands, by means of a property rights regime or a flexible licensing regime, to provide indoor deployments with the ability to respond more dynamically to the changes in demand. Moreover, such spectrum reforms may drive spectrum decentralization to stimulate user-centric innovation.

Finally, this thesis compares DSA with other alternative mechanisms, such as national roaming and end-user multihoming. The three compared mechanisms may improve the economic efficiency of mobile networks. In indoor networks, while end-user multihoming and national roaming addresses coverage problems, DSA may increase the efficiency further by addressing congestion problems. In outdoor networks, national roaming and end-user multihoming may improve coverage problems.

Keywords Dynamic spectrum access and management (DSA, DSM), transaction cost economics, evolutionary economics, agent-based modelling, system dynamics

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Tiivistelmä

Radiospektrin hallinta sijaitsee mobiilin ja langattoman Internetin ytimessä ja sen tärkeys vahvistuu yhteiskuntamme tärkeimmissä prosesseissa. Uusien palveluiden kasvava kysyntä tekee spektristä entistä niukemman resurssin ja motivoi viranomaisia edistämään tehokkaampaa spektrin käyttöä. Tässä kontekstissa, dynaamiset spektrin liityntäteknologiat (Dynamic Spectrum Access (DSA)) sekä näihin liittyvä dynaaminen spektrin hallinta tarjoavat uusia keinoja alikäytetyn spektriresurssin (ns. valkoiset tilat) uudelleen käyttämiseen ja jakamiseen.

Tämä tutkimus soveltaa agenttipohjaista mallinnusta sekä systeemidynamiikkaa ja analysoi spektrin hallintaa hyödyntäen dynaamista uusi-instituutionalista talousteoriaa. Toisin sanoen, tutkimustyö yhdistää transaktiokustannusten sekä evoluution talousteoriaa ja analysoi alati muuttuvaa ICT-ekosysteemiä näitä hyödyntäen.

DSA vähentää spektrin transaktiokustannuksia ja auttaa määrittelemään selkeästi spektrin käyttöoikeudet. DSA täyttää näin perusedellytykset, jotta Coasen teoreemaa voidaan soveltaa spektripolitiikassa; toisin sanoen, ottaa asteittain käyttöön omistusoikeusjärjestelmiä spektrin hallinnassa.

Analysoimalla eri skenaarioita tämä väitöskirja osoittaa, että sisätilojen verkot ovat erityisen lupaavia DSA teknologioiden käyttöönotossa. Jos sisätilojen verkot käyttävät korkeimpia taajuuksia, ne vaativat vähemmän koordinaatiota hyödynnettäessä spektrin transaktioita. Työ korostaa, että spektrin lakiuudistusten pitäisi kannustaa spektrin transaktioita korkeimmilla taajuuksilla sekä sisätilojen verkoissa (esim. small cells, 5G, IoT ja M2M-palveluissa). Regulaattoreiden tulisi lisätä joustavuutta spektrin jakomenetelmissä ja käyttöoikeuksissa, esim. omistusoikeuden tai joustavan lisenssin järjestelmillä. Näin ollen, sisätilojen verkot voisivat vastata paremmin ja dynaamisesti kysynnän vaihtelevuuteen. Lisäksi spektrin lakiuudistusten tulisi ajaa spektrin hajauttamista sekä lisätä käyttäjäkeskeistä innovaatiota.

Lopuksi työ vertailee DSA:ta vaihtoehtoisiin menetelmiin, kuten kansallinen roaming ja loppukäyttäjän multihoming (end-user multihoming), jotka voivat kasvattaa taloudellista tehokkuutta erilaisin keinoin. Kolme vertailtua menetelmää lisäävät kaikki soluverkkojen tehokkuutta. Sisätilojen verkoissa end-user multihoming ja kansallinen roaming parantavat kattavuuden ongelmia ja lisäksi DSA voi lisätä tehokkuutta parantamalla ruuhkaongelmia. Ulkotilojen verkoissa, kansallinen roaming ja end-user multihoming voivat taas parantaa kattavuuden ongelmia.

Avainsanat Dynaaminen spektrin liityntä (Dynamic Spectrum Access (DSA)) ja hallinta, transaktiokustannusten talousteoria, evoluutiotalousteoria, agenttipohjainen mallinnus, systeemidynamiikka

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Preface

"If you are going through hell, keep going"
—Winston Churchill

"Silloin kun on loppunut, se on loppunut"
—Tapio Soikkeli

This has been a long trip, but a nice one. A trip with smiles and sorrows, with light and darkness, summer and winter. Looking backward I realized that I have been a lucky man, who has worked with extremely valuable people, literally speaking from all around the world.

First of all, I want to show my enormous gratitude to professor Heikki Hämmäinen. He has a deep knowledge of the industry and an extraordinary capacity to put interesting people and topics together into an enjoyable and unique research environment. I have learnt a lot from Heikki, going from the *big picture* (i.e. the general perspective) to the *devil* (i.e. details). I also had the opportunity to share a lot of funny moments with him and the members of his team, for example in the so-called winter and summer events, which included sports, sauna and nice food.

Also I want to thank to my dear supervisors from the PUC of Chile: professors Ricardo Paredes and Vladimir Marianov. They have been extremely flexible, patient and supportive, giving always their perspectives and ideas to continue this thesis as a very unusual cotutelle until a successful completion.

Many thanks to my international co-authors: Oliver Holland from UK and Varadharajan Sridhar from India. Oliver received me twice in London during these years and I spent a wondeful time in King´s College. With Oliver we were able to hit all the simulation records resulting in several publications. On the other side of the world, Sridhar was with me an incredible collaborative coathor, even though I have never met him directly (only through Skype).

As mentioned, I am very happy of having worked with a very valuable group of people at Aalto University, members of our research team, most of them already holding a PhD title. Many thanks to Thomas Casey, who was the one to introduce myself to the world of Cognitive Radio. Thomas is a very inspiring person, enthusiastic and full of ideas. It was really nice to have him during the first period of this thesis. Also thanks to Henna Suomi, who collaborated with me in one of the most exiting papers of this thesis. Henna was a very motivated coathor and an enthusiastic team member. Many thanks to Ben Finley, Mike Katsigiannis, Tapio Soikkeli, Antti Riikonen, Tapio Levä, Nancy Zhang, Juuso Karikoski, Alexander Vesselkov and Jaume Benseny. Also thanks to the more senior members of the team: Kalevi Kilkki, Juuso Töyli and Pekka Kekkolahti. Also thanks to other collaborative people from the Communication and Networking Department who participated in the EECRT project, especially to Sebastian Sonntag and Kalle Rutik.

I also wanted to thank to the people of COST TERRA project; all those who participated in this extraordinary international forum made from my work an extremely interesting experience. Especially thanks to Marja Matinmikko and her enthusiastic and happy team from Oulu, and to Arturas Medeisis from Lithuania, for being such a nice host and organizer of the activities of COST TERRA.

Many thanks to my family. They have supported me from Chile in this long trip throughout the years, too many years. To my parents Mario and Cecilia; because of them I have the engineering in my blood. Thanks to my brothers and sisters: Pía, Cecilia, Alejandra, Ignacio and Mario. Thanks to my nephews and nieces.

Finally, thanks to my friends from Chile and Finland. Thanks to my friends from TKK/Aalto: Ville Salonen, Tommi Välimäki, Johan and Markus Jansson, Pekka Wetterstrand, Veikko Havu, Juha Ulvinen, Jesse García, and so many others. Thanks to other friends from Finland: Cyril de Vaumas, Jemi Katko, Heikki Sorasahi and so many others.

Thanks to my friends from Chile: to old classmates from high school (Cristóbal Poblete, Santiago Lecaros, Francisco della Maggiora, Sergio Ossa, Felipe Donoso, Rafael Araya, José Miguel Ossa, etc.), to all those who participated in the Alborada team during the years 2011-2016 (especially thanks to Pablo Salinas, to Aarón Osorio for designing the picture for this thesis, to Pablo Cabello for constantly disturbing me during this research process, to Andrés and Lucas Vogt, Koko Metzner, John Henríquez, José Luis Enberg, Daniel Fuentes, Luis Xavier Ortega, Cristóbal Lozano, and so many others), to the people of Volcán Quizapu (Ruy-Pérez, Mendez and Álvarez families), to the Chilean-Finnish community (Antti, Ilari and Amaru), to my colleagues from Universidad de los Andes, to Agustín Aubert for repairing the Vitara and to Domingo Carbone for just being. Each one of them has plaid an important role as a supporter of this thesis.

Helsinki, 19th August 2016
Santiago de Chile, 2nd September 2016

Arturo Basaure

Contents

List of Abbreviations

2G	2nd Generation
3G	3rd Generation
3GPP	3rd Generation Partnership Project
4G	4th Generation
5G	5th Generation
ABM	Agent-based modelling
ARPU	Average revenue per user
CA	Carrier aggregation
CAPEX	Capital expenditures
COST	European Cooperation in Science and Technology
CR	Cognitive radio
CRS	Cognitive radio system
D2D	Device-to-device
DSA	Dynamic spectrum access
DSM	Dynamic spectrum management
eSIM	Embedded subscriber identity module
ETSI	European Telecommunications Standards Institute
FDD	Frequency division duplex
IEEE	Institute of Electrical and Electronics Engineers
IEFT	Internet Engineering Task Force
IoT	Internet of things
ISM	Industrial, scientific and medical frequency band
ITU	International Telecommunications Union
LAA	Licensed assisted access

LAN	Local area network
LAO	Local area operator
LSA	Licensed shared access
LTE	Long term evolution
M2M	Machine-to-machine
MD	Mobile device
MNO	Mobile network operator
MNP	Mobile number portability
MPTCP	Multi-path transport control protocol
MVNO	Mobile virtual network operator
NRA	National regulatory authority
OPEX	Operational expenditures
PAWS	Protocol to Access white space (WS) database
PL	Pluralistic licensing
PLMN	Public land mobile network
PMSE	Programming making and special event
QoE	Quality of experience
QoS	Quality of service
RAN	Radio access network
RAT	Radio access technology
RF	Radio frequency
RRS	Radio reconfiguration system
SAS	Spectrum access system
SD	System dynamics
SDO	Standard developing organization
SDR	Software defined radio
SIM	Subscriber identity module
SINR	Signal to interference and noise ratio
TDD	Time division duplex
TVWS	TV white space
Wi-Fi	Wireless fidelity

WLAN	Wireless local area network
WRAN	Wide regional area network
WRC	World Radio Conference
WSD	White space device

List of Publications

This doctoral dissertation consists of a summary and of the following publications which are referred to in the text by their numerals

1. Basaure, A., Marianov, V., & Paredes, R. (2014). Implications of dynamic spectrum management for regulation. Telecommunications Policy. Vol 39 (7), 563–579, DOI: 10.1016/j.telpol.2014.07.001

2. Basaure, A., Holland, O. (2015). Optimizing spectrum value through flexible spectrum licensing. IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN), 130-141, DOI: 10.1109/DySPAN.2015.7343897

3. Kliks, A., Holland, O., Basaure, A., & Matinmikko, M. (2015). Spectrum and license flexibility for 5G networks. IEEE Communications Magazine, 53(7), 42-49, DOI: 10.1109/MCOM.2015.7158264

4. Basaure, A; Sridhar, V; Hämmäinen, H. (2015). Adoption of Dynamic Spectrum Access technologies: A System Dynamics approach. Telecommunication systems. DOI: 10.1007/s11235-015-0113-7

5. Suomi, H., Basaure, A., & Hämmäinen, H. (2013, October). Effects of capacity sharing on mobile access competition. In 21st IEEE International Conference on Network Protocols (ICNP), 2013, 1-6, DOI: 10.1109/ICNP.2013.6733661

6. Basaure, A., Suomi, H., & Hämmäinen, H. (2016). Transaction vs. Switching Costs - Comparison of Three Core Mechanisms for Mobile Markets. Telecommunications Policy. Vol 40 (6), 545-566, DOI: 10.1016/j.telpol.2016.02.004

Author's Contribution

Publication 1: Implications of dynamic spectrum management for regulation

Paredes suggested the suitability of the Coase theorem for this topic, Basaure did the analysis, the simulation and wrote the manuscript, which was discussed with and revised by Marianov and Paredes.

Publication 2: Optimizing spectrum value through flexible spectrum licensing

The analyzed scenarios were defined by Holland and Basaure. Basaure did the simulation, analysis and wrote the manuscript, and Holland provided constant feedback and support, especially related to technical aspects of the simulations.

Publication 3: Spectrum and license flexibility for 5G networks

Kliks coordinated the manuscript. Holland and Matinmikko provided the most important ideas for the manuscript and Basaure did the scenario analysis and simulations.

Publication 4: Adoption of Dynamic Spectrum Access technologies: A System Dynamics approach

Basaure wrote the draft version of the paper, including the analysis and the simulations. Sridhar provided constant feedback and revised the paper. Hämmäinen revised the paper and participated in discussions.

Publication 5: Effects of capacity sharing on mobile access competition

Hämmäinen suggested the initial idea for the analysis. Suomi wrote the main ideas of the manuscript, including the analysis on switching costs. Basaure wrote the analysis related to transaction costs. Suomi and Basaure revised the paper.

Publication 6: Transaction vs Switching Costs - Comparison of Three Core Mechanisms for Mobile Markets

In a first stage, the paper was written by Basaure with the constant feedback and support from Suomi. In a second and final stage, the paper was finalized by Basaure, with the constant feedback and support from Hämmäinen.

1. Introduction

1.1 Motivation

Spectrum management is in the core of mobile and wireless communications and therefore of vital importance for assuring the role of Internet as an enabler of societal processes. In recent decades, Internet has progressed from a useful network to a necessity, and its importance is expected to grow further. From this perspective, radio spectrum enables interconnection of stationary infrastructures (cities, houses, hospitals, schools, etc.), activities (health, education, public transport, production, logistic, entertainment, etc.) and mobile users (humans, devices and even animals).

Spectrum is a scarce resource subject to technical and economic constraints. Technology enables increasingly efficient use of spectrum. Based on technology developments, national regulatory authorities (NRA) continuously update the rules for accessing the spectrum. Their main purpose is to promote efficient spectrum usage; for example, by stimulating competition between spectrum holders, including mobile network operators (MNOs). As part of the economic efficiency objective, NRAs aim to improve the service supply and its quality-to-price ratio in the long run. In other words, together with the productive efficiency driven by the adoption of new technologies, regulation aims at increasing allocative, distributive and dynamic efficiencies. Furthermore, an increase in productive efficiency provides room for additional improvement in the other components of economic efficiency.

The increasing demand for new services makes the spectrum scarcer and urges NRAs to allocate additional spectrum to mobile services. The recent allocation of the new spectrum released by the digitalization of TV broadcast (i.e. digital dividend) to mobile network operators (MNOs) is one such example. In addition, new technologies increase the efficiency in spectrum assignment.

In this context, dynamic spectrum access (DSA) technologies and the related dynamic spectrum management (DSM) have become a major topic of interest. A dynamic assignment of spectrum in time and place has a potential to significantly increase the economic efficiency by rapidly reallocating the spectrum over time (allocative efficiency), fostering innovation and emerging services (dynamic efficiency), and contributing in the redistribution of resources (distributive efficiency) by allowing new entrants. However, until this date, the academic and research activity has not been followed by the industry engagement. Since DSA technologies are disruptive in nature, they may bring more threats than opportunities to MNOs. In such an uncertain scenario, MNOs seem to be missing a sufficient reason for investing in these technologies.

Regulation plays an important role in facilitating the introduction of new DSA technologies. Moreover, DSA may drive major changes in regulation wherefore it is important to understand the related complexity. The needed techno-economic analysis is further complicated due to a diverse set of DSA technologies and standards that are still being developed.

1.2 Research problem and scope

This thesis contributes to a better understanding of the requirements and implications of deploying DSA technologies into the Internet access markets. The opportunities and risks of dynamically assigning spectrum are assessed, focusing on regulation as a means to stimulate economic efficiency. In other words, the thesis aims at answering the following main question:

Q: Which are the efficiency gains obtained from a dynamic spectrum management and which are the main regulatory requirements that allow those gains?

More specifically, when answering the main question, the following sub-questions are elaborated:

Q1: How do benefits from spectrum transactions vary for different dynamic spectrum management scenarios?

Q2: How could DSA adoption happen in mobile and wireless Internet markets?

Q3: How does DSA compare against other alternative mechanisms for increasing economic efficiency of mobile and wireless Internet markets?

The first sub-question requires a feasibility analysis of different cases of spectrum transactions. The second sub-question addresses the conditions for a successful adoption of DSA technologies. Finally, the third sub-question aims at comparing DSA with other mechanisms that may increase economic efficiency. Each sub-question provides a different perspective for answering the main question.

This thesis comprehends the regulatory aspects of spectrum management for wireless and mobile Internet access, both wide-area cellular networks and local-area networks with wireless access, such as Wi-Fi. The chosen scope includes standards developing organizations (SDOs), such as the 3rd Generation Partnership Project (3GPP), the European Telecommunications Standards Institute (ETSI), the Institute of Electrical and Electronics Engineers (IEEE) and the Internet Engineering Task Force (IEFT). From a stakeholder perspective, the scope includes MNOs, other operators providing Internet access such as the so-called local area operators (LAOs), network and device manufacturers, end-users and finally national regulatory authorities (NRAs) and policy makers.

This thesis excludes issues related to pure fixed Internet access services and their possible interaction with mobile services, such as fixed-mobile service bundling or competition between fixed and mobile services.

1.3 Research approach and methods

This thesis applies a multidisciplinary research approach which combines natural and design sciences. It employs two modelling and simulation methods, namely agent-based modelling and system dynamics. While agent-based modelling studies a complex system of interacting agents from a bottom-up perspective, system dynamics analyses holistically the most important characteristics of a system from a top-down perspective. In general, this thesis builds models to evaluate the potential gains obtained from managing spectrum dynamically and the regulatory requirements allowing those gains.

1.4 Content of the thesis

This compilation thesis consists of the following introductory chapters and six publications. This chapter introduces the motivation, research questions and the content of the thesis. Chapter 2 presents the most relevant literature review and background information related to the research questions. Chapter 3 provides an overview of the underlying economic theories supporting the performed analysis. Chapter 4 describes the research approach, process and methods of this thesis. Chapter 5 summarizes the main results of the publications. Finally, Chapter 6 discusses the results and limitations, and provides the main conclusions of the thesis. In addition, the original publications are included as appendices.

