Metadata of the chapter that will be visualized in SpringerLink

Book Title	Cognitive Radio Policy and Regulation
Series Title	4748
Chapter Title	Economic Aspects of CR Policy and Regulation
Copyright Year	2014
Copyright HolderName	Springer International Publishing Switzerland

Corresponding Author	Family Name	**Nolan**
	Particle	
	Given Name	**Keith**
	Suffix	
	Division	CTVR/The Telecommunications Research Centre
	Organization	Trinity College Dublin
	Address	Dublin, Ireland
	Email	knolan2@tcd.ie
Author	Family Name	**Gonçalves**
	Particle	
	Given Name	**Vânia**
	Suffix	
	Division	
	Organization	iMinds-SMIT, Vrije Universiteit Brussel
	Address	Brussels, Belgium
	Email	vgoncalves@gmail.com

Abstract

This chapter turns to evaluation of techno-economic aspects of CR development and regulation, considering both the attractiveness of existing regulatory frameworks and the benefits of creating the new ones. This is important since it may be shown that the regulatory framework may have significant impact on economic benefits and viability of CR market adoption. Section 4.1 offers discussion of the potential for new business cases centred on the use of white space spectrum in the context of cellular networks. Section 4.2 is focusing on business scenarios and models for use of GDBs in TV white spaces. The following Sect. 4.3 provides a primer regarding the dynamics of the wireless communication market and how these can strongly influence the success or failure of a new technology. Section 4.4 considers potential business scenarios for spectrum sensing based on a set of parameters—ownership, exclusivity, tradability and neutrality. Section 4.5 looks at the prospects of business case for CR against the uncertainties of the spectrum market and opportunistic spectrum access circumstances. The chapter is concluded with the techno-economic analysis and case study in Sect. 4.6 that contemplates economic value of CR and secondary access. This builds a solid basis for answering the ultimate questions about business viability of CR, including considerations of cost versus capacity, investments, uncertainty and risk.

Chapter 4
Economic Aspects of CR Policy and Regulation

Keith Nolan and Vânia Gonçalves

Abstract This chapter turns to evaluation of techno-economic aspects of CR development and regulation, considering both the attractiveness of existing regulatory frameworks and the benefits of creating the new ones. This is important since it may be shown that the regulatory framework may have significant impact on economic benefits and viability of CR market adoption. Section 4.1 offers discussion of the potential for new business cases centred on the use of white space spectrum in the context of cellular networks. Section 4.2 is focusing on business scenarios and models for use of GDBs in TV white spaces. The following Sect. 4.3 provides a primer regarding the dynamics of the wireless communication market and how these can strongly influence the success or failure of a new technology. Section 4.4 considers potential business scenarios for spectrum sensing based on a set of parameters—ownership, exclusivity, tradability and neutrality. Section 4.5 looks at the prospects of business case for CR against the uncertainties of the spectrum market and opportunistic spectrum access circumstances. The chapter is concluded with the techno-economic analysis and case study in Sect. 4.6 that contemplates economic value of CR and secondary access. This builds a solid basis for answering the ultimate questions about business viability of CR, including considerations of cost versus capacity, investments, uncertainty and risk.

K. Nolan (✉)
CTVR/The Telecommunications Research Centre, Trinity College Dublin, Dublin, Ireland
e-mail: knolan2@tcd.ie

V. Gonçalves
iMinds-SMIT, Vrije Universiteit Brussel, Brussels, Belgium
e-mail: vgoncalves@gmail.com

A. Medeisis and O. Holland (eds.), *Cognitive Radio Policy and Regulation*,
Signals and Communication Technology, DOI: 10.1007/978-3-319-04022-6_4,

4.1 The Emergence of Whitespace Network-Based Business Cases

Keith Nolan and Jacek Kibilda

CTVR/The Telecommunications Research Centre, Trinity College Dublin, Dublin, Ireland

4.1.1 Introduction

The emergence of whitespace networks, and whitespace communications in general, provides an opportunity to, at least partially, meet the ever-growing demand for mobile data communication and to support new business cases. Many whitespace network solutions proposed so far realise coordination and rendezvous over licensed or unlicensed spectrum. In this chapter we explore a protocol for networks that rely solely on whitespace spectrum. AQ1

This work builds on [1], to where the reader is guided for further information beyond this chapter.