1.5 Main economic and technical concepts

This thesis is a multidisciplinary study combining economics with technology. Consequently, some terms coming from the technology domain may have another meaning in the economic domain, and vice-versa. This section provides a summary of the most important terms to help readers with either technical or economic orientation to rapidly capture the necessary parts of the other domain.

The main economic concepts employed in this thesis are defined as follows:

<u>Allocative efficiency:</u> the state in which the production represents consumer preferences or, in other words, a point in which the marginal cost equals the marginal price.

<u>Competition:</u> the effort of two or more parties acting independently to secure the business of a third party by offering the most favourable terms (Merriam-Webster Online dictionary).

<u>Cooperation</u>: similar or complementary coordinated actions taken by firms in interdependent relationships to achieve mutual outcomes or singular outcomes with expected reciprocation over time (Anderson & Narus, 1990).

<u>Distributive efficiency</u>: the ability of the economy to redistribute resources (or purchasing power) to maximize social welfare.

<u>Dynamic efficiency</u>: addresses the trade-off between the short and long terms to generate the maximum value creation. It includes innovation as key aspect.

Economic efficiency: general term to indicate that scarce resources are optimally utilized to maximize social welfare. It can be subdivided into allocative, productive, distributive and dynamic efficiencies.

Ex-ante regulation: regulatory rules based on predefined obligations imposed to involved firms for a particular case or event.

Ex-post regulation: regulatory monitoring based on a general law prohibiting anticompetitive behaviours. This type of regulation includes arbitration and law enforcement.

Productive efficiency: the ability to maximize the output with the minimum amount of input.

Property rights: regime in which actors own the resource until they sell it to a new owner.

Retail market: refers to those economic transactions happening between a firm and a consumer (business-to-consumer relationship).

Switching costs: are one-time costs that a buyer faces when switching from one provider to another (Porter, 1980) and explain the market concentration and the monopoly power of incumbent firms.

Transaction costs: are those induced when employing the price mechanism offered by the market when transferring a resource from one holder to another (Coase, 1937) and they explain the level of vertical integration of an industry.

Usage rights: regime in which actors employ the resource during a predefined period of time as indicated in a license defined by a regulatory authority (or licensor).

Wholesale market: refers to those economic transactions happening between firms (business-to-business relationship).

The main technical concepts employed in this thesis are defined as follows:

Cognitive Radio (CR): initial concept as defined by Mitola (2000), according to which end-user devices can observe, orient, plan, decide, act and learn (i.e. cognitive cycle).

Cognitive radio system (CRS): "A radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained" (ITU, 2009). In this work, CRS is one type of implementation within dynamic spectrum access technologies.

Dynamic spectrum access (DSA) technologies: consist of a set of protocols and standards allowing end-users and operators to dynamically transmit in the unused or underutilized spectrum at different time and/or locations. In concrete, this work defines two types of DSA technologies. Firstly, operator-centric DSA enables two or more operators to transmit in the same frequency band, transferring spectrum from one base station to another between different operators. The spectrum transfer decision is made by the involved operators without the direct intervention of the end-user terminal. And secondly, user-centric DSA allows individual end-user devices to transmit in a spectrum band, while it is being employed by another party (i.e. end-user or operator). The spectrum is shared between end-users (e.g. as license-exempt) or it is transferred from one base station to another between different operators; however, driven by the decision of the end-user terminal, even though such transferring can be facilitated directly or indirectly (i.e. through a third party) by the spectrum holder. While operator-centric DSA permits operators to trade or share spectrum between them, user-centric DSA allows end-users to transmit in a spectrum band, causing spectrum to be shared or transferred from one party to another.

Dynamic spectrum management (DSM): is the process of dynamically assigning the spectrum in place and time enabled by DSA technologies.

End-user multihoming: refers in this context to any mechanism, solution or protocol enabling the end-user to maintain several simultaneous subscriptions to different MNOs. End-user multihoming allows end-user devices to access different networks enabling end-user traffic to be served by several MNOs (Suomi, 2014).

National Roaming: is a mechanism enabling an end-user device of a given MNO to obtain access from another MNO of the same country, anywhere, or on a regional basis. The availability of the obtained access depends on agreements between MNOs. National roaming allows MNO traffic to be served by another MNO.

Opportunistic access: refers to different type of user devices accessing the shared spectrum without high or any coordination, and thus the secondary or co-primary user does not require permission from the primary user to transmit. This term is not related to the economical meaning of opportunism (i.e. opportunistic behaviour).

Primary spectrum access: type of access in which the transmitting end-user terminal is not being constrained by the transmission of other end-user terminals having a higher priority.

Secondary spectrum access: type of access in which the transmitting end-user terminal is constrained by other end-user terminals having a priority access.

Software-defined radio (SDR): "A radio transmitter and/or receiver employing a technology that allows the radio frequency (RF) operating parameters including, but not limited to, frequency range, modulation type, or output power to be set or altered by software, excluding changes to operating parameters which occur during the normal pre-installed and predetermined operation of a radio according to a system specification or standard" (ITU, 2009).

Spectrum sharing: scheme in which two or more parties transmit in the same frequency band following some predefined transmission rules.

Spectrum transaction: one party holding spectrum transfers part of its spectrum to another party at a given price and with predefined rules (the price could equal zero, e.g., in case of commons). It could happen as a momentary lease or as a permanent sale and with different access conditions (e.g., secondary or co-primary access).

White space (WS) or spectrum hole: those points in frequency, time and space unoccupied by any transmission.

2. Background

2.1 New requirements for radio spectrum exploitation

The constant increase in demand for mobile and wireless Internet access urges MNOs, LAOs and NRAs to obtain more radio spectrum as well as more capacity from the given spectrum. According to CISCO (2015), the mobile data traffic of 2014 was nearly 30 times the amount of year 2000, during 2014 the mobile data grew 69%, and it is expected to grow tenfold between 2014 and 2019. Even though forecasts are typically inaccurate, these numbers indicate a clear tendency for a rapid traffic growth. For instance, smartphones represented only 29 % of total global handsets in use in 2014 but 69 % of total global handset traffic; and fourth-generation (4G) connections generated 10 times more traffic on average than 3G connections. This indicates considerable room for additional traffic growth. In addition, the importance of indoor traffic is increasing; in fact, 46% of total mobile data traffic was offloaded onto the fixed network through Wi-Fi or femtocell during 2014. Finally, new services related to the Internet of things (IoT) are reaching a considerable volume; for instance, globally there were nearly 109 million machine-to-machine (M2M) wearable devices in 2014.

Historically, mobile has substituted fixed in telephony; and a similar evolution is taking place due to the emergence of Internet and broadband (Grzybowski, 2014). Some authors argue that mobile broadband has a higher impact on economic development than fixed broadband (Thompson & Garbacz, 2011); moreover, mobile broadband may have the potential to fill the rural gap of digital divide (Prieger, 2013). On the other hand, the new demand for Internet access requires denser wireless networks, which stresses the importance of fixed infrastructure. In short, both fixed and mobile networks are likely to remain important in the future.

METIS[1] categorizes future network requirements in three types of services: very high data rate (extreme mobile broadband), high number of devices (massive machine-type communication) and high reliability (ultra-reliable machine-type communication). These requirements combine high density with high availability, and push the technology development towards different areas. One

[1] METIS is a consortium of 29 partners coordinated by Ericsson with the objective of laying the foundation for a future mobile and wireless communications system for 2020 and beyond. It is co-funded by the European Commission as an Integrated Project under the Seventh Framework Programme for research and development (FP7).

such area is the small-cellular network development for serving indoor traffic, which still faces technical challenges such as interference management (Hoydis, Kobayashi & Debbah, 2011; and Andrews, Claussen, Dohler, Rangan & Reed, 2012).

With the transition from analogue to digital broadcasting systems, the valuable released frequencies (i.e. digital dividend) are being allocated to mobile broadband services around the globe, indicating the need for additional spectrum for mobile Internet. However, the allocation of the digital dividend is only a temporal relief of the congestion and coverage problems suffered by mobile and wireless networks. Therefore, MNOs still need to manage their radio spectrum more efficiently, and the interest towards dynamic spectrum access persists.

2.2 Spectrum assignment

Auction is the most widely adopted mechanism to assign exclusive access rights to radio spectrum. In fact, auctions have been conducted in the US since 1994 and in Europe since 2000. Auctions have gradually become dominant replacing administrative mechanisms such as beauty contests. Ronald Coase (1959) was the first author suggesting the suitability of employing the price mechanism of the market (i.e. auctions) for assigning radio spectrum. It took however several decades before the first spectrum auction was finally organized[2].

Auctions are considered more efficient than administrative mechanisms (i.e. beauty contests), since they assign the spectrum to the one having the highest private valuation. However, challenges in auction design (Cramton, 2013) may cause harmful outcomes, such as overbidding (French, 2009). However, it is argued that no empirical evidence exists supporting that auctions are distortionary (Morris, 2005). In addition, auctions have facilitated new entrants (Madden, Bohlin, Tran & Morey, 2014).

On the other hand, the industrial, scientific and medical (ISM) band has been assigned for common access. First established by the ITU in 1947 and then defined in 1985 for spread spectrum technologies including WLAN networks such as Wi-Fi, the license-exempt regime has successfully served wireless Internet access during the last years (Negus & Petrick, 2009). The tragedy of the commons did not prevent the adoption of Wi-Fi, because such tragedy applies when the resource is *unmanaged* (Hardin, 1998), and systems transmitting in the ISM band have tight limits of transmission power.

In general, the spectrum can be assigned either through a license or with property rights. In the first case, the licensee has access right to a spectrum band for a predefined period of time and with predefined conditions; in the second case, the spectrum holder enjoys ownership. In addition, the spectrum is assigned to

[2] Even though the auctioned object is typically a license to transmit in a frequency band rather than the frequency band in itself, the assignment mechanism utilizes the price in line with Coase. In addition, the conditions of the licenses are becoming more flexible (i.e. market oriented).

one holder exclusively or to everybody for common use. Latest technology developments enable dynamic spectrum management (i.e. transactions) requiring new intermediate schemes between exclusive and commons assignments and a higher degree of flexibility in the conditions of the license.

2.3 Dynamic spectrum access (DSA) technologies

DSA technologies consist of a set of protocols and standards allowing end-users and operators (e.g., MNOs, LAOs, etc.) to dynamically transmit in the unused or underutilized spectrum at different time and/or locations. This enables two or more parties (e.g. operators) to employ the same frequency band. DSA technologies radically change the spectrum assignment mechanisms and may facilitate higher spectrum efficiency.

According to the original concept defined by Mitola as Cognitive Radio in 2000, the end-user device could observe, orient, plan, decide, act and learn (i.e. cognitive cycle). Several years later, IEEE (2008) defined the concepts and terminology related to DSA[3], and ITU (2009) defined Cognitive Radio Systems (CRS) and Software defined radio (SDR) (see definitions in section 1.5). At the same time, they recognized the need for further study on the benefits and applications of DSA.

World Radio Conference (WRC) showed in 2012 an emerging interest in the potential of Cognitive Radio Systems (CRS), even though it was decided not to change the ITU Radio Regulations. Around the WRC of 2012 most of the effort focused on the development of the dynamic access of TV white spaces (TVWS), due to their good propagation characteristics. Many expected that this may be a promising first step towards the diffusion of DSA technologies, for instance by enabling mobile broadband in rural areas or by allowing programming making and special event (PMSE) devices, such as wireless microphones, to operate in the TVWSs[4]. After years of standardization, testing and deployment work, the interest moved from TVWS towards other whitespaces at higher frequencies. From a technical perspective, the development work has gradually moved from devices deploying Software Defined Radio (SDR) capabilities towards coexistence of systems based on spectrum database; and from a primary-secondary (hierarchical) spectrum sharing towards a co-primary spectrum sharing scheme.

DSA standardization efforts come from different SDOs, such as IEEE, IETF, 3GPP and ETSI, as summarized in Table 1. Each effort is typically driven by specific industry players (operator, manufacturer, etc.), which explains the main design decisions and enabled applications.

The IEEE has defined a set of standards to facilitate the coexistence of systems in the TV frequency bands, such as IEEE 802.11af, 802.16h and 802.19 (Xiao,

[3] For this thesis, please refer to the definition of DSA in section 1.5. For a more general definition of this term, please refer to IEEE (2008).

[4] WRC 12 finally decided to allocate the 694 – 790 MHz band to mobile broadband services; however, it committed for WR15 to provide additional spectrum for mobile services including sharing compatibility issues, and to give a solution for white space devices (WSDs).

Hu, Qian, Gong & Wang, 2013). These standards enable, for instance, the Wi-Fi deployment in TVWSs (or so-called super Wi-Fi) (Flores, Guerra, Knightly, Ecclesine, & Pandey, 2013). In addition, the IEEE has developed the 802.22, an alternative standard, to provide rural broadband by means of a wide regional area network (WRAN) that may also be deployed for Device-to-Device (D2D) communication (Lei & Shellhammer, 2009). Finally, IEEE has more recently standardized, in the 802.11ah, a Wi-Fi extension for M2M applications in the license-exempt bands below 1GHz. This includes home networks, industrial process automation, video surveillance, and smart grid communications (Zhang et al., 2012).

Table 1. Summary of DSA standards (adapted from Publication 4)

	Driven by	**Adopted by**	**Wide / local area**	**System design**	**Target frequencies**	**Status**	**Example of application**
3GPP CA	Network manufacturers and MNOs	Operator	Local	Modular	MNO´s frequencies, license-exempt	Standardized for LTE-A, license-exempt bands. May be extended for inter MNO	Indoor small cells deployment with licensed and license-exempt frequencies
3GPP D2D		End-user	Local	Modular	License-exempt bands or MNO´s frequencies	Included in LTE (3GPP Release 12) for initial development	Communicate with nearby terminals (D2D), public safety (TETRA replacement)
ETSI RRS LSA		Operator	Wide	Modular	2.3 GHz	Ongoing standardization (ETSI TS 103 154 (10/2014), TS 103 235)	Get additional spectrum for MNOs
ETSI RRS Reconfigurable MD	Device manufacturers	End-user	Local	Modular	MNO´s frequencies	Ongoing standardization (TR 102 967, TS 103 094)	Through *Radioapps* provide end-users additional radio functionality, extra coverage (indoor, outdoor through ad-hoc)
ETSI WSD	TV operators	End-user	Local	Integral	TVWS	Standardized (EN 301 598, TS 103 143)	PMSE (e.g., microphones), MCWSD (manually configurable WSD)
IEEE 802.11af/.19/.16h	Wi-Fi manufacturers	End-user	Wide	Modular	TVWS	Standardized	Wi-Fi in TVWS (super Wi-Fi)
IEEE 802.11ah		End-user	Local	Modular	900 MHz	Ongoing standardization	Wi-Fi extension for M2M applications
IEEE 802.22	Regulator	End-user	Wide	Integral	TVWS	Standardized	Rural broadband (WRAN)
IETF PAWS	Application developers	End-user	Wide	Integral	TVWS (initially)	Standardized	Secondary access through geolocation database
Weightless (open standard)		Both	Wide	Integral	TVWS	Some deployments (Neul and other providers)	IoT (M2M, smart cities)

On the other hand, the IETF initiated at the beginning of 2012 the standardization of the communication between mobile devices and a white space database, also referred as to Protocol to Access White Space or PAWS (Manusco, Probasco & Patil, 2013). The standardized database enables DSA by providing the geographical information on the available frequencies to mobile devices (Ghosh, Naik, Kumar & Karandikar, 2015 and Paavola & Kivinen, 2014). Simultaneously, ETSI Radio Reconfigurable Systems (RRS) works on several parallel standardization efforts (Mueck, 2014) described as follows. The ETSI RRS Reconfigurable mobile device (MD) provides mobile devices additional radio functionality through *radio-applications*, such as extra coverage at indoor or outdoor locations. The ETSI RRS licensed shared access (LSA) (Palola et al., 2014) enables a MNO or another operator to temporally acquire additional spectrum from another incumbent spectrum holder. Finally, ETSI white space device (WSD) allows mobile devices such as Programme Making and Special Events (PMSE) and Manually Configurable White Space Devices (MCWSD) to transmit in the TVWS band.

The 3GPP works in two standardization efforts. Firstly, the LTE Carrier Aggregation (CA) (4G Americas, 2014) creates a virtual wideband carrier from segments of spectrum across different bands. These bands can be licensed (Yuan, Zhang, Wang, Yang, 2010) or license-exempt (Alkhansa, Artail, & Gutierrez-Estevez, 2014). Secondly, the 3GPP device-to-device (D2D) has been included in the LTE operation (3GPP Release 12) (Lin, Andrews, Ghosh & Ratasuk, 2014) for initial development, allowing mobile devices to access the license-exempt spectrum. The 3GPP D2D has the purpose of replacing the public safety networks (Terrestrial Trunked Radio or TETRA). Finally, Weightless (Webb, 2012), an open standard developed by Neul (UK based company), is applied to some IoT applications such as M2M and smart cities.

2.4 Spectrum occupancy

Researchers have conducted measurements to assess the level of spectrum occupancy and to determine the possible benefits of DSA technologies. One of the early results (Janka & Dorfman, 2005) gave a surprising 6% of average occupancy; however, this study considered the whole available spectrum from 400MHz to 7.2GHz in both rural and urban areas. Studies on spectrum occupancy require a higher level of detail, since spectrum is more valuable in those places with higher demand and consequently with higher occupancy. Obviously aggregated data is not useful for drawing conclusions. In this line, McHenry & McCloskey (2006) presented a measurement comparison of several cities of USA, in which the average occupancy highly varied over frequency bands and locations, ranging from 5% to 75%, being the TV bands (25-75%), the cellular bands (30-50%) and the license-exempt band in the 2.4GHz (10-30%) the most utilized. Other bands presented a considerable room for occupancy improvement. Moreover, Wellens, Wu and Mähönen (2007) reported that, according to their measurement performed in Aachen, Germany, the frequencies from 20MHz to 3GHz are highly occupied, while those higher than 3GHz are rarely occupied. Additionally, when measurements were performed indoors, those frequencies from 1 GHz to 3GHz were also found underutilized in some periods of time. A summary of different spectrum measurement campaigns can be found in Patil, Prasad and Skouby (2011).

2.5 Impact of DSA on market dynamics

The standards described in section 2.3 enable multiple scenarios of spectrum transactions. From a general perspective, DSA technologies decrease costs associated with spectrum transactions at two different levels: wholesale (inter-operator transactions) and retail (end-user driven transactions). Transaction costs are incurred when employing the price mechanism offered by the market, when performing an economic exchange. The importance of these costs was firstly recognized by Coase (1937). Transaction costs can be categorized into (i) search and information costs; (ii) bargaining costs, which in this case can be identified with coordination costs; and (iii) policing and enforcement costs, which in practice are costs of measuring the output (Dahlman, 1979). Additionally, Alston and Gillespie (1989) include (iv) asset specificity costs (e.g., spectrum specificity); (v) agency costs (e.g., if principal-agency problem arises when outsourcing an activity); and (vi) shrinking costs (e.g., if a party cannot be controlled by the counterpart).

At retail level, user-centric DSA standards reduce end-user switching costs by permitting individual user devices to transmit in a spectrum band while the same spectrum is being employed by another party (i.e. end-users or operator). In this case, switching costs include also the transaction costs of end-user trading (Klemperer, 1987). For clarity, this thesis analyses separately inter-operator transaction costs and end-user switching costs. Switching costs are defined as one-time costs that a buyer faces when switching from one provider to another (Porter, 1980) and they constitute an entry barrier, since they determine the monopoly power of incumbent firms. Burnham et al. (2003) characterize switching costs by classifying the types of resulting costs into financial, procedural and relational. If switching costs are high, firms have higher bargaining power towards buyers. Consequently, this thesis claims that DSA decreases inter-operator transaction costs (business-to-business relationship) and end-user switching costs (business-to-consumer relationship). DSA standards, which decrease inter-operator transaction costs, stimulate wholesale trading and cooperation between involved operators; while DSA standards decreasing user switching costs promote retail competition between operators.

Figures 1 and 2 depict the evolution of transaction and switching costs caused by DSA technologies. In both figures, the first stage represents the current status, in which no spectrum transactions take place between parties. In the second stage of Figure 1, standards such as 3GPP Carrier Aggregation (CA), ETSI RRS LSA and in some cases 3GPP D2D enable spectrum transactions between MNOs. 3GPP CA may also take advantage of the license-exempt bands. In such a situation, all cost items considerably decrease: spectrum becomes less specific, while the information, coordination and measurement costs are decreased due to automation. DSA technologies based on spectrum database enables spectrum transactions between operators. Such transactions may be driven by end-user terminals (second stage of Figure 2) or by operators (third stage of Figure 1). In a user-centric transaction, standards such as ETSI WSD, IEEE 802.11af or IEEE PAWS push user-switching costs down related to financial and procedural costs, since a database approach provides the end-user with the ability to transmit in different frequency bands. In an operator-centric transaction, DSA technologies decrease costs related to spectrum specificity and information costs. Finally, in an operator-centric evolution (fourth stage of Figure 1), spectrum transactions based on sensing technologies, for instance ETSI RRS Reconfigurable MD, may decrease coordination and measurement costs until its minimum. In a user-centric one, sensing technologies diminish procedural costs (third stage of Figure 2).

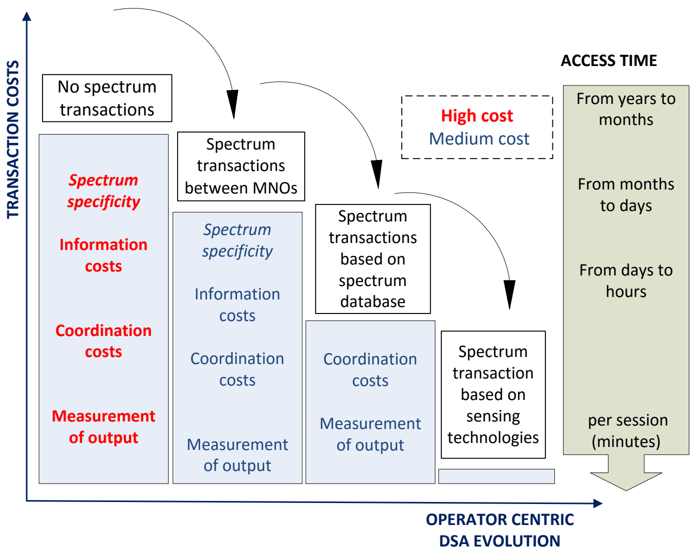

Figure 1. Evolution of transaction costs due to DSA (adapted from Publication 1)

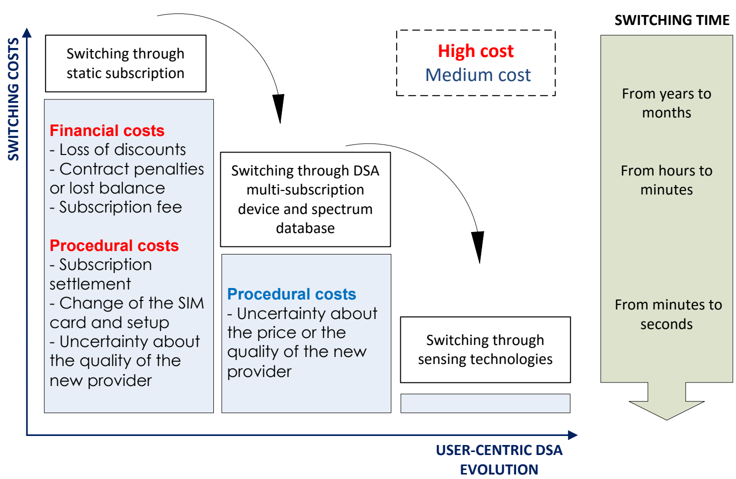

Figure 2. Evolution of user switching costs due to DSA (adapted from Publication 5)

The aforementioned cost elements may also depend on the implemented trading mechanism, and in particular, on the level of centralization. A high level of centralization demands higher CAPEX to reduce coordination costs, while a decentralized system requires less coordination (and CAPEX). Besides this, the development of DSA technologies gradually reduces OPEX related to the maintenance of trading information, allowing more sophisticated trading mechanisms. As an example, Yoon, Hwang and Weiss (2012) compare three alternative trading mechanisms, and conclude that under current assumptions of technology, direct trading still performs better than the alternative mechanisms (brokerage system and auction based mechanism).

2.6 End-user versus operator centric adoption scenarios

A successful adoption of DSA technologies requires a coordinated effort of all stakeholders, including end-users, mobile device manufacturers, network equipment manufacturers, MNOs, other spectrum holders, SDOs, NRAs and policy makers. From an adoption perspective, this work defines two alternative scenarios: user-centric and operator-centric adoption, to indicate the stakeholder who is making the final adoption decision. In a user-centric adoption, the user device having the DSA capabilities transmits in the available spectrum on a dynamic basis. The transmission decision is performed by the end-user devices, and it is supported by the operator network or, in some cases, it is performed in a D2D fashion. In the user-centric case, the spectrum can be shared as commons or it can be transferred between operator networks; however, driven by the decision of end-user terminals. On the other hand, in an operator-centric adoption, the operators deploy DSA and its associated dynamic spectrum management into their networks to employ spectrum more efficiently. The dynamic transmission logic is provided by the network equipment manufacturer and it does not require a direct intervention of the end-user terminal. In this case, spectrum is transferred between two or more operators. These scenarios are summarized in Table 2.

Table 2. Summary of DSA adoption scenarios (adapted from Publication 4)

Adoption scenario	**User-centric**	**Operator-centric**
Definition	The end-user adopts a mobile device, capable of transmitting dynamically in a common spectrum or in a spectrum band belonging to another party. The transferring of spectrum is driven by the decision of end-user terminals.	The operator adopts the DSA functionality in their network, to dynamically transmit in a spectrum band belonging to another party. Spectrum is transferred between operators.
Provider	Device manufacturers provide DSA capabilities to the user device. End-user spectrum access is supported by the operator.	Network manufacturer provides DSA capabilities to the network elements.

In addition to the adoption mode, DSA technologies can be characterized by the type of competition they encounter in the market. A technology competes with network effect, if an increase in the number of adopters increase the benefits of end-users or operators adopting the technology. Network effect produces in the adopted technology a critical mass requirement, beyond which it exponentially diffuses until a saturation point at which the adopter number stabilizes. On the other hand, if a new technology replaces an older one, such technology is competing with substitution effect. In this type of competition, the replacement could involve an internal process or an end-user service, and it typically happens at the saturation point of the older technology.

Previous Table 1 identifies different standards competing with network or substitution effects. Those standard with modular design act as an enabler by replacing an older module or process, and thus typically exhibits substitution effect. For instance, 3GPP CA, ETSI RRS LSA and IEEE 802.11af are substituting an older mechanism by adding a new functionality (the capability of aggregating different frequencies, of communicating with a spectrum database or transmitting in a new frequency band). Thus, a substitution may happen at different levels; as an internal process of an operator, as the case of 3GPP CA, or as a service offered to the end-user. Examples of this last case may be a M2M or D2D service based on DSA functionality replacing a similar service based on older technology; or a small-cellular (indoor) coverage facilitated by DSA substituting a macro-cellular coverage, which does not support DSA. Moreover, sometimes the substitution happens at end-user or service level, even though the technical change has happened at a process level. Standards may also compete with network effect when they offer a similar functionality. For instance, IEEE 802.11af with IEEE 802.22; and 3GPP D2D or 3GPP CA with ETSI RRS Reconfigurable MD. Finally, standards competing against an older established system also exhibit network effect. Examples of such case may be ETSI WSD deployment of PMSE devices or Weightless deployments of M2M applications.

2.7 New spectrum regimes

Exclusive licensing and license-exempt regimes have successfully coexisted favouring the emergence of cellular and wireless Internet access technologies. Nevertheless, the latest technology developments permit managing spectrum more dynamically.

On one hand, license conditions may become more flexible in terms of service and technology neutrality and reselling rights. Thus, the spectrum regime may evolve from a *command-and-control* towards a property rights regime, in which the spectrum holder has ownership over the spectrum and decides the access conditions; however, within some minimum set of restrictions defined by the NRA. On the other hand, the current regime based on exclusive and commons licensing may evolve towards spectrum sharing schemes, which allows multiple parties to coexist within the same frequency band. In such a scheme, spectrum holders are allowed to perform transactions by selling or leasing part of their spectrum (in place or/and time).

From a general perspective, DSA can enable three types of spectrum sharing schemes (Zhao & Sadler, 2007) : (i) *dynamic exclusive sharing* in which the incumbent operator employs the exclusively assigned spectrum with certain flexibility, including reselling rights of the whole or part of the assigned band; (ii) *hierarchical access sharing* in which one user group can transmit with priority in a spectrum band while the other group transmits with secondary rights without harmfully interfering the primary user as defined by policies and (iii) *open sharing* in which all users transmitting in the shared spectrum band enjoy equal priority. Each sharing scheme requires a different level of coordination between involved parties. Depending on whether the secondary or co-primary user needs permission to transmit, the deployed scheme may be further classified into cooperative or non-cooperative spectrum sharing (Chapin and Lehr, 2007). Non cooperative spectrum sharing does not involve trading between operators, but it is rather driven by the end-user terminal as an opportunistic access. Cooperative spectrum sharing typically involves spectrum trading driven by the operators.

The above mentioned three-tiered categorization has been adopted by both the USA and the EU; however, with different approaches. The following Figure 3 summarizes the three types of spectrum sharing, indicating the terminology used in the EU and the USA for each level.

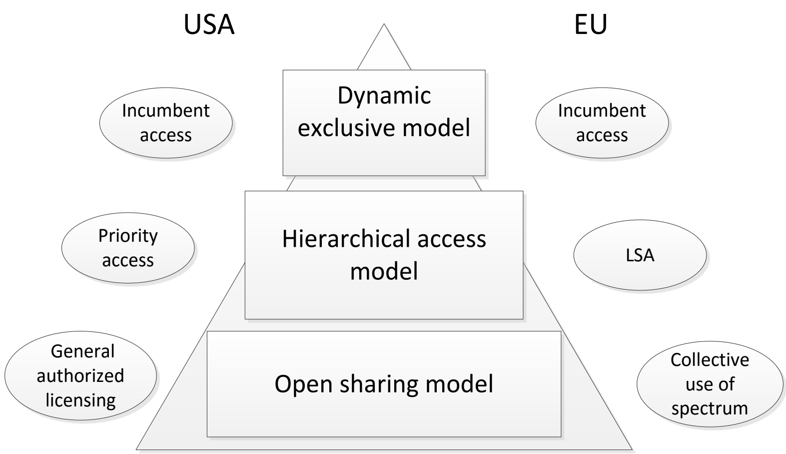

Figure 3. Three-tiered spectrum sharing framework.

In Europe, the most important efforts for introducing new spectrum regimes have been the Licensed Shared Access (LSA) and Collective Use of Spectrum (CUS) approaches.

In LSA, a spectrum holder accepts a secondary operator to transmit in the same frequency band with a predictable quality for the involved parties (EC COM, 2012, 478). LSA was originally developed by network manufacturers (Qualcomm and Nokia), intended for MNOs as a means to obtain additional spectrum. Later, the European Commission extended this concept to include other cases. More generally, LSA allows spectrum transactions with predictable interference levels and it has been recently standardized by ETSI (ETSI RRS LSA).

CUS is a general framework allowing individual users and devices to transmit in the same frequency band and at the same time; in a particular area and under well-defined conditions. One such example is Light licensing (ECC Report 132, 2009) which enables common access to a frequency band, with certain guarantee for quality of service. Light licensing requires a more simplified issuing procedure than an exclusive licensing regime, but a more detailed registration mechanism than a license-exempt regime. Light licensing permits a coordinated sharing mechanism in which different types of users are supported (RSPG11-392, 2011), however easing the burden of coordination, registration and licensing. Light licensing may also work as private commons in which users set the conditions for license-exempt transmission. Light licensing is mostly suitable for systems with limited interference.

Finally, pluralistic licensing (Holland et al., 2012) was introduced in 2012 as a new flexible licensing regime which considers explicitly the interference as a tradable characteristic of the spectrum. Pluralistic licensing enables the spectrum holder to accept secondary or co-primary transmissions in a spectrum band, under the condition that the interference produced by these transmissions are defined by parameters and rules that are known beforehand by licensees and can be agreed and adjusted as needed. These parameters can be implemented in several alternative ways; for instance, as a fixed amount of interference or as a known formula with changing values and a related revenue mechanism. In addition, pluralistic licensing can be mediated by the regulator (via license fees linked to the produced interference) or through a price mechanism offered by the market. Since pluralistic licensing is a flexible and wide concept, it may allow any of the three types of spectrum sharing through co-primary or primary-secondary schemes. However, until the date, this regime has not been deployed.

In the USA, the Spectrum Access System (SAS) proposes a hierarchical model with three types of end-users implemented through a geolocation database: incumbent, secondary and tertiary users. Incumbent end-users can transmit in a spectrum band with priority, since such spectrum has been already allocated to incumbent operators. A secondary license permits an operator to provide secondary access to users, who are registered in a spectrum database. Finally, tertiary users, who have a very light license condition, similar to the current Wi-Fi users, can transmit in those pieces of spectrum which are not being used by primary or secondary end-users. In other words, tertiary end-users transmit opportunistically by means of a general authorization.

All the aforementioned licensing schemes facilitate spectrum sharing through transactions or as a common (free) access. Additionally, a spectrum regime allowing transactions may be based on property rights, meaning that spectrum holders have ownership over the spectrum instead of usage rights defined by a license with a predefined expiration date. A property rights regime provides the best incentives to perform transactions under low spectrum concentration and high industry coordination. High spectrum concentration disincentivizes transactions since incumbent operators prefer to maintain their monopoly power, and low industry coordination (for instance, if industry players choose different non compatible standards) increases transaction costs. In both cases, the spectrum owner or holder needs to manage the generated interference based on predefined rules (i.e. ex-ante regulation) to incentivize compatibility. From this perspective, spectrum transactions may be classified according to the traded rights: mode (use or ownership), extent (complete transfer or shared spectrum) and duration (short/long lease versus short/permanent sale) (Caicedo & Weiss, 2007). The evolving nature of technology and changing conditions of the market makes that most NRAs have favoured, until this moment, a scheme based on licenses rather than on ownership.

2.8 Spectrum transaction scenarios

This thesis analyses different types of spectrum transactions on a case-by-case basis. Thus, it performs a sensitivity analysis for five different scenarios which represent the most interesting cases from a regulatory perspective. These cases are diverse in terms of the chosen frequency bands, system and end-user requirements. The main technical focus of interest is the interference produced by the end-user devices and network elements coexisting in the same frequency band. This study assesses the parameters affecting the benefits generated by the analysed spectrum transactions to discover the most feasible cases.

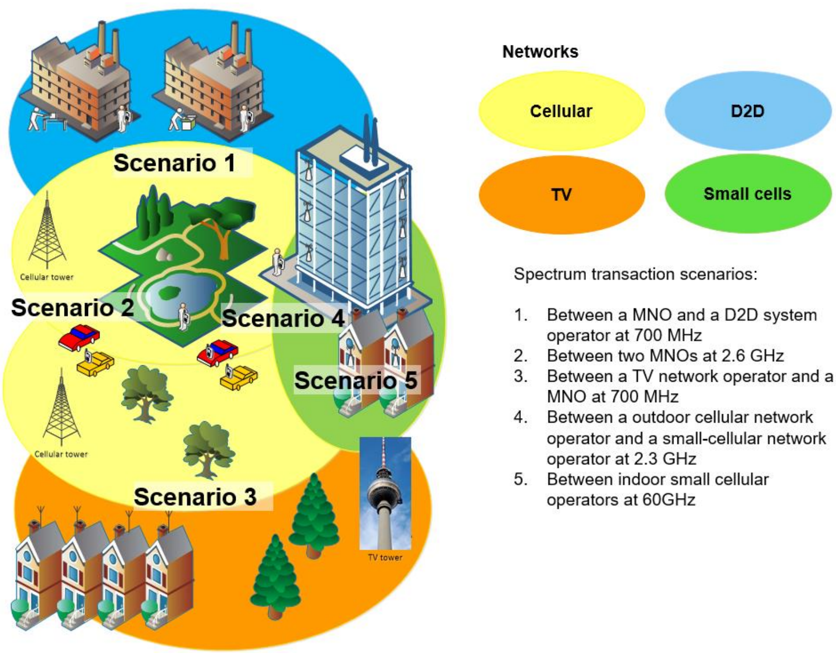

Figure 4. Spectrum transaction scenarios

The scenarios are summarized in Figure 4. Scenarios 1 and 3 deal with systems transmitting in the 700MHz (i.e. digital dividend). This band is chosen because it started the discussion on spectrum sharing, even though latest efforts have focused on higher frequency bands. In scenario 1, a cellular network shares spectrum with a D2D system in adjacent locations. In scenario 3, a cellular network transmits in TVWSs, while the TV network coexists in the same frequency band. Scenarios 2 and 4 analyse other mobile bands of interest below the 3GHz; namely the 2.3GHz and 2.6GHz bands. In scenario 2, two cellular networks belonging to different MNOs transmit in the 2.6GHz band in adjacent areas, one network having priority over the other. Scenario 4 analyses the interaction between an outdoor cellular network transmitting in the 2.3GHz band and an indoor small-cellular network transmitting in the same frequency band. Finally, scenario 5 presents the interaction between different indoor small-cellular deployments transmitting in the so-called millimetre-waves (i.e. 60GHz).