The proposed protocol allows both communication to the broader network (via the access point) and direct device-to-device links over whitespaces. To showcase the capabilities of the proposed solution we investigate a proof-of-concept software defined radio experiment. Using the experimental platform, we have evaluated the overheads of whitespace operation, which come in the form of an extra delay in association and a throughput loss of approximately 15 % of that achievable with licensed spectrum. The goal is to provide the groundwork for new business cases based on the use of wireless communications systems operating in whitespace spectrum. AQ2

Studies show that 100 and 58.6 % of Internet traffic generated by smartphones and PCs, respectively, is carried over wireless interfaces. 69 and 57 % accounts for Wi-Fi, which operates in unlicensed spectrum, and 31 and 1.6 %, respectively, accounts for cellular interfaces operating in licensed spectrum [2]. These numbers show that licence-exempt (or unlicensed) spectrum already plays a vital role in meeting the capacity challenge related to the mobile data crunch. The amount of transmitted mobile data will continue to grow, at an estimated compound annual growth rate (CAGR) of 78 % from 2011 to 2016 [3]. To support this demand we need even more pervasive Wi-Fi deployments, which are, however, limited by interference stemming from unlicensed operation.

Another possible solution to meet this demand is to increase the cellular network's density, which comes in the form of small cells (e.g. femtocells) that operate in a licensed spectrum underlay to macro cells. However, there is an alternative at hand—whitespace spectrum and CR technologies.

Whitespaces are defined by the Internet Engineering Task Force (IETF), as portions of the frequency spectrum that are assigned to a particular use but are unoccupied at specific locations and times [4]. This definition implies the existence of incumbent services, which have prioritised access to the spectrum and whose signals should be protected from harmful interference stemming from other whitespace-operating services. An example of whitespaces are TV whitespaces (TVWS), which are portions of the frequency spectrum made available after the digital TV switchover in the UHF/VHF spectrum in certain geographical locations. To protect incumbent services of the UHF/VHF spectrum, such as Digital Video Broadcasting—Terrestrial (DVB-T), communications regulators in the US and Europe selected a GDB (GDB) technique as the most feasible, and, thus, the only mandatory solution [5, 6]. Hence, devices that desire to operate in the TVWS will have to interact with GDBs to obtain complete information about spectrum availability.

One of the objectives of the TVWS regulation in Europe was to allow high efficiency and flexibility in spectrum usage at the widest possible ranges of uses and technologies [5]. CRs are ideally crafted for this purpose, as they are wireless communication systems aware of their environment, which learn from this environment and adapt to any statistical variations in it, to achieve, for example, higher reliability or spectral efficiency [7]. A number of scenarios are envisaged for CRs operating in TVWS, for example, remote sensing and machine to machine communications, indoor/outdoor local area networks or ad-hoc (direct) communication between portable devices [5]. Realisation of these scenarios will require a certain level of control and coordination between CR devices; in other words, the formation of a network. In [8], networks over TVWS are formed based on an enriched Wi-Fi protocol and spectrum availability information determined based on local spectrum sensing. The latter, however, does not conform to the subsequent decisions made by the regulators to mandate GDBs as a mean for protection of incumbent services. A more conservative approach to formation of networks operating over TVWS is to rely on out-of-band control messages using existing radio access technologies in licensed or unlicensed spectrum, e.g. [9, 10].

Drawbacks of this approach include the need for additional channels in some licensed band, or reliance on the congested ISM band. Having in mind these problems and the recent decisions of the major communications regulators, our goal is to design a network that relies solely on whitespace spectrum.

This section focuses on the design, development and evaluation of a spontaneously created whitespace network, i.e. a network which relies solely on whitespace spectrum and an outline of potential business cases.

In Fig. 4.1, we depict an example instance of a whitespace network where control channels are deployed dynamically whenever and wherever possible to enable coordination and rendezvous between devices operating in whitespaces. Some of these devices, which have the capability to directly query the GDBs, may self-select to become whitespace access points, to arbitrate and control whitespace communications of other devices (subordinate devices). The subordinate devices, which could be, for example, sensors that belong to a home automation system, would typically have no means of communication with the GDBs. Moreover, these subordinate devices would use whitespace spectrum intermittently to connect to