Each of these scenarios can be linked to a type of spectrum sharing model, as illustrated in Figure 5. Scenario 1 represents a dynamic exclusive model, in which the incumbent allows secondary transmission of D2D devices. This case can be easily extrapolated to other type of services, for instance M2M communication deployed in a factory environment. Scenarios 2, 3 and 4 represent a hierarchical access model, such as LSA, in which one party has priority over the other. These scenarios may be deployed by means of a geolocation database, which works as an authoritative register allowing the transmission of secondary users. This database maintains information on primary devices to decide on secondary transmission based on statistical information. Scenarios 4 and 5 represent an open sharing model in which individual networks transmit in the same spectrum band with equal priority. In such cases, the coordination between adjacent networks will impact on the quality of service (QoS) and experience (QoE). Note that scenario 4 can lie under two models.

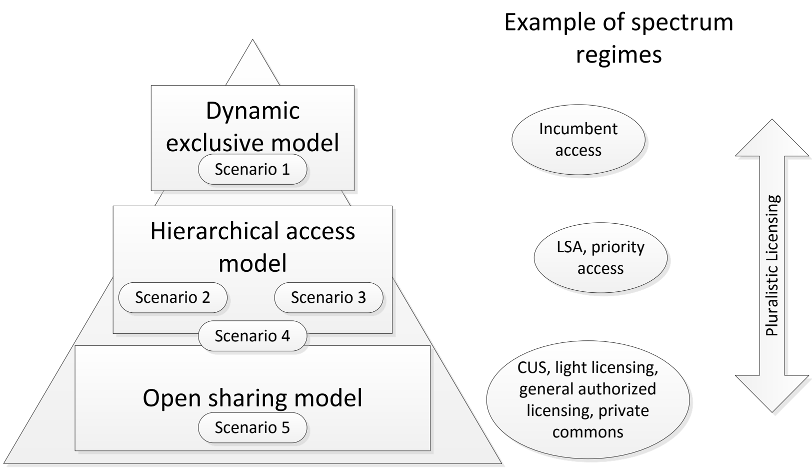

Figure 5. Analysed scenarios mapped in the three-tiered sharing framework and with different spectrum regimes.

2.9 Other competing mechanisms

DSA technologies decrease costs of spectrum transactions and thus they induce economic efficiency. In addition to spectrum transactions, this thesis touches other competing technologies which can decrease inter-operator transaction costs or end-user switching costs.

The thesis compares three mechanisms which increase economic efficiency by decreasing transaction or switching costs, within the scope of MNOs. Besides DSA, national roaming[5] decreases costs of network capacity transactions between two MNOs. In addition, end-user multihoming[6] enables the end-user device to maintain simultaneous subscriptions to different MNOs and thus to significantly decrease switching costs. Markendahl (2009) compares different existing cooperative mechanisms, including national roaming, mobile virtual network operators (MVNOs) and infrastructure sharing. This thesis chooses national roaming from the list of existing mechanisms, and compares it with two emerging mechanisms: end-user multihoming and DSA. Each mechanism stimulates cooperation or competition at a different level (spectrum, capacity or user traffic), which makes this comparison especially relevant for understanding the importance of DSA.

Table 3. Comparison of the target mechanisms (adapted from Publication 6)

Mechanism	**DSA**	**National Roaming**	**End-user multihoming**
Market mode	Operator-driven	Operator-driven	End-user driven
Cost impact	Inter-MNO transaction costs (search and information costs)	Inter-MNO transaction costs (search and information costs)	End-user switching costs (financial and procedural costs)
MNO-subscriber relationship	Static subscription	Static subscription	Fast switching between subscriptions
MNO-MNO relationship	Spectrum trading through brokerage system	Roaming contracts (home MNO controls)	Competition for user choice
Trading type	Wholesale	Wholesale	Retail
Trading event	Access to spectrum band, (e.g., minutes, hours, days)	End-user session	End-user session
Spectrum management	Dynamic	Static	Static
Required CAPEX (MNO)	High	Low	Low
Required OPEX (MNO)	Medium	Medium	Low
New spectrum regulation needed	Yes	No	No
Standards development needed	Yes	No	No
Other requirements	Spectrum trading mechanism	Access price regulation	Metered pricing

Table 3 summarizes a comparison between the three mentioned mechanisms. First of all, each mechanism has a different cost impact; either on transaction or switching costs. As a consequence, each mechanism affects differently the MNO-subscriber and inter-MNO relationships, as indicated in the Table. Regarding the capital requirements, DSA demands major investments; however, it depends on the detailed implementation. End-user multihoming and national roaming are not capital intensive. DSA requires a brokerage trading system

[5] See definition in section 1.5

[6] See definition in section 1.5

which does not own or hold spectrum, but it mediates trading to maximize social welfare by matching demand and supply. Such system could be run by the regulator or by a third party. In addition, DSA requires MNOs to deploy base stations capable of accessing spectrum dynamically (e.g., Anchora, Mezzavilla, Badia & Zorzi, 2012), and it requires operational and capital expenses related to running a centralized server database, and maintaining real-time information on spectrum trading. Note that in this case the higher the frequencies, the lower the coordination requirements.

In the case of national roaming, additional costs are incurred due to home network routing and the related double book-keeping MNOs should maintain. Finally, in the case of end-user multihoming, the number of subscriptions is increased, causing additional costs to maintain up-to-date SIM and location information. Additionally, end-users may not be willing to maintain several flat-rate subscriptions, and consequently MNOs need to deploy, for instance, metered pricing, which also adds complexity to the charging and billing process.

The deployment of DSA decreases inter-MNO spectrum transaction costs related to search and information, while the related brokerage system decreases bargaining, and policing and enforcement costs. A national roaming mechanism decreases searching and information costs, while the related trading arrangement (how MNOs make the book-keeping and charge to each other) decreases the bargaining and policing and enforcement costs. Finally, end-user multihoming decreases both financial and procedural costs of switching.

Besides the above mentioned requirements, while end-user multihoming may face the unwillingness of MNOs, national roaming and DSA encounter regulatory challenges. For national roaming, the regulator should monitor roaming prices and conditions to maintain a fair competition. DSA requires a new spectrum regime allowing and promoting transactions to secure the spectrum supply and to avoid market concentration.

3. Relevant economic theories

This section presents an overview of the main economic theories related to the area of study of this thesis.

3.1 Transaction cost economics (Ronald Coase)

This thesis analyses spectrum transactions from technical and economic perspectives. In economic theory, Ronald Coase was the first in recognizing the importance of transaction costs for explaining the existence of the firm and the dynamics of the market (1937, 1960). According to the Coase theorem, a sufficiently low (ideally zero) transaction cost and clearly defined property rights induce transactions which result in an efficient outcome, regardless of the initial resource assignment. Most notably, Coase was the first author in suggesting auctions as an efficient mechanism for spectrum assignment (1959), several decades before the first auction was finally organized. After Coase, several authors have further analysed the firm and the market from a transaction cost viewpoint, one main contributor being Williamson (1975). Williamson expanded the work of Coase into a field called New Institutional Economics (NIE), in which he distinguishes four levels of social analysis: social theory, economics of property rights, transaction costs economics and neo-classical economics. In this framework, the first level deals with informal institutions, such as customs, traditions and norms. The second level is related to the institutional environment (the rules of the game). The third level deals with the governance. Finally, the fourth level refers to the market, in which transactions occur and prices are adjusted. This research deals mainly with the second and third levels; in other words, with the rules of the game and the game in itself. In a perfect world (i.e. property rights are well defined and transaction costs are zero) the government can step aside, except for law enforcement and arbitration when needed. Currently, spectrum management is gradually evolving due to technology development, and therefore the rules and the governance of spectrum may go through a regulatory and management evolution. As stated by Williamson, processes at these levels are slow and they typically take several years.

3.2 Evolutionary economics (Joseph Schumpeter)

Together with transaction costs, this research addresses the evolutionary behaviour of spectrum management. Since most of DSA technologies are still under development, an evolutionary approach provides us with the right tools for analysing such scenario. Though founded by Veblen (1898), evolutionary economics have been later developed by Joseph Schumpeter (1934), who explained the driving forces of economic development endogenously. Thus, the development of technology happens from within the system; from the entrepreneur individual initiative. Schumpeter (1934) highlights the role of the entrepreneur for the economic development, who produces innovations by new combinations of productive factors, such as labour and land. Schumpeter explains the economic world as having a cyclical behaviour (i.e. business cycles), and the innovation as the main factor for initiating a new cycle. In this context, he defines *creative destruction* as the "*process of industrial mutation that incessantly revolutionizes the economic structure from within, incessantly destroying the old one, incessantly creating a new one*" (Schumpeter, 1942).

This field is considered as belonging to non-equilibrium economics (as opposite to equilibrium or neoclassical economics), in which economic agents dynamically learn from the environment and cause changes by means of innovations.

The ideas of Schumpeter on economic growth and industrial dynamics stimulated a set of new modelling techniques, the so-called Schumpeterian or evolutionary models. These models emphasize the diversity and heterogeneity of economic agents (and their behaviours), and the notion that economic change or evolution is endogenous (it comes from within rather than exogenous, which comes from outside the system).

Even though Schumpeter did not support the idea of applying biological analogies to economic analysis (1954), many neo-Schumpeterian authors have incorporated them into their models. The first such author was Alchian (1950), who described the behaviours of firms by means of natural selection. Later, with the development of computer technology, Nelson and Winter (1982) presented a model, in which the firm is the basic unit of evolution, and the macroeconomic properties are affected from the microeconomic behaviours of these units (i.e. agents). This work is summarized in a well-known book, which frequently serves as a starting point for many Schumpeterian models. Other important characteristic of Schumpeterian models is the fact that firms are categorized into innovative and imitative firms (Winter, 1984).

Since Nelson and Winter, neo-Schumpeterian models have proliferated in the literature. This thesis focuses on the so-called artificial life (a-life) or agent-based models.

3.3 Coase meets Schumpeter

This thesis addresses the regulation of spectrum from an evolutionary and transaction cost perspectives and thus it combines transaction costs (i.e. institutional) and evolutionary economic theories. Such combination has been suggested in the literature; however, it has not been widely applied and therefore, it still involves certain level of novelty. Some references supporting a research approach including Coase and Schumpeter perspectives are summarized as follows. Foss (1994) argues that a neo-institutional economics requires an evolutionary perspective to address the analysis of the market dynamics. He denominates this resulting research field as *dynamic neo-institutionalism*. In the urban planning area, Lai and Lorne (2014) identify that Coasean transaction cost reduction and Schumpeterian innovations have no inherent contradictions, but Coasean institutional arrangements enable both Coasean exchange efficiency and Schumpeterian innovations. In this way, a new regulation can promote innovation while also being a mechanism to reduce transaction costs. On the other hand, Zawislk et al. (2012) investigate the characteristics of the firm, and claim that any firm when born is primarily focused on technological development (Schumpeterian innovation) or transactional efficiency (Coasean transaction costs), and in a second stage, managerial (management of innovations) or operational (operational efficiency due to decreased transaction costs). Finally, Langlois (2007) emphasizes that transaction costs are always costs of novelty and change, and therefore the firm, which is always entrepreneurial, faces the problem of coordination and achieves a cost advantage in the market, when the design and direction of tasks add value and higher coordination to manage uncertainty.

In line with the above cited literature, this thesis approaches spectrum management and regulation from a dynamic neo-institutional perspective, analysing transactions by means of neo-Schumpeterian simulation tools.

4. Research design and methods

This section describes the overall research design of the thesis: the research approach and process, together with the methods for analysing the research questions. This section additionally compares the utilized methods based on the obtained results.

4.1 Research approach

This thesis combines design and natural science research approaches (March & Smith, 1995). Natural science is concerned with explaining the natural phenomena (how and why the nature is), including traditionally research in physical, biological, social, and behavioural domains. Design science deals with artefacts (artificial phenomena as opposed to natural phenomena) and how they are built to attain a goal. In other words, while natural science investigates the reality, design science studies human creations. This thesis constantly combines natural and design approaches in every analysis. For instance, the main studied phenomena are: (i) spectrum, which is a natural resource and (ii) the technologies managing such resource, which are artefacts. In addition, the regulatory and economic perspectives are also subject of natural science, since they are related to social and behavioural domains. Natural science consists of discovery and justification. Discovery generate and propose scientific claims to theorize. Justification employs the hypothetico-deductive method to deduct theories from observational hypotheses. Design science, rather than proposing theories, creates in different forms: constructs (conceptualization to characterize and describe the phenomena), models (representation of the reality), methods (set of underlying constructs and a representation –model- of the solutions) and implementations (realization of an artefact in its environment). In short, if natural science theorizes and justifies, the design science builds and evaluates.

Being more concrete, this thesis contributes to, and utilizes the methods of systems and management sciences. Systems science analyses systematically a system. Management science is concerned with the quantitative analysis and solutions in business and management (North & Macal, 2007). From this perspective, this thesis analyses the management of a system, from top-down and bottom-up approaches, and both qualitatively and quantitatively.

By employing the framework of March & Smith (1995) which combines natural and design sciences, Figure 6 illustrates the performed research activities of this thesis: build, evaluate, theorize and justify; and the main research output: models, to provide policy guidelines and prescriptions. Models are based on multidisciplinary constructs and methods, and look at instantiations to justify their assumptions (implementations, standardization, testbeds, etc.). The main contribution of this thesis is to provide novel linkages between concepts (i.e. constructs) of different disciplines within the scope of spectrum regulation.

		Research activities			
		Build	Evaluate	Theorize	Justify
Research outputs	Constructs				
	Model				
	Method				
	Implementation				

Figure 6. Research activities and output of this thesis indicated in yellow.

Modelling and simulation activities have a longer tradition in system engineering (Sinha, Paredis, Liang & Khosla, 2001), but their importance is increasing in organizational and management fields (Harrison, Lin, Carroll & Carley, 2007). In fact, this thesis suggests that system level modelling and simulation are a powerful means to analyse regulatory challenges of complex systems, such as the constantly evolving ICT ecosystem.

4.2 Research process

The research process applied herein can be described as *iterative and incremental*; and in concrete, incremental discovery, design, and development of models and simulations (such as described by North and Macal, 2007). This process has its roots in the *iterative and incremental development* of software engineering, which opposes to a sequential or *waterfall* development process (activities such as requirement, design, implementation and verification are performed sequentially). The iterative and incremental process has been formalized by the *agile manifesto* in 2001, but its practice has been applied since mid-1950s (Larman & Basili, 2003). The main idea of such process is to develop a model incrementally, allowing the researcher to take advantage of what has been learned during the development of the previous incremental of the model. At each iteration, design modifications are made either by simplifying the model or by adding functionality.

In the discovery phase, modelling allows partial models to be build offering insights on industry dynamics. The discovered insights can lead to improvement to either real-world issues or model design. Then, such design improvements lead to further model development and consequently this process is repeated incrementally until the model is mature enough to obtain answers to the pursued research questions.

4.3 Research methods

This section presents the applied modelling and simulation methods; agent-based and system dynamics modelling. Both are based on evolutionary economics and can be linked with the neo-Schumpeterian tradition.

4.3.1 Agent-based modelling

Agent-based modelling has its roots in artificial life, a multidisciplinary field of research developed by mathematicians and computer science specialists. Von Neumann and Ulam proved in the early 1950s that an initial configuration of cells could reproduce itself by following a set of rules (Kwasnicki, 2007). The artificial life was called agent-based modelling to distinguish it from the alternative approach of describing an interactive population of individuals based on differential equations (e.g., Lotka-Volterra equations). Agent-based modelling performs a bottom-up study of complex adaptive systems, which emphasizes the adaptation of individuals given a simple set of rules. Thus, it employs local information to analyse emerging system behaviours. Currently, agent-based modelling is being utilized to study a broad set of complex adaptive systems, such as biological, social, engineering, manufacturing, financial and business systems. Recent references of agent-based modelling include various research areas; for instance, technology diffusion (Palmer, Sorda, & Madlener, 2015), the dynamics of insect infestation (Anderson & Dragicevic, 2015) and smart grid energy networks (de Durana, Barambones, Kremers & Varga, 2014).

An agent-based approach is suitable when the natural representation of a problem consists of interacting agents. Agent-based modelling involves (Macal & North, 2010): (i) a set of agents, which are self-contained, autonomous, have a state, are social, adaptive, goal-directed and heterogeneous; (ii) agent relationships, meaning that agents are connected through a network or topology; in other words, they have a neighbourhood; and (iii) agent environment which is the spatial location related to other agents and characteristics, that constraint agent actions.

Agent-based modelling studies a complex adaptive system which includes a planner unit (i.e. regulator) that is reactive and goal-directed, and it can change the rules of the game. Thus, it analyses whether designs proposed for economic policies, institutions and processes will result in socially desirable system performance over time. According to Tesfatsion (2006) an agent-based model has the following characteristics: (i) constructive understanding of processes involved in the model, such as production, pricing, and trade processes, from the perspective of the interacting agents; (ii) agents are constantly striving for survival and they should be able to prosper over time; (iii) agents (e.g., firms) are necessarily in rivalry with other agents competing for market power; (iv) the interaction between agents is based on their behaviour, which brings uncertainty, and on their learning process; (v) agents are able to interact, the model should define the role of organizations and conventions, which determine, for instance, the trading process, the exit and entry requirements, etc.; (vi) the resulting model describes the emerging performance obtained from the complex interactions among structural attributes, institutional arrangements, and individual behaviours. In an agent-based model everything affects everything else.

Agent-based modelling carries some disadvantages. One such disadvantage is that every model requires the construction of an economic model which is dynamically complete; for instance, it should not need the intervention from the modeller during the simulation. Other disadvantage is the scalability constraint with large-scale systems with thousands of agents. Finally, the difficulty of validating the models against empirical data because of the mentioned drawbacks. As a main advantage, agent-based modelling possesses high flexibility for describing real-world phenomena, bringing together micro-individual behaviours, interaction patterns and global regularities. Recent advances of computational tools are making this approach more suitable for solving and analysing a broader set of real-world problems.

4.3.2 System dynamics

System dynamics is another simulation technique developed by Jay Forrester in the 1950s for analysing business, technical and social problems encountered by managers in corporate systems (Forrester, 1958). System dynamics models a whole system or process which is dynamic and changes over time, from a top-down perspective (as opposed to bottom-up perspective of agent-based modelling). A system dynamics model analyses complex systems by means of flows and stocks, endogenous feedback loops and time delays. One central concept in system dynamics is the feedback loop which exists whenever decisions made by agents in a system affect the overall state of the system.

The roots of system dynamics go back to control engineering. Nevertheless, as a modelling technique it belongs to evolutionary economics, since it typically follows one or more of the following characteristics (Radzicki and Sterman, 1994): (i) path dependency; (ii) ability of self-organization; (iii) multiple equilibria; and (iv) chaotic behaviour. In addition, the non-linear relationship between variables causes that the active structures of a system change as simulation proceeds and therefore such a model is evolutionary. Moreover, in system dynamics, the iterative process of making the perceptions explicit and testing through simulation generate the real value of a model.

Thus, system dynamics is suitable for analysing complex adaptive systems from a top-down perspective. It offers a complete approach to study dynamic economic systems consisting of non-linearities and feedback processes which are not in equilibrium and evolve over time. The most recent references belong to various research areas; for instance, healthcare system (Rashwan, Abo-Hamad, & Arisha, 2015), social behaviours (Babader, Ren, Jones & Wang 2015) and systems planning and production (Kuai, Li, Cheng & Cheng, 2015). In telecommunications, Casey (2013) extensively applies system dynamics modelling in his doctoral thesis to study the evolution of wireless access technologies.

4.3.3 Comparison of research methods

Both agent-based and system dynamics modelling can be classified as neo-Schumpeterian methods, since they analyse evolving market dynamics. However, their modelling approach and focus are different, for instance, in the relationship among entities in the model and in the level they perform their analysis (Parunak, Savit & Riolo, 1998). While agent-based modelling focuses on entities (i.e. agents), system dynamics focuses on observables which are measurable characteristics of interest. Thus, agents interact with each other through their behaviours, and observables relate to each other by system level equations.

Agent-based modelling is more recent than system dynamics and they present different advantages. Agent-based modelling is more appropriate when the analysed system is characterized by a higher level of localization and decisions are more distributed. On the contrary, system dynamics is more suitable if the system is analysed as a whole, and therefore by its centralized characteristics.

Agent-based modelling and system dynamics may also be combined, as Borshchev & Filippov (2004); Scholl (2001); and Swinerd & McNaught (2012) suggest. However, this interesting approach is out of the scope of this work. This thesis prefers to analyse DSA technologies by means of these two methods separately, since each method is suitable for answering a different research question. Based on the obtained results, Table 4 briefly compares these methods. Agent-based modelling analyses the individual agent behaviours from a bottom-up approach, by defining their behaviours and analysing their emergent system-level interactions. This method is flexible in terms of the level of abstraction, but it tends to describe the details of agent behaviours, and thus it requires a low to medium level of abstraction. Due to the previous fact, the time frame of analysis is short to medium (from hours to months) and indicates a low ability to scale, being especially useful for analysing local behaviours of agents. On the other hand, system dynamics modelling applies a top-down analysis of the system, by describing the relation between system-level observables. Thus, it possesses a higher level of abstraction since it focuses on the most important feedback loops of the whole system, aiming at simplifying the model as much as possible. Moreover, it indicates a high ability to scale and its time frame is typically longer (from months to years).

Table 4. Comparison between agent-based modelling and system dynamics

	Agent-based modelling	***System dynamics***
Approach	Bottom-up	Top-down
Focus	Agent behaviours	System-level observables
Level of abstraction	Low-Medium	High
Ability to scale	Low	High
Time frame	Short-medium	Long

4.4 Research output

The research output consists of six publications which are summarized in Table 5. Publication 1 answers the main research question in general by analysing the conditions of the Coase theorem and its implications for spectrum management. Publication 1 is the starting point for the whole thesis and it introduces the other publications. Publications 2-6 additionally incorporates an evolutionary perspective into the analysis of DSA technologies. Publications 2 and 3 performs a feasibility analysis for different cases of spectrum transactions. Publication 4 investigates the adoption of DSA technologies and how market structure (and policy decisions) affects such adoption. Finally, Publications 5 and 6 compare DSA technologies with other alternative mechanisms that could be used for increasing the economic efficiency of the Internet access market.

Methodwise, the thesis combines top-down and bottom-up analyses. Publications 1, 2, 3 and 6 are based on agent-based modelling, which is a bottom-up approach, since it analyses the individual behaviour of agents. On the other hand, Publication 4 employs system dynamics modelling, which is a top-down approach and it focuses on the overall system (or industry) level dynamics and characteristics. Publication 5 presents a qualitative analysis of transaction and switching costs. In general, besides the type of approach, all publications are supported by literature review, expert interviews (even though they were not formalized), and a constant interaction with a testbed implementation project (End-to-end cognitive radio testbed, EECRT) and other views from an international research project (COST Action IC0905 TERRA). Additionally, each publication typically combines both bottom-up and top-down approaches, since it analyses economics and technology. However, in each paper, one of these components is more relevant. As illustrated in Figure 7, Publication 1 combines a bottom-up method with a top-down analysis. Publications 2 and 3 have a strong bottom-up component, since they explore the interference management, the main technical constraints of spectrum usage. Publications 5 and 6 still employs a bottom-up approach, however their top-down component is more relevant, since they analyse the overall market. Finally, Publication 4 performs a top-down analysis of the interaction between market structure and technology adoption.

Table 5. Summary of publications

ID	Type of publication	Authors	Title	Research Question(s)	Methods
1	Journal paper (Telecommunications policy)	Basaure, Marianov & Paredes	Implications of DSM for regulation	Q	Agent-based modelling
2	Conference paper (DySPAN 2015)	Basaure & Holland	Optimizing spectrum value through flexible spectrum licensing	Q, Q1	Agent-based modelling
3	Journal paper (Communication Magazine)	Kliks, Holland, Basaure & Matinmikko	Spectrum and licence flexibility for 5G networks	Q, Q1	Agent-based modelling
4	Journal paper (Telecommunication systems)	Basaure, Sridhar & Hämmäinen	Adoption of Dynamic Spectrum Access technologies: A System Dynamics approach	Q, Q2	System dynamic modelling
5	Conference paper (CSWS 2013)	Suomi, Basaure & Hämmäinen	Effects of capacity sharing on mobile access competition	Q, Q3	Qualitative analysis based on literature review
6	Journal paper (Telecommunications policy)	Basaure, Suomi & Hämmäinen	Transaction vs. Switching Costs - Comparison of Three Mechanisms for Future Mobile Market	Q, Q4	Agent-based modelling

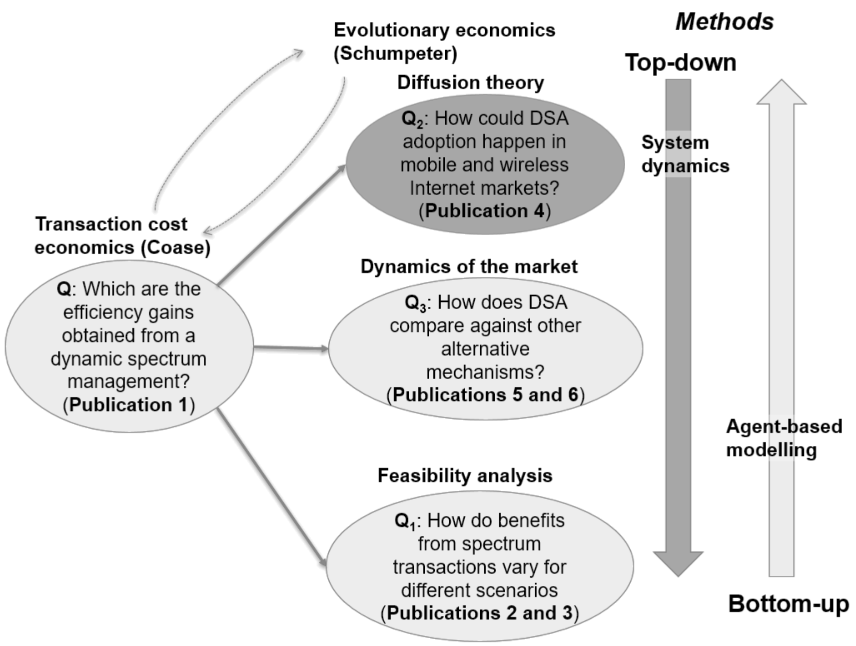

Figure 7. General scheme of research output

5. Modelling, Analysis and Results

The following section presents the most important models developed in this thesis for analysing the set research questions. These models and the related analysis summarize the research output of the thesis. Each model is presented with its corresponding results.

5.1 Implications of DSA for regulation

This first modelling exercise focuses on an ideal mobile market in which DSA technologies are fully deployed and transaction costs are zero. The purpose is to compare different spectrum regimes in a scenario with zero transaction costs. By comparing these regimes, the study assesses the potential benefits of deploying DSA technologies. Thus, this model aims to answer the main research question from a general perspective without dealing with the topics of the three subquestions.

This model is not intended to describe the reality in detail, but rather to understand the potential gains of spectrum transactions and the factors determining these gains. Therefore, it is a conceptual model, which employs the Coase theorem as the underlying economic framework explaining the gains from transactions. Factors determining the value of the spectrum are listed as follows: (i) transactions are valuable because spectrum is scarce and its valuation is heterogeneous (i.e. varies with place, time, frequency and usage); (ii) DSA decreases spectrum transaction costs; (iii) DSA helps to clearly define spectrum property (or usage) rights, especially regarding interference management between the involved parties; and (iv) spectrum transactions require a competitive market (i.e. low market concentration) [7]. The following model is built based on these factors and compares different spectrum regimes which have been proposed in the context of DSA.

Model

The model simulates a competitive market allowing spectrum transactions. The simulation assumes three similar MNOs and four LAOs per type of area (home, office or public). This setup emphasizes diversification of operators to

[7] See Publication 1 for further details

enable all beneficial transactions. This model presents a general scheme of capacity transaction between MNOs and of spectrum sharing between LAOs under different spectrum regimes. A mobile user is served by an MNO or LAO. This model additionally emphasizes the heterogeneity of service demand, in terms of capacity and quality requirements, and the diversification of service supply.

The simulation setup depicted in Figure 8 assumes that spectrum and network capacity transactions are performed between MNOs and between MNOs and LAOs. A centralized trading system acts as a mediator by publishing trading information each hour, 24 times a day. Spectrum is traded at operator level, but the access is granted at user level. In such case, the mobile user requests permission from a local spectrum database, which grants access under predefined conditions of interference and QoS. Such access can be provided by MNOs or LAOs. The model assumes 20 types of services, categorized by QoS class (from 1 to 4) and capacity requirement, as indicated in Table 6. Since transaction costs are zero, mobile users can be served by any MNO or LAO if the user is in the same coverage area (home, office, or public). Users follow traffic and location patterns obtained from measurements performed in Helsinki (see Publication 1 for further details).

Finally, the value of the service is defined by its capacity and quality requirements. Thus, each served unit of traffic has the following valuation: Unit Value (QoS 1) > Unit Value (QoS 2)> Unit Value (QoS 3)> Unit Value (QoS 4).

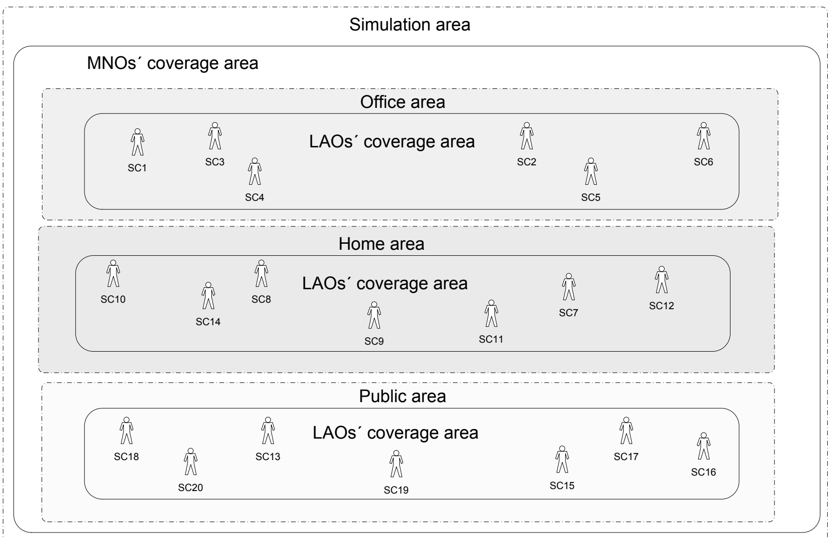

Figure 8. Simulation setup.

Table 6. Service categorization (adapted from Publication 1)

Service type (capacity requirement) \ Traffic class (QoS requirement)	Conversational (QoS 1)	Streaming (QoS 2)	Interactive (QoS 3)	Background (QoS 4)
Super-high multimedia (e.g., premium service)	SC1	SC6	SC11	SC16
High multimedia (e.g., video streaming)	SC2	SC7	SC12	SC17
Medium multimedia (e.g., Internet browsing)	SC3	SC8	SC13	SC18
Low rate data and low multimedia (e.g., messaging services)	SC4	SC9	SC14	SC19
Very low rate data (e.g., M2M services)	SC5	SC10	SC15	SC20

Table 7 summarizes the simulation scenarios. The first scenario describes the current situation of MNOs consisting in a combination of exclusive and commons regimes, which includes mobile offloading in Wi-Fi networks (i.e. LAOs). The second scenario simulates a cooperation scenario, in which MNOs can share or trade spectrum and network capacity between them, but maintaining the current exclusive regime. This may occur by allowing network operators to join their licenses for a shared access or through any type of cooperation mechanism, such as infrastructure sharing. In addition, mobile users offload their traffic to local-area networks based on a commons regime. For the remaining scenarios (LSA, pluralistic and light licensing) network capacity and spectrum are traded in the market. User access spectrum by means of a spectrum database, which holds real-time information. Different regimes achieve different levels of QoS. For instance, while light licensing can provide end-user with QoS level 3, LSA is able to achieve QoS level 2. Pluralistic licensing can provide from QoS levels 4 to 1, depending on the agreed conditions. Additionally, the adaptive pluralistic licensing regime assumes that each operator can modify its interference level over time according to the information they have on the demand.

Table 7. Simulation scenarios, assumptions (adapted from Publication 1)

Scenario for Simulation	**Transactions allowed**	**Available QoS (1 highest, 4 lowest)**	**Adapt interference in time?**
Mobile offloading based on opportunistic use of commons	No	QoS 4	No
Operator cooperation based on commons and exclusive regimes	No	QoS 1 (exclusive) and QoS 4 (commons)	No
Spectrum market based on LSA licensing	Yes	QoS 1(from mobile operators) and QoS 2 (from local operators)	No
Spectrum market based on Light licensing	Yes	QoS 1 (from mobile operators) and QoS 3 (from local operators)	No
Spectrum market based on Pluralistic licensing, fixed interference	Yes	QoS 1 (from mobile operators) and QoS 1 to 4 (from local operators)	No
Spectrum market based on Pluralistic licensing, adaptive interference	Yes	QoS 1 to 4 (from mobile and local operators)	Yes

Results

The simulation results are summarized in the following Figure 9. These graphs show, in average, the amount of traded or shared spectrum and network capacity capacity per each QoS class (from 1 to 4). Figure 9 (a) depicts the starting point or current situation based on opportunistic mobile offloading. Figure 9 (b) includes cooperation or spectrum sharing between wide area networks of MNOs, and others allows spectrum transactions between MNOs and LAOs based on different spectrum regimes: LSA (Figure 9(c)), light licensing (Figure 9(d)), and pluralistic licensing (Figures 9(e)(f)).

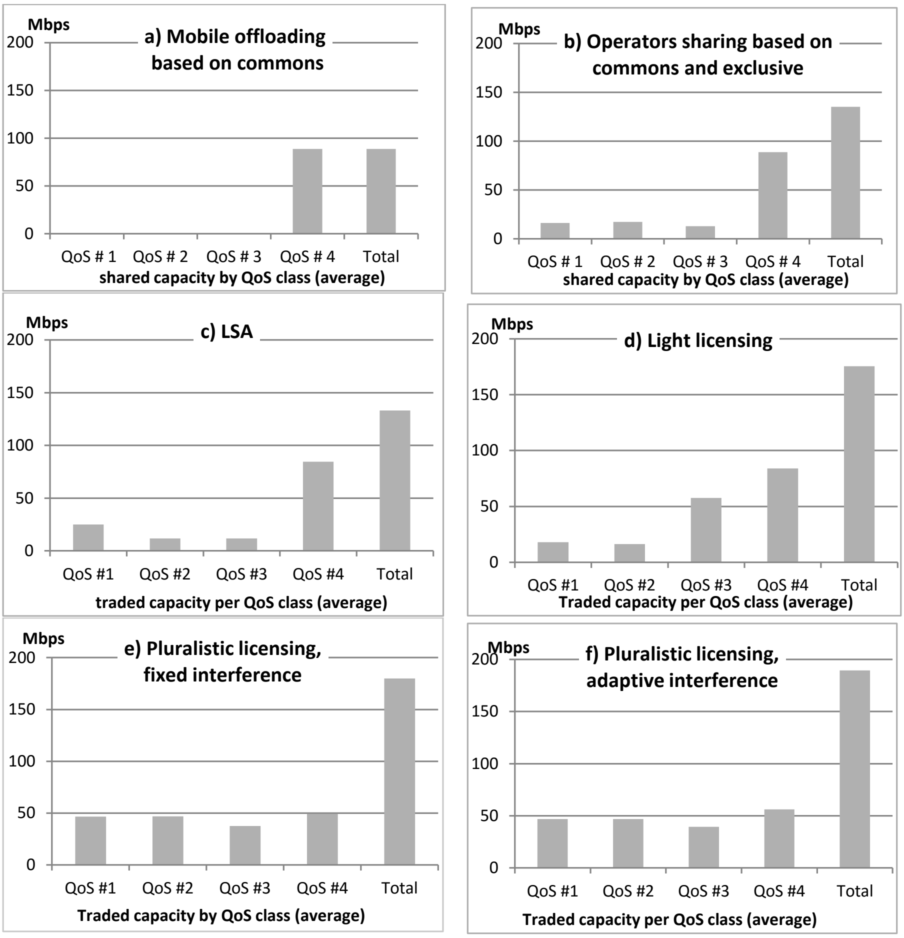

Figure 9. Simulation results (adapted from Publication 1)

The simulations results show significant potential gains with a flexible spectrum regime allowing transactions. These results are based on the assumption of heterogeneity of service valuation, and the ability of DSA technologies for detecting these valuations and to trade accordingly. Even though these technologies are still under development and have not been successful deployed, DSA can effectively decrease transaction costs if spectrum usage rights are better defined. DSA facilitates detecting and trading spectrum on a real-time basis (or near real-time) by establishing interference parameters as a tradable characteristic of the spectrum. Thus, DSA decreases transaction costs and improves the definition of usage rights.