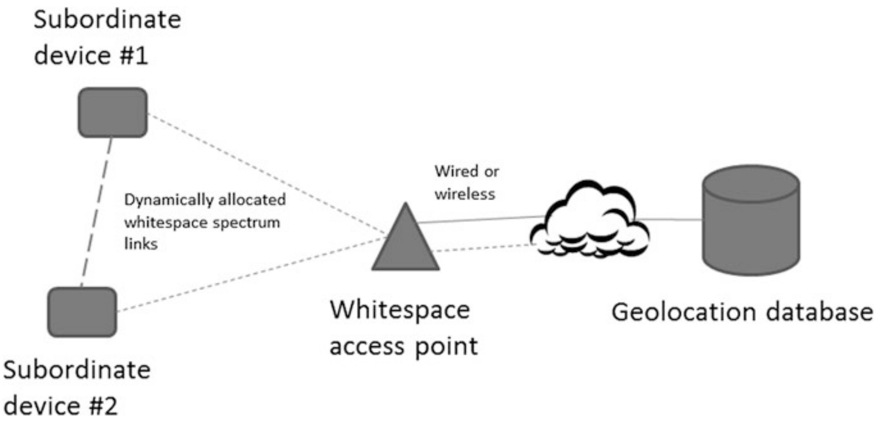


Fig. 4.1 Example instance of a whitespace network

the internet (via the access point's backhaul), or to perform direct device-to-device communications.

Specifically, we examine a protocol that enables operation of whitespace networks with the use of GDBs, dynamic control channels deployed depending on the whitespace spectrum availability, cyclostationary signatures used for control channel identification, and performance monitoring to improve the whitespace allocation. The proposed protocol allows both communication to the broader network (via the access point) and direct device-to-device links. As part of our work, we have implemented a proof-of-concept software defined radio experiment that showcases the capabilities of the proposed solution. Using the experimental platform we have evaluated the trade-offs related to operating exclusively in whitespaces, without relying on licensed spectrum for control channels. These trade-offs come in the form of an extra delay in the order of hundreds of milliseconds and a throughput of up to 85 % of that achievable with licensed spectrum links.

4.1.2 Key Enablers of Dynamically Created Whitespace Networks

In order to build a network that solely operates in whitespace spectrum one needs to overcome a challenge related to the protection of incumbent services and to ensure coordination and rendezvous among the whitespace devices. In our work we overcome these challenges by relying on: GDBs, dynamic control channels, and cyclostationary signatures. In the following we give a brief introduction to each of the above mentioned concepts.

4.1.2.1 GDBs

In principle, a GDB is a database that contains up-to-date information on the spectrum available at any given location and time instance, enriched with other types of related information, such as the duration of availability, maximum effective radiated power permitted, or adjacent channel leakage ratio [4]. GDBs are populated with information created by modelling the propagation of known incumbent transmitters (for example as in [11]), where the model's parameters and algorithms are selected by the authority operating the database. Such whitespace information is provided to the devices on a temporal basis, and whitespace devices need to periodically request the information, where the period is set according to the requirements of the local regulator. Whitespace devices are not allowed to transmit until they have successfully received up to date information on the available channels. When a device has no possibility to directly (without the use of whitespaces) connect to the database, another whitespace device may act as a proxy for the device's queries [4]. In recent years, communication regulators world-wide have mandated GDBs as the only required solution to protect the incumbent services in the TV whitespaces, e.g. [5, 6]. Hence, in our work, we rely solely on GDBs to protect incumbent services and to provide information on the whitespace spectrum opportunities.

4.1.2.2 Dynamic Control Channels

In general, control channels are deployed to organise mobile devices and convey network control information, for example, identification, synchronisation, channel allocations (restrictions) or network policies. In order to facilitate the distribution of control channels for CRs the European Telecommunications Standards Institute Reconfigurable Radio Systems Technical Committee (ETSI TC RRS) has recommended two ways forward: (1) out-of-band, where the control channels are distributed over a globally dedicated physical channel, (2) in-band, where the control channels are transported over a specific radio access technology using separate or an existing control channel. The former has the disadvantage of requiring additional spectral resources and global harmonisation.

The latter is a viable solution for systems operating in licensed bands with fixed operational frequency and high level of coordination, which use whitespaces only temporally to extend network capacity. However, for systems that intend to rely solely on whitespaces it poses some difficulties, as the allocated operational frequency may change depending on the incumbent user behaviour. Herein, we propose a reliable solution for an in-band control channel in whitespaces, which is dynamically deployed depending on the whitespace availability. The centre frequency of this control channel is allocated based on the GDB information. Subordinate whitespace devices will acquire this centre frequency through the detection of a physical layer signature inserted in the transmitted waveform of the control channel, as described in the following subsection.