This is an important observation, since both a reduction in transaction costs and clearly defined property (or usage) rights provide the conditions for the Coasean implications on policy.

The obtained gains are significant and rely on the changing nature of the service demand, which varies in time and place. This creates diversity and volatility in service valuation, which further increase when the spectrum is scarce. Even though this simulation model highly simplifies the reality, it addresses an important issue by claiming that the widely adopted exclusive and commons regimes offer considerable room for improvement.

Pluralistic licensing has been recently proposed by Holland et al. (2012) to address the increasing sophistication required by spectrum transactions. From a Coasean perspective, transactions should take place between private participants, i.e. through contracts between MNOs, rather than being defined by the regulator. Thus, private contracts are more dynamic with changing conditions of the market, since the interference tolerance may be adapted if initial conditions change. In addition, local licenses may be bought and sold to adapt the network supply to the changing demand. From a technical perspective, local area networks (such as Wi-Fi or small cells) are far more flexible than wide area cellular networks for adapting to changing conditions.

5.2 Feasibility study on spectrum transaction cases

Based on the previous results, the following model simulates different bilateral spectrum transactions based on real world conditions. The previous section analysed spectrum transactions without technical details. This section conducts a feasibility study comparing the obtained benefits from different spectrum transaction scenarios, considering the interference as a tradable characteristic of the spectrum. Thus, this section performs a sensitivity analysis of the parameters affecting spectrum transactions between private operators to develop a general framework which facilitates spectrum trading. The analysed cases describe different types of operators and end-users. For each case, the model finds the conditions for spectrum value optimization. Note that from a regulatory perspective, the NRA is a facilitator, which defines the rules for enabling transactions, increasing coordination and lowering transaction costs. Prices are a private decision of the involved parties, and therefore this section does not perform any calculations on pricing. This section answers the following research question: How do benefits from spectrum transactions vary for different dynamic spectrum management scenarios?

Model

This following model performs a feasibility analysis of the five scenarios presented in section 2.8. It models spectrum transactions between two operators, based on a primary-secondary or co-primary scheme. In a primary-secondary transaction, the primary and secondary users have different priorities, while co-primary users transmit with equal priority. This model is intended to reflect a pluralistic licensing scheme, however, it can be easily extrapolated to other more general schemes allowing spectrum sharing; for instance, to the three tiered sharing framework (see Figure 5). Specifically, this model assumes that the coordination between the involved operators is provided by a spectrum database, which knows or calculates the technical characteristics and geographical coverage of the primary users to allow the secondary or co-primary users to transmit. An example of rules for the co-primary and secondary transmissions have been defined by the FCC (2010). Thus, such database grants permission to transmit within a predefined area (coverage area) and within certain mobility restrictions (leasing distance). The performance of the co-primary and secondary transmissions may be further improved by means of more advanced sensing capabilities to obtain real-time information on primary location.

The first scenario represents an urban area in which the primary system consists of five-cells-wide section of a cellular network. The secondary users are transmitting directly through device-to-device (D2D) communication system, outside the primary coverage area and without any specific network infrastructure (see Figure 10 for a graphical representation). Both systems transmit in the 700 MHz band and the simulation describes the downlink behaviour in a FDD scheme. The secondary users request the spectrum database each time they move over their leasing distance.

The second scenario models two separate cellular networks transmitting in the 2.6GHz frequency band in close geographical proximity, as depicted in Figure 11. The two networks and their users have similar characteristics, except that one system has a priority over the other (i.e. primary and secondary). The simulation describes the downlink behaviour in a FDD scheme. This scenario can also be modelled as a co-primary spectrum transaction.

The third scenario describes a TV primary system coexisting with a cellular secondary system located in the surrounding area of the TV coverage, both transmitting in the 700MHz band, following a TDD scheme, as depicted in Figure 12. The analysed scenario and related frequency band have been subject of public discussion (EU COM, 2013), and they can also be a reflection of the ETSI WSD standard. Cellular devices access the TVWSs after checking with a spectrum database, as in the first scenario. TV primary receivers require a strict minimum level of signal-to-interference-and-noise-ratio (SINR) which is assured through a margin representing a certain confidence level.

The fourth scenario, depicted in Figure 13, represents a spectrum transaction between an outdoor cellular network (e.g., macro or micro cells) acting as the primary system and an indoor small-cellular network (e.g., femto cells) acting as the secondary system, both transmitting in the 2.3 GHz band. The coverage areas are delimited by the outdoor-indoor interface and a spectrum database works as an authoritative register for secondary users.

Finally, the fifth scenario analyses two adjacent indoor areas; for instance, two buildings separated by a street in a residential area, each one deploying a local area network by means of a small cellular network (e.g., pico or femto cells), as depicted in Figure 14. This scenario implements a co-primary scheme, in which each local network is managed autonomously, and all systems are transmitting in the 60GHz band (i.e. millimetre-waves).

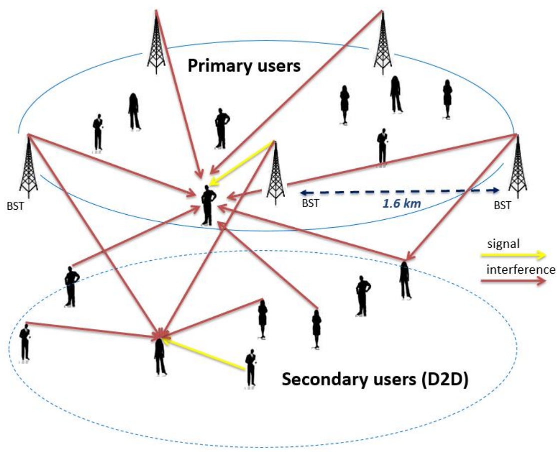

Figure 10. Scenario 1 (adapted from Publication 2)

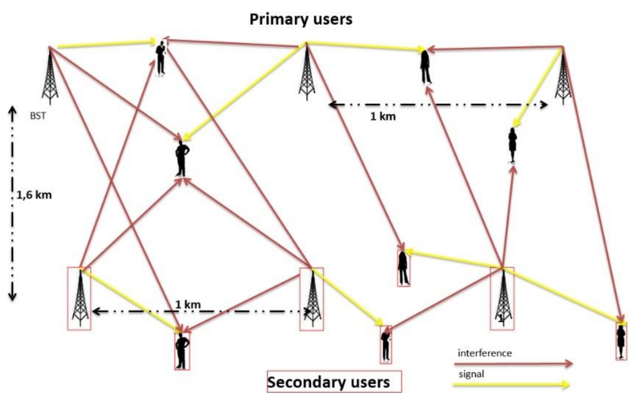

Figure 11. Scenario 2 (adapted from Publication 3)

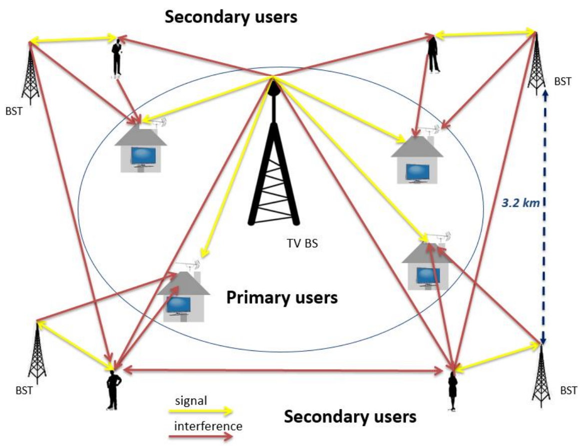

Figure 12. Scenario 3 (adapted from Publication 2).

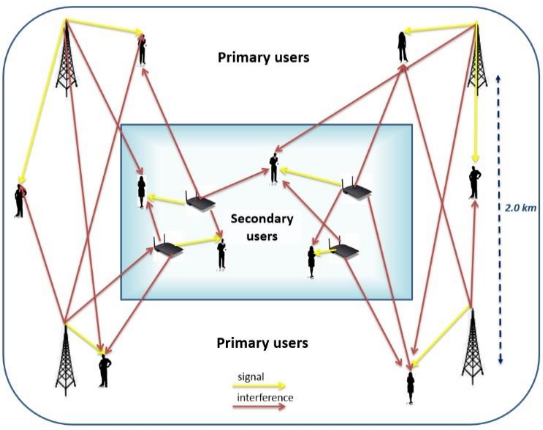

Figure 13. Scenario 4 (adapted from Publication 2)

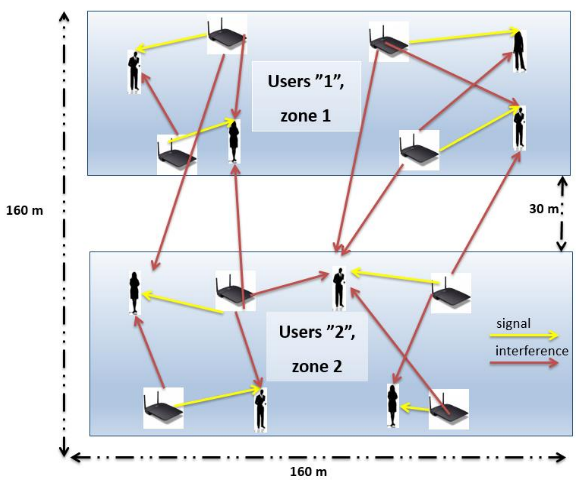

Figure 14. Scenario 5 (adapted from Publication 2)

Results

This section presents the potential gains for the simulated scenarios. For each scenario, different user utility functions are selected, such as represented by Figure 15. The shapes of these functions (e.g., concave versus convex range) describes the criticality of multimedia requirements in terms of SINR (assumed proportional to throughput and perceived QoS) and they are cathegorized into real-time, not real-time and strict real-time.

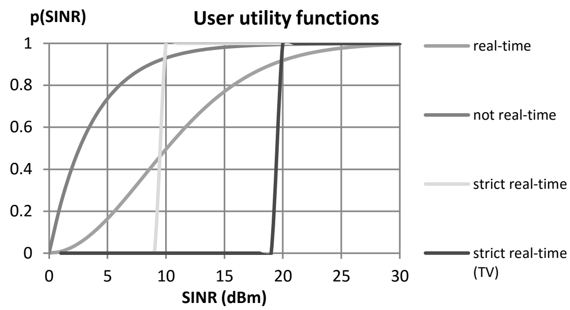

Figure 15. User utility functions (adapted from Publication 2)

In Figures Figure 16, 17, 18, 19 and 20, the total benefits are calculated based on individual user benefits for each operator and for all users. The costs of sharing are obtained by calculating the incremental energy costs incurred by the operator when adapting its transmission power. For all analysed scenarios, spectrum transactions result in additional benefits, indicating that the obtained gains are larger than the losses caused by interference. Figure 16 shows that the first scenario achieves its optimal interference level with primary base stations transmitting at 46dBm of power, when primary users have real-time and secondary users have not-real time requirements. The optimal interference depends on the user utility functions, the separation distance between coverage areas and the leasing distance of secondary users. The results of the second scenario (Figure 17) indicate a trade-off between the perceived QoS of each MNO, in which the network having priority (and more users) should transmit with higher transmission power than the secondary network to achieve the optimum. Figure 18 shows that, in the third scenario, when the primary operator is a TV network (with strict real-time requirements), the secondary system should transmit with low power and consequently the overall benefits of this scenario are limited; however, spectrum transaction is still beneficial. In the fourth and fifth scenarios (Figures 19 and 20), the optimum is achieved when both networks are transmitting with relatively high power to optimize their own QoS. Scenario five additionally highlights the importance of internal coordination for achieving the optimal benefits. In short, while the outdoor scenarios (1, 2 and 3) indicate a trade-off in QoS between the involved parties; the indoor scenarios (4 and 5) do not follow such a trend, since the interference is reduced by the walls.

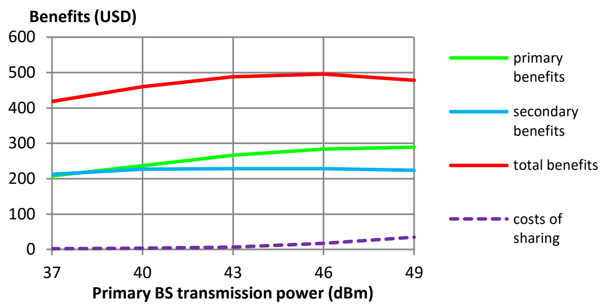

Figure 16. Simulation results for scenarios 1: Primary MNO (real time), secondary D2D devices (not real-time secondary) (adapted from Publication 2)

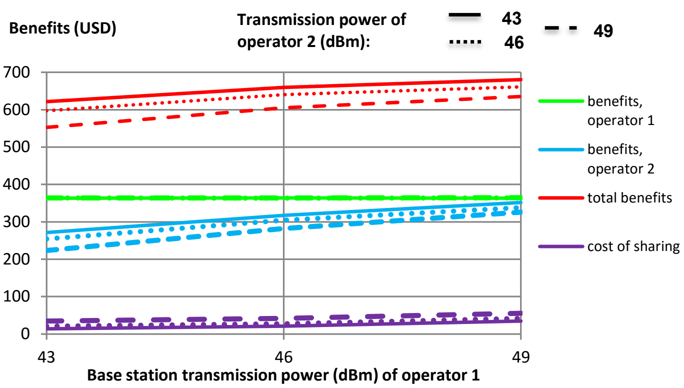

Figure 17. Simulation results for scenarios 2: Primary and secondary MNOs, all users require real-time service (adapted from Publication 2)

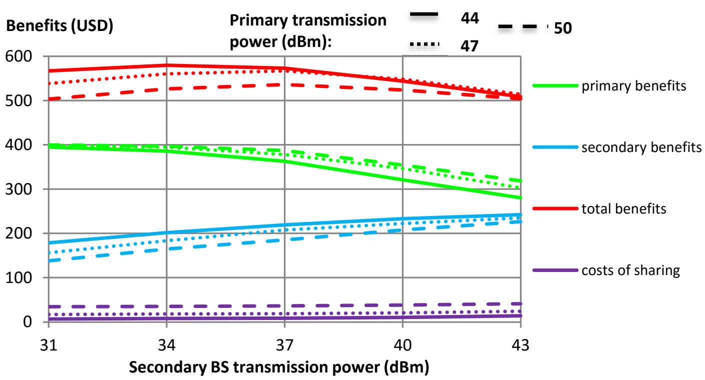

Figure 18. Simulation results for scenarios 3. Primary TV operator (strict real-time), and secondary MNO (not real-time) (adapted from Publication 2)

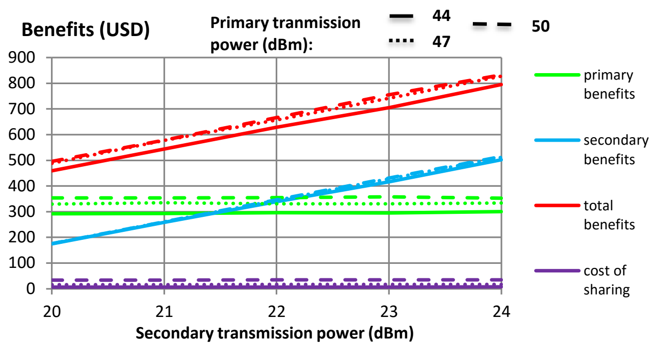

Figure 19. Simulation results for scenarios 4. Primary MNO (outdoor) and secondary femto-cell operator (indoor). Both have real-time requirements (adapted from Publication 2)

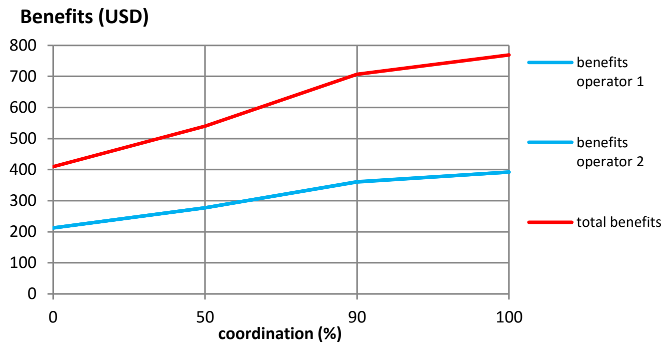

Figure 20. Simulation results for scenario 5. Two small cell operators, all users have similar requirements (adapted from Publication 2)

This simulation exercise assesses the benefits of spectrum transactions, which include interference as a tradable characteristic of the spectrum. Thus, it performs a feasibility analysis of realistic spectrum transaction between two operators, based on the state-of-the-art DSA technologies and on the pluralistic licensing concept. The results show that the optimal level of interference is usually above zero; therefore, spectrum transactions should consider the interference that a spectrum holder is able to receive and generate. A spectrum regime needs to provide operators with an economic incentive to accept a certain level of interference to maximize the value of the spectrum. Moreover, spectrum transactions should consider user utility functions. This observation holds for both primary-secondary and co-primary schemes.

In all analysed scenarios, this study indicates that for a given spectrum band, a demand increase will result in additional benefits if voluntary transactions are allowed. Therefore, a scheme which restricts transactions or minimizes interference, such as exclusive licensing, is never optimal. The optimal level of interference will depend on service requirements and user utility functions.

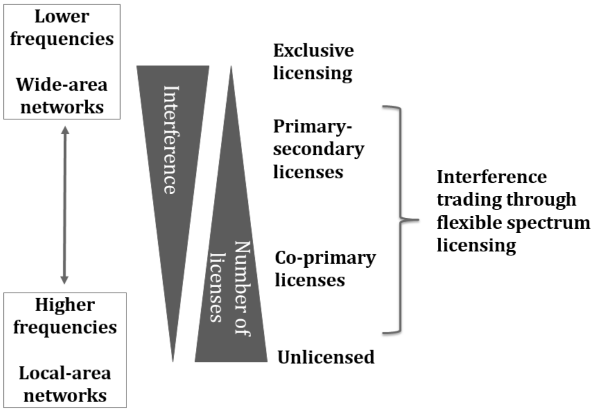

Figure 21. Scheme of simulation results: frequencies and type of regime

Figure 21 summarizes the obtained results. In general, spectrum transactions are beneficial when they consider the interference in the transaction. However, those cases which generate the least amount of interference are especially beneficial; in concrete, in indoor-outdoor and indoor transactions. Between exclusively assigned low frequency bands and license-exempt high frequency bands, medium range frequencies may be beneficially traded in a primary-secondary or co-primary fashion. From this middle range, lower frequencies may be more suitable for a primary-secondary scheme, while higher frequencies may be more suitable for co-primary scheme.

The previous observations may be especially interesting for the deployment of future indoor networks, including 5G, small cells and emerging IoT applications, since they require less coordination than wide-area networks. For very high frequencies (i.e. millimetre-waves), the most suitable regime may be the license-exempt, since those frequencies do not require coordination between spectrum holders. For outdoor cellular networks, LSA seems to be the first practical implementation for spectrum trading, being its benefits smaller than those of the indoor scenarios.

5.3 Adoption of DSA technologies

The previous sections 5.1 and 5.2 analyse the benefits of spectrum transactions. This section models the adoption of DSA technologies, to understand the requierements for a successful DSA deployment. Since DSA changes the way spectrum is managed, and spectrum assignment is in tight relation with the industry structure, this modelling work performs a top-down analysis based on system dynamics to understand the interaction between technology adoption and industry dynamics. This analysis considers two main elements affecting the adoption of DSA technologies: (i) industry openness, defined as entry and exit barriers, and (ii) spectrum centralization which is the mode spectrum is assigned, its associated usage rights and consequent concentration. As described in sections 2.3 and 2.6, DSA standards may be adopted by operators or by end-users. In addition, DSA technologies compete with network or substitution effect, depending on the type of design a standard is implementing. This section answers to the following research question: How could DSA adoption happen in Internet access markets?

Model

This work performs a synthesis of previous modelling work, specifically the spectrum management modelling of Sridhar, Casey and Hämmäinen (2013), the industry openness dynamics of Davies, Howell and Mabin (2008), the network effect modelling of Sterman (2000) and the substitution effect formulation of Pistorius and Utterback (1996). Figure 22 presents a system dynamics representation of a competition model with network and substitution effects.

System dynamics employs causal loop diagrams to visualize the relation between variables in a system. Diagrams consist of nodes and edges; nodes represent variables, while edges depict the relationship between variables. The sign and direction of the edges indicate the type of relationship forming a causal link; two nodes change in the same direction if the sign is positive, or they change in opposite direction if the sign is negative. A causal or *feedback loop* is the result of a closed sequence of causal links. The feedback loop is *reinforcing* (denoted as R) if a variation in any variable propagates through the loop and returns to the initial variable with the same direction, further stimulating the initial variation. The feedback loop is *balancing* (denoted as B), if a variation in any variable propagates through the loop and returns to the initial variable in opposite direction, causing the contrary effect.

Figure 22 (a) models the network effect produced by the path dependence of two competing technologies. In this figure, the variable adoption (of user- or operator-centric devices) describes the performance of each type of device. The adoption level positively affects the installed base of these devices; and this higher installed base leads to higher levels of compatibility and hence attracts more adoption of such devices. This in turn increases the market share of these devices, which constitutes a reinforcing network effect (loops R1 and R2). However, an increase in attractiveness of one type of device decreases the share of the other type of device, which slows down the rate of adoption and causes a saturation in the adoption of the other type of device, as depicted by balancing loops B2 and B1.

Figure 22 (b) illustrates the substitution effect, by employing a predator-prey competition model, which is mathematically described by the Lotka-Volterra equations and describes technological substitution (Pistorius & Utterback, 1996). This model exhibits a similar logic than the previous model, but with a different relation between the two competing technologies: the growth of user-centric devices (predators) leads to the substitution of operator-centric devices (prey). Hence, the reinforcing loops R1 and R2 originate the substitution balancing loop B1.

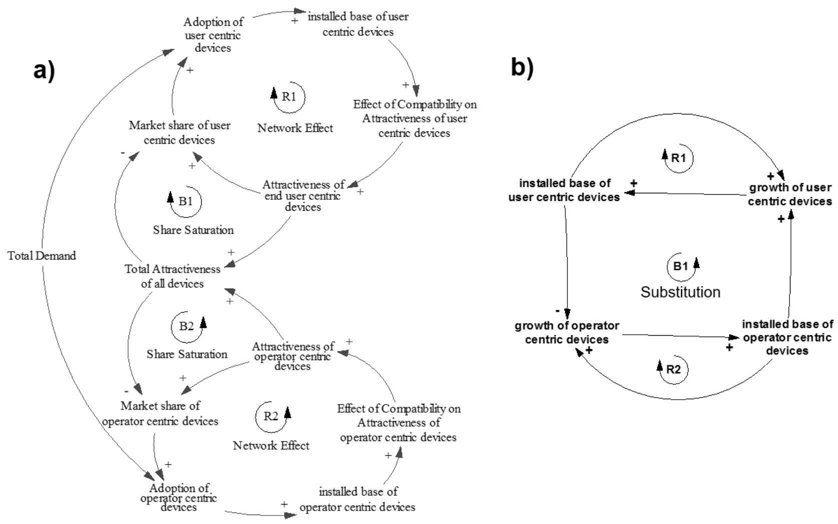

Figure 22. System dynamics representation of DSA adoption with network and substitution effects (adapted from Publication 4).

Figure 23 (a) adapts the model on spectrum management developed by Sridhar, Casey and Hämmäinen (2013). This model explains that a centralized spectrum management incentivizes a wholesale spectrum market, thus leading to adoption of operator-centric DSA technologies, depicted as reinforcing loop R3 (wholesale); and at the same time discouraging a user-centric adoption in the retail market. On the other hand, a market driven and decentralized spectrum assignment incentivizes user-centric adoption of DSA technologies in the retail market, depicted as reinforcing loop R4 (retail). In the wholesale loop, high spectrum concentration stimulates operator-centric spectrum sharing and trading that subsequently stimulates high spectrum concentration, without any need for a decentralized spectrum regime. In the retail loop, lower spectrum concentration induces end-users to drive the spectrum market, which in turn promotes user-centric devices to be deployed and thus promoting a decentralized spectrum regime. The reinforcing loops R5 and R6 show that the growth in one type of devices reduces the demand for the other type of devices.

Figure 23 (b) adapts the model describing the industry openness developed by Davies, Howell & Mabin (2008). This model explains that low entry barriers (i.e. open industry) favoured by regulators to stimulate competition can have a negative impact on investments due to a decrease in operator profits. This leads to a reinforcing loop (R7), because a decrease in prices opens the industry further. In a similar manner, increasing entry barriers due to a regulatory effort to improve QoS, provides market participants incentives to invest in operator-centric infrastructure, which decreases industry openness and disincentivizes user-centric DSA technologies, causing the reinforcing loop R8. At the same time, lowering entry barriers (i.e. opening the industry) decreases the willingness to invest in operator-centric infrastructure, making the user-centric proposition attractive for old and new industry actors (reinforcing loops R9 and R10).

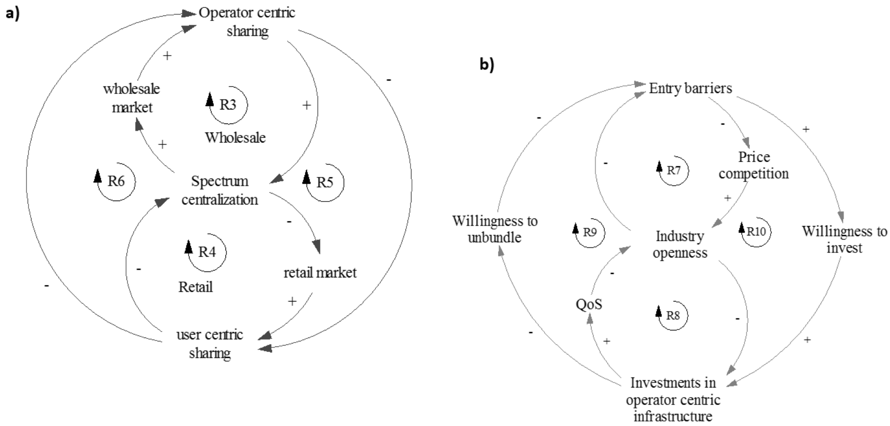

Figure 23. System dynamics representation of industry openness and spectrum centralization (adapted from Publication 4).

The integrated models consist of the merging of Figure 22 and Figure 23. See Publication 4 for further details. Thus, spectrum centralization and industry openness affect the adoption of user- and operator-centric technologies for both types of competition; with network and substitution effects. The model assumes a spectrum regime allowing transactions, which may happen at retail or at wholesale levels. If the spectrum regime is centralized, spectrum sharing or trading is performed between operators. If the spectrum regime is decentralized, spectrum transactions are driven by end-users.

Results

Table 8 summarizes the simulation results of the adoption models with network and substitution effects. With high network effect, the adoption of user-centric devices is only successful under open industry and decentralized spectrum. With substitution effect, user-centric devices are adopted with a decentralized spectrum, regardless the industry openness. In all other cases, operator-centric adoption dominates.

Table 8. Summary of the results

	SPECTRUM	INDUSTRY	OPERATOR-CENTRIC	USER-CENTRIC
NETWORK EFFECT	CENTRALIZED	OPEN	√	
		CLOSED	√	
	DECENTRALIZED	OPEN		√
		CLOSED	√	
SUBSTITUTION EFFECT	CENTRALIZED	OPEN	√	
		CLOSED	√	
	DECENTRALIZED	OPEN		√
		CLOSED		√

These observations are relevant to the current discussion on DSA adoption for two reasons. Firstly, most of the countries have a centralized spectrum; and secondly, most of the DSA standards have been developed for end-users. This means that most of the DSA efforts will not be successfully adopted in most countries under current spectrum conditions, as described by Table 9.

Thus, if few operators continue to hold most of the spectrum, an operator-centric adoption of standards such as ETSI RRS LSA, 3GPP CA and open standards like Weightless offering specific IoT integral solutions may dominate. For markets with decentralized spectrum, end-user adoption dominates for open industries, including for standards with modular design, such as 3GPP D2D, ETSI Reconfigurable MD, IEEE 802.11af and 802.11ah, and for standards with integral design, such as ETSI WSD, Weightless, IEEE 802.22 and IEFT PAWS. In closed industries, end-user adoption dominates for modular standards and operator-centric adoption dominates for integral standards.

Table 9. Application of the results

SPECTRUM	INDUSTRY	NETWORK EFFECT	SUBSTITUTION EFFECT
CENTRALIZED	OPEN	WEIGHTLESS	ETSI RRS LSA, 3GPP CA
	CLOSED		
DECENTRALIZED	OPEN	ETSI WSD, WEIGHTLESS, IEEE 802.22, IEFT PAWS	3GPP D2D, ETSI RRS RE-CONFIGURABLE MD, IEEE 802.11AF, IEEE 802.11AH
	CLOSED		

DSA technologies involve a wide set of standards and solutions with different design and applications. This work aims to understand how these technologies may be adopted by operators or end-users. This work synthesizes the previous literature to explain such adoption. This is a question of interest given the uncertainty that these solutions present in the current market. Thus, this work provides a deeper understanding on the relation between mobile market and DSA technologies than the previous literature.

The standardization efforts of DSA can be divided into: (i) end-user centric with modular design; (ii) end-user centric with integral design; (iii) operator-centric with modular design; and (iv) operator-centric with integral design. Previous Tables Table 8 and Table 9 describe the conditions for a successful adoption for each type of solution. The system dynamics modelling developed herein describes how the industry structure affect the standard suitability and how the adopted standard affects back the industry structure.

In general, operator-centric DSA standards, such as 3GPP CA and ETSI RRS LTA, are therefore expected to dominate in most countries, which present a centralized spectrum. On the other hand, user-centric DSA standards may be adopted in countries with decentralized spectrum. The main reasons for this are the investment incentives and the lock-in of DSA technologies, as described by the system dynamics models. These observations emphasize the need for a more decentralized spectrum management in line with current DSA development, for instance, when assigning spectrum for new infrastructure deployment.

5.4 DSA against other alternative mechanisms

Finally, this last modelling work compares DSA with other alternative mechanisms, as described in section 2.9. Previous sections have explored the potential of DSA technologies. However, the techno-economic challenges of DSA may limit the potential benefits, at least initially, to only few cases. This section investigates other alternative solutions for increasing economic efficiency at outdoor and indoor networks. Thus, the following model compares inter-MNO spectrum transactions against two other mechanisms that increase market dynamics at different levels: national roaming which promotes network capacity trading, and end-user multihoming which allows the end-user to rapidly switch from one network to another. While transaction costs affect the industry structure and determine the level of vertical integration, switching costs determine the market concentration and the monopoly power of incumbent firms. This section answers to the following research question: How does DSA compare against other alternative mechanisms for increasing economic efficiency of Internet access markets?

Model

The following agent-based model analyses the interaction between three MNOs and seventy-two end-users accessing mobile networks (see publication 6 for details on assumptions). Figure 24 depicts the simulation setup for the location of base stations of three MNOs. On the left side, the MNOs have a colocated topology and on the right side a non-colocated topology. In the colocated topology, MNOs have similar network coverages and they cooperate in passive elements (same location of antenna sites). In the non-colocated topology, MNOs show higher network coverage disparities. The colocated topology may describe an outdoor cellular network deployment, while the non-colocated topology may also be seen as a simple indoor deployment based on small-cellular networks. In general, both outdoor and indoor cases are equally represented by the same simplified simulation scheme, being the difference that in the indoor case each base station depicts a local network consisting on several small cells.

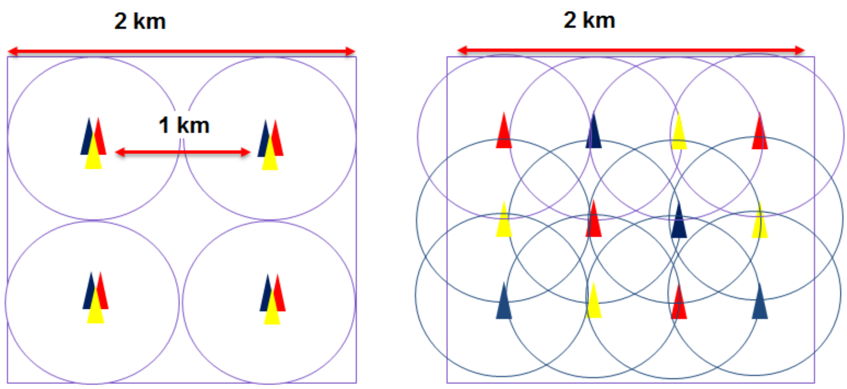

Figure 24. Simulation setup. (Left) collocated topology (Right) non-colocated topology (Adopted from Publication 6)

Switching and transaction costs are modelled in the simulation as described as follows. Switching costs are defined by the easiness for the end-user to switch from one MNO to another. Switching happens when the perceived benefits of switching, in present value, exceed the switching costs. Thus, the switching costs are estimated by the end-user based on his/her own experience on QoS failures and on the availability of information. A failure in QoS is defined in terms of signal strength (i.e. out of coverage) and congestion (i.e. not enough capacity). Switching costs are high when the end-user switches MNO only after tolerating many QoS failures. For the simulation, user switches after 10 failures for high switching costs, which roughly represent the switching cost of a manual SIM card replacement. The simulation assumes for this case that the end-user chooses another MNO randomly. When switching costs are at a medium level, then end-users switch MNO after only one failure, for instance through multi-SIM devices. The simulation assumes for this case that the end-user chooses the closest base station. Finally, switching costs are low, when end-users can proactively choose in each access the base station offering the best QoS (i.e. lowest congestion). This phase represents, for instance, the deployment of automated eSIM in which the real-time QoS comparison is based on MPTCP. Such deployment provides the end-user an automated switching decision capability based on previously user-configured settings.

Transaction costs are quantified via the break-even point between scale benefits and transaction costs. Thus, they describe the level of coordination between MNOs and its impact on the related costs items. In national roaming the costs are shown by the number of available roaming agreements for end-users. When transaction costs are high, the inter-MNO book-keeping is performed on a retail level by the involved MNOs and the routing is non optimal (i.e. through the home network), and thus roaming agreements will not be available for end-users. Thus, these high transaction costs are modelled by zero roaming agreements. Transaction costs are medium level if the inter-MNO book-keeping is performed at wholesale level. This situation is modelled as one roaming agreement available to end-users. Transaction costs are low when the inter-MNO book-keeping happens at wholesale level and routing is optimized through the visited network. This requires a higher level of trust and a well-defined trading mechanism. In the simulation, this situation corresponds to a full national roaming.

The transaction cost assumptions for DSA specifically describe a femto-cellular network deployment; however, this can be also extrapolated to outdoor networks (e.g., LSA scenario). Currently, spectrum trading between operators is non-existent for outdoor networks. With the deployment of indoor femto-cellular networks, the base station customer (e.g. home owner) experience a high demand in its network since he/she wants to provide access for an identified group of end-users (e.g. home guests). In such situation, inter-MNO carrier aggregation (CA) enables the femto-cellular customers to obtain additional spectrum. In the simulation, the transaction costs are medium when spectrum trading is managed manually, for instance in time-slots of 3 hours. Transaction costs are low, when spectrum transactions are automated and performed in time-slots of 3 minutes (i.e. the length of one iteration) without direct interaction of the femto-cellular customer. In this DSA scenario, spectrum transactions are performed upon request, mediated by a broker. CA permits to aggregate bandwidth of different sizes, from 1.4 to 20 MHz, and thus provides high flexibility in the amount of traded spectrum. The broker only coordinates transactions and does not own or hold any spectrum. This means that each femto network can temporally increase its capacity by acquiring additional spectrum.