4.1.2.3 Cyclostationary Signatures

Communication signals of contemporary radio systems have many inherent periodicities which come as a consequence of coupling stationary signals with, for example, periodical waveforms or training sequences. These periodicities may also arise as a consequence of typical communications procedures, such as sampling or multiplexing. One way to observe them is to perform first order and second order cyclostationary analysis to discover specific correlation patterns in time or in the spectral domain of the signal, respectively. However, these periodicities may also be intentionally embedded into the physical signal as so called cyclostationary signatures. A cyclostationary signature can be inserted in an OFDM signal by mirroring one or more selected subcarriers. The arising periodicities can be observed through the spectral correlation function (SCF), at a cyclic frequency that corresponds to the ratio of the spectral distance between the mirrored subcarrier set and the useful symbol duration. Cyclostationary signatures can be detected by sweeping across the bands of interest and performing circular correlations on the received signal samples. When the signature is present in the received signal, a spike in the SCF is observed and the receiver can start decoding the received signal. In case the signature can no longer be detected, the receiver will start sweeping the band until the signature is found again and a new centre frequency is determined. The cyclostationary signatures can be used to identify specific radio systems, specific access networks in coalitions of access networks or to enable rendezvous in dynamic spectrum access networks.

4.1.3 Addressing the Technical and Business Challenges

In order to meet the challenges discussed above, we have designed a dynamic spectrum access and allocation protocol (DSAAP). This allows for the coordinated operation of a dynamic spectrum access network deployed in whitespaces for OFDM-based systems. In general, the DSAAP operations are performed as follows (the subsequent steps are also depicted in Fig. 4.2):

(1) When a new whitespace device that is able to connect to the Internet is switched on, it checks with the GDB for any available frequency channels;
(2) If a channel is found, the device locally reserves this particular channel for secondary spectrum operation and becomes a whitespace access point. A whitespace access point periodically transmits a broadcast signal, which announces the availability of the whitespace access point in the specific frequency channel to any other whitespace devices. The transmitted broadcast signal has an embedded unique cyclostationary signature, which can be assigned as in [12] and detected with a cyclostationary feature detector

Layout: T1 Standard SC | Book ID: 318863_1_En | Book ISBN: 978-3-319-04021-9
Chapter No.: 4 | Date: 24-12-2013 | Page: 7/74

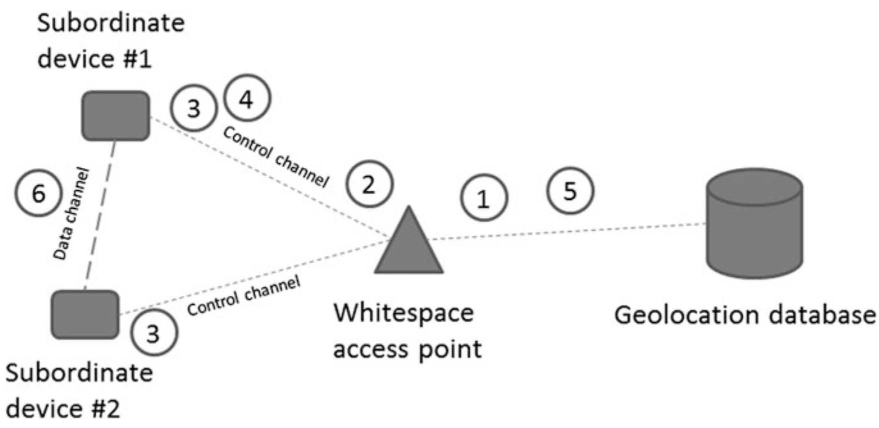


Fig. 4.2 Steps involved in the DSAAP operation

described earlier. The broadcast signal carries information required to coordinate the cell's operation, such as the rendezvous channel or temporal spectrum allocations for whitespace devices;

(3) When another whitespace device, which has no Internet connectivity, arrives in the coverage region of the whitespace access point, it sweeps the whitespace bands to detect the broadcast signal. If the broadcast signal is detected, the device decodes it and reads the cell's information. Then, using the rendezvous channel it associates with the access point and stays on the detected channel listening to the broadcast signal, becoming a subordinate device. If another whitespace device arrives, a similar procedure follows;

(4) Whenever one of the subordinate devices requires transmission to another local device (or to the Internet), it requests (using the rendezvous channel) whitespace operation;

(5) The access point queries the database and allocates a whitespace channel that meets the demands of the requested transmission, indicating to both the whitespace devices the centre frequency, assigned bandwidth, spectrum availability determination period, and the peer device's MAC address for direct device-to-device transmission;

(6) The information is embedded to the control channel and both devices receiving the information reconfigure their radio front-ends to operate on the specific centre frequency and start the data transmission. During the data transmission, the subordinate devices constantly monitor the connection quality. If the connection quality is sufficient and the spectrum availability determination time elapses, both devices leave the transmission channel and repeat the whole procedure. However, if during the transmission one of the devices observes a significant drop in the connection quality (by means of, for example, an increase in the frame error rate), then that device reconfigures to

the rendezvous channel and sends a report to the access point. The access point will use the measurement information conveyed in the report to improve any subsequent data channel allocations.

The use of licenced spectrum on a nationwide basis can introduce significant cost overheads due to licencing fees in exchange for exclusivity. The other extreme is licence-exempt usage for type-certified devices and non-exclusivity however the trade-offs include low transmission power restrictions, narrow spectrum segments, and uncoordinated usage potentially resulting in interference. A rules-based approach based on TVWS relaxes the requirement for type certification. Coupled with dynamic control channels and database coordination, the viability of new business cases relying on a flexible and scalable wireless communications architecture can be increased.

If pitched as complementary technologies to cellular network deployments, TVWS-based network deployments can support long range, latency-tolerant applications and short range/high building penetration applications. Examples include machine to machine communications, remote sensing, and telematics, wireless data storage and backups where periodic high-bandwidth data transfers can be performed over short ranges, security in remote areas, mobile healthcare e.g. conveying in-ambulance image and patient monitoring information to the emergency ward.

4.1.4 Conclusion

In this section we presented a wireless network, where all the control and data communications occur using whitespace spectrum. We have outlined a number of potentially viable market opportunities for TVWS networks and have described an access method and spectrum allocation protocol to help enables reliable control channel deployment and efficient data communication over whitespaces. Moreover, our discussion focuses on the use of direct device-to-device links over whitespaces. The goal of our work was to examine how networks relying solely on whitespaces could be used to build the groundwork for future radio systems thus helping to increase the attractiveness of this approach to the market.

Acknowledgments The material is based upon works supported by the Science Foundation of Ireland under grants no. 10/CE/I1853 and 10/IN.1/3007, Framework Programme 7 (FP7) CREW project under grant no. ICT-258301, FP7 CogEU project under grant no. ICT-248560. This work was also supported in part by COST Action IC0905 TERRA through a Short Term Scientific Mission.

Layout: T1 Standard SC | Book ID: 318863_1_En | Book ISBN: 978-3-319-04021-9
Chapter No.: 4 | Date: 24-12-2013 | Page: 9/74

4.2 Business Scenarios and Models for Use of GDB in TV White Spaces

Gintarė Sukarevičienė[1, 2], Vladislav V. Fomin[1] and Mike Katsigiannis[3]

[1]Vytautas Magnus University, Kaunas, Lithuania
[2]Vilnius Gediminas Technical University, Vilnius, Lithuania
[3]Aalto University, Espoo, Finland

Geolocation Databases (GDB) as enabler of CR operation is one of the major elements of Dynamic Spectrum Access Information Infrastructure (DSA II). Regulators across the globe have been showing a preference towards a GDB approach for the so-called TV White Spaces (TVWS), as it becomes essential to ensure overall efficiency of radio spectrum for the existing and emerging wireless communication services. Unfortunately, despite the recent advancements in TVWS GDB business scenarios, uncertainties exist with regard to the future technologies and value network configurations for GDB use and access in TVWS spectrum range and elsewhere, for. e.g. in some specific spectrum bands such as bands that are allocated for public Digital Audio Broadcasting (DAB) services (e.g. VHF T-DAB band), 1452–1492 MHz (e.g. L band), radar bands and fixed service bands.

Thus, while future business models are a common concern of private operators and regulatory frameworks are under discussion in e.g. European Commission and the major Standards Development Organizations (SDOs), such as ETSI, CEPT, CEN, it becomes important to analyze the economic feasibility of GDB use and access from different points of view within the future DSA II architectures and services. It remains to be seen how collaboration among different stakeholders can be established around the use of GDB, for example:

- For the development of which (novel) services GDB will play a crucial/enabling role?
- How the standardization of GDB access protocols for different wireless services will be unfolding?
- How acceptable to different stakeholders business models for GDB operation and access can be found/developed?

All these questions require both technology-oriented and business-oriented analysis and modeling.

4.2.1 The Concept of DSA II

The concept of Dynamic Spectrum Access (DSA) stands