Table 10 summarizes the simulated transaction and switching costs for each mechanism. Note that the level of costs between different mechanisms are not directly comparable, but the cost levels aim to match with the major cost reduction steps as enabled by technology.

Table 10. Definition of transaction and switching costs

	Switching costs	**Transaction costs**	
	End-user multihoming	**National Roaming**	**DSA**
	Number of experienced failures, after which the user switches MNO	*Number of roaming agreements available for a user*	*Frequency of spectrum trading transactions*
Low	0 (automated eSIM)	2 (wholesale, optimal routing)	3 minutes (femtos, automated inter-MNO CA)
Medium	1 (manual multiSIM)	1 (wholesale, home routing)	3 hours (femtos, manual inter-MNO CA)
High	10 (SIM replacement)	0 (retail, home routing)	Never (no femtos)

Results

The simulation results of Figures Figure 25, Figure 26, Figure 27 and Figure 28 show that any of the three analysed mechanisms (national roaming, DSA or end-user multihoming) can dynamically improve the allocative efficiency of the mobile market. In other words, a decrease of switching or transaction costs, that is, an increase of competition or cooperation, can result in higher efficiency. The model simplifies the complex reality and the simulation results are rather qualitative than quantitative; however, they describe well the underlying dynamics. In practice, the market efficiency improvement opportunity depends on the quality difference between networks.

While end-user multihoming is the most cost effective mechanism for increasing allocative efficiency, DSA is especially suitable for scenarios with high congestion. National roaming is an alternative choice to end-user multihoming for a regulator willing to promote cooperation between MNOs.

In general, any of these mechanisms can change the current market dynamics. Therefore, the regulator has little incentive to introduce them, if MNOs can maintain a good performance in terms of coverage, congestion and blackouts. Correspondingly, if the market suffers from performance problems, the regulator may consider promoting these mechanisms.

Moreover, the level of colocation of base stations highly affects the efficiency attained by these mechanisms. Thus, colocation decreases the opportunity of these mechanisms, while non-colocation (and their consequent coverage disparity) increases the opportunity. However, in reality, MNOs practice both approaches; they colocate part of their base stations to reduce costs and, at the same time, increase coverage in other areas through a non-colocated topology. Therefore, a balanced combination of cooperation and competition is needed to achieve higher efficiency. This observation is in line with literature suggesting that if cooperation enhances social welfare, the maximum degree of competition may not be efficient (e.g., Canegallo, Ortona, Ottone, Ponzano & Scacciati, 2008). Additionally, the simulation results are relevant for the small cellular networks based on non-colocated topology. Since small cells present coverage and capacity disparities together with challenges for developing a good business case; any of these mechanisms may be very relevant for MNOs in such deployments.

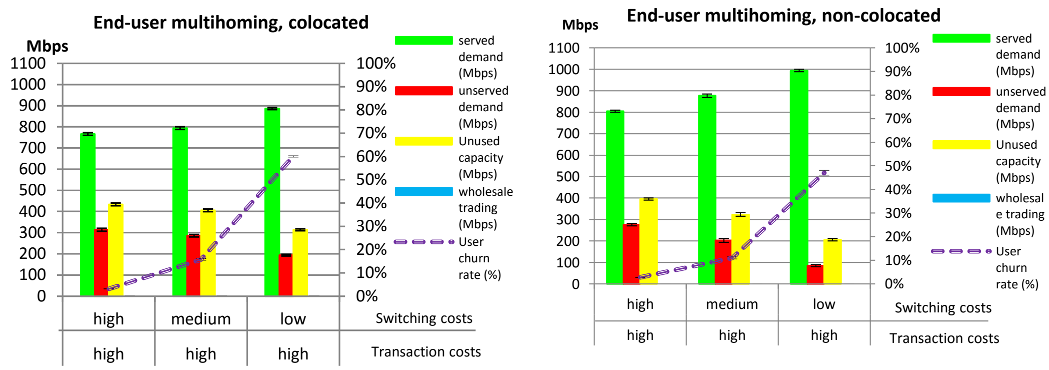

Figure 25. Simulation results of end-user multihoming

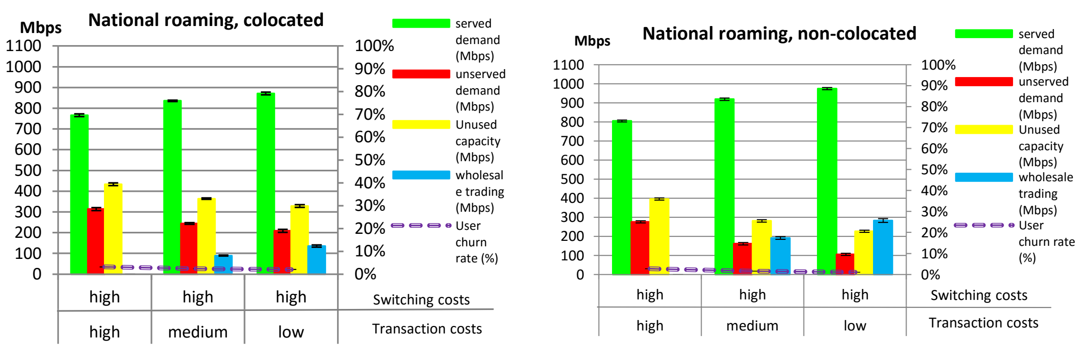

Figure 26. Simulation results of national roaming

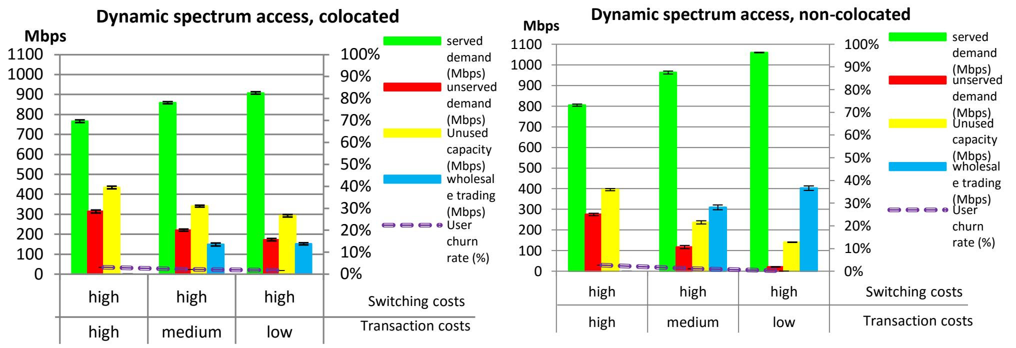

Figure 27. Simulation results of DSA

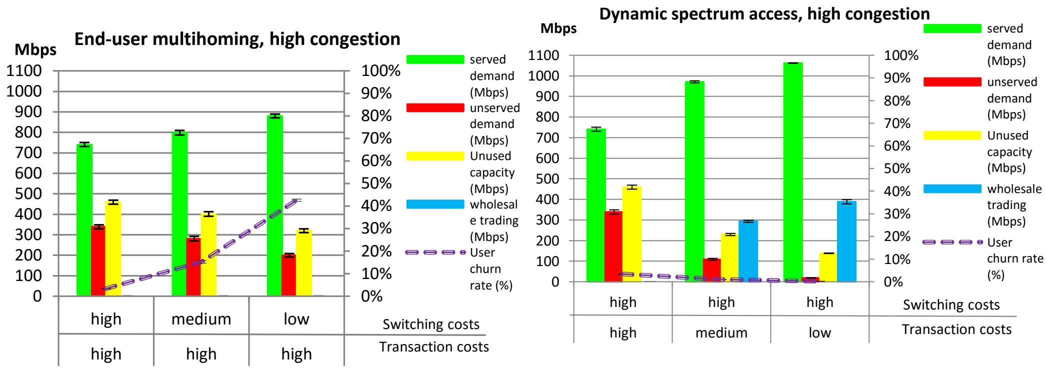

Figure 28. Simulation results of end-user multihoming and DSA with high congestion

Table 11. Observations

Observations	DSA	National roaming	End-user multihoming
Simulation performance	Most efficient in non-colocated topology and high congestion	In par with other mechanisms in colocated topology	Slightly more efficient than national roaming
Main strategic challenge	Business and technical coordination between MNOs	Trust between MNOs	Reluctance of MNOs
Initial use case - indoors	Extension to femto-cellular national roaming or end-user multihoming via inter-MNO CA	Cooperative femto-cellular deployment	Competitive femto-cellular deployment
Initial use case - outdoors	-	Coverage support for entrant MNOs. Security network with foreign SIM.	High-availability MVNOs, e.g. authorities, IoT applications
Regulator's means to push mechanisms	Set quality targets. Include trading in new spectrum licenses. Establish or act as a broker.	Set coverage targets. Include national roaming requirement in new spectrum licenses and regulate roaming prices.	Set coverage (and quality) targets. Push retail competition through unbundling of subscription and device.

The simulation results indicate that DSA attains highest efficiency with non-colocated network topology (Figure 27) and high congestion (Figure 28). However, deployment of dynamic spectrum trading through DSA technologies may take a longer time since they still face technical challenges. When network topology is colocated and congestion is low, all three mechanisms behave similarly, while when topology is non-colocated end-user multihoming outperforms national roaming. Additionally, when national roaming and end-user multihoming are simulated together, the efficiency is driven by the technology with higher performance and, in general, their effect is not cumulative.

Each mechanism faces its own challenges. MNOs are reluctant to end-user multihoming, since it stimulates retail competition. Moreover, this mechanism avoids MNOs to have visibility over user behaviour and forces to develop new business models based on intense competition and metered pricing. The main challenge of national roaming is the trust required to deploy optimal routing and wholesale capacity trading which turn pricing toward an Internet like model. In the case of DSA, real-time trading requires high coordination, both from a business and technical perspectives. In general, spectrum trading initially seems more feasible for higher frequencies and indoor use cases, since they require less coordination due to shorter propagation range.

The analysed mechanisms are especially promising for indoor deployments, since small cellular networks, such as femto-cells, are typically non-colocated. Thus, national roaming may provide indoor networks a cooperative mechanism and end-user multihoming a competitive one. DSA may provide to national roaming deployment (or end-user multihoming) an extension for additional network efficiency, addressing congestion problems. In outdoor networks, national roaming may continue facilitating new MNO, while end-user multihoming may provide high-availability services, such as those related to public safety and security. Both end-user multihoming and national roaming are suitable mechanisms for a market which suffers from coverage problems.

6. Discussion

6.1 Opportunities for DSA technologies

The current static spectrum management based on exclusive and license-exempt regimes can be significantly improved by introducing a more flexible spectrum regime allowing transactions, taking carefully into account the generated interference between involved parties. DSA, which gradually decreases transaction costs and improves interference management, provides the basic conditions for the Coasean implications on policy; in other words, it gradually pushes spectrum management towards a property rights regime.

DSA technologies are still under development and cannot yet be seen as a general remedy for market efficiency. From the analysed cases, indoor deployment is most promising for DSA technologies. The coexistence of two or more systems in the same frequency band is much more feasible in indoor areas, or between outdoor and indoor areas, since these scenarios require less coordination (i.e. less effort to decrease transaction costs). However, indoor deployments which include small-cellular networks, IoT and M2M applications, are still under development.

Another interesting observation is that most DSA standards are user-centric, while most countries assign spectrum in a centralized fashion. Therefore, DSA requires spectrum reforms to succeed, especially in higher frequencies intended for new indoor deployments.

Outdoor networks also show room for improvement in allocative efficiency. However, the logic and dynamics of outdoor infrastructure is more in line with other alternative mechanisms, such as national roaming and end-user multi-homing. Only under extreme spectrum scarcity, spectrum trading may be attractive for outdoor deployment. In the case of indoor deployment, higher frequencies facilitate the local reuse of such spectrum bands. Given this, static outdoor deployment should address coverage requirements, whereas indoor and local deployments may focus on congestion. Thus, flexibility in spectrum assignment, being a property right or a flexible licensing regime, provides indoor networks with the ability to respond more dynamically to the changes in demand. Therefore, DSA technologies facilitate new indoor infrastructure deployments rather than more efficient use of the existing wide-area cellular infrastructure.

6.2 Indoor versus outdoor spectrum management

This work observes the contrasts between higher and lower frequency bands; and between indoor and outdoor network deployments. Results suggest that DSA technologies are more relevant for indoors and high frequencies due to several reasons. Publication 1 shows that DSA is especially beneficial for serving user traffic variations in local demand. Publications 2 and 3 compare the benefits of different spectrum transaction cases and conclude that indoor transactions bring more benefits than outdoor transactions. Publication 4 highlights the need for spectrum decentralization for a successful user-centric DSA deployment. Such spectrum reforms may be much more feasible in higher frequencies which have not been yet assigned to MNOs. Publication 6 also concludes that indoor deployment presents the highest potential for DSA because of the naturally non-colocated topology. In addition, it claims that DSA may extend the benefits of national roaming or end-user multihoming by solving congestion problems.

Regarding spectrum regime, Publication 1 highlights that under zero transaction costs and well defined usage externalities (i.e. interference), a property rights regime should be optimal. However, since DSA gradually decreases transaction costs and gradually improves the definition of usage rights, a flexible licensing scheme, which includes interference as a tradable characteristic of the spectrum, may be a suitable means for increasing spectrum efficiency in the shorter run.

Additionally, Publication 2 argues that a very high frequency band, such as millimetre waves, should be set license-exempt, since neighbouring networks transmitting in those frequencies generate very little interference. In practice, an exclusive and tradable local license in the millimetre wave frequency band (i.e. above 6 GHz) may have a similar impact as a license-exempt regime, since the venue owner manages the indoor spectrum. In addition, co-primary (indoor) and primary-secondary (outdoor-indoor) regimes are suitable for middle range frequencies (e.g., 3-6 GHz). Finally, exclusive licensing is most suitable for lower frequencies (e.g., below 2 GHz). These three categories may also be mapped to the three tiered sharing framework: dynamic exclusive sharing, hierarchical sharing and open access.

Publication 4 emphasizes the need for spectrum decentralization to facilitate a user-centric DSA adoption. Even though an operator-centric DSA deployment brings some benefits to the end-user, user-centric innovation may be more beneficial, especially at local network deployments, reducing entry barriers and improving the service supply. Thus, this thesis suggests a decentralized spectrum policy for assigning new spectrum, especially in the higher frequency bands. Along this line, the regulator should opt for an ex-ante definition of spectrum trading and sharing rules to increase coordination and decrease transaction costs, especially regarding the interference. Such regulation favours new entrants against an ex-post antitrust approach, which permits incumbents to enjoy their dominant position.

Publication 6 suggests that the three compared mechanisms increase allocative efficiency dynamically. While national roaming and end-user multihoming address especially coverage problems and increase efficiency in the existing infrastructure (shorter term), DSA addresses congestion in new indoor infrastructure (longer term). In the licensed bands, spectrum transactions may temporally increase the utilization level of base stations. However, in practice, this is more challenging since outdoor networks have been deployed for static spectrum and network capacity. In addition, alternative mechanisms, such as national roaming or end-user multihoming, are more suitable for outdoor infrastructure for addressing coverage problems.

6.3 User-centric versus operator-centric innovation

This thesis analyzes the relationship between market structure and DSA. So far, NRAs have typically assigned the mobile spectrum to few MNOs, mainly because of large investment requirements. DSA permits NRAs to drive a more decentralized spectrum policy to allow new entrants and new service innovation. The little interest of MNOs towards DSA suggests that user-centric innovation is more likely to come from new actors.

From a regulatory perspective, the main objective is to maximize the value obtained from spectrum. With this purpose, spectrum policy should stimulate both operator-centric innovation (outdoor) and user-centric innovation (indoor).

Therefore, DSA and the other analysed mechanisms such as end-user multihoming, may provide NRAs a tool for evolving from closed to more open innovation systems. NRAs should keep in mind that user-centric focus is applicable to new infrastructure, for instance indoor and emergent services, rather than to the already deployed cellular networks which have so far followed the operator-centric innovation process.

6.4 Limitations

This thesis analyses different DSA scenarios at system level, with special focus on the following comparisons: indoor versus outdoor deployments; high versus low frequency bands; and user-centric versus operator-centric innovation. However, the present work does not consider in detailed the emerging IoT services and the possible interaction with fixed networks. In addition, this thesis does not compare different indoor deployments (e.g., small-cellular networks against Wi-Fi), for instance, by doing a cost-benefit analysis for each option. Since this thesis focuses on regulation, it was a strategic choice to leave certain analyses out of scope. In any case, the reader is encouraged to read additional literature (e.g., Kang, 2014) for a comprehensive understanding of the topic.

Finally, this thesis has not included in detail the usage patterns and user behaviour; and therefore the main conclusions are qualitative rather than quantitative.

6.5 Future work

Dynamic spectrum management and consequently spectrum regulation are still areas under development. This thesis provides some guidance for future spectrum regulation. Concrete solutions and spectrum regimes will depend on the progress of DSA technologies; for instance, the millimetre wave solutions and more generally on the small-cells or alternative indoor networks, and finally on the emergence of new IoT and M2M services.

Future work may include a more detailed analysis on new services and applications, their related spectrum requirements and concrete policy implications. In fact, DSA can play an important role in emerging services such as smart city applications related to energy, transportation, security applications, etc. Each application may have specific challenges, since each one is related to other industry. For instance, while in general a property rights or flexible licensing regimes may stimulate innovation, some particular emerging services require further analysis on a case-by-case basis.

Regarding the employed methods, this thesis combines agent-based and system dynamics modelling for studying the implications of DSA for regulation. Such combination may be suitable for analysing other disruptive technologies such as those emerging services mentioned above.

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Spectrum management is in the core of Internet access and therefore of vital importance for assuring the most important processes of our society. The increasing demand for new services makes the spectrum scarcer and urges national regulatory authorities (NRAs) to promote a more efficient spectrum usage. In this context, dynamic spectrum access (DSA) technologies and the related dynamic spectrum management (DSM) provide new ways of managing spectrum, by dynamically reassigning the underutilized spectrum (i.e. white spaces).

This thesis employs a combined approach consisting of agent-based modelling and system dynamics to study spectrum management by means of dynamic neo-institutional economics. Thus, this work combines transaction cost and evolutionary economics into the modelling and analysis of the constantly evolving ICT ecosystem.

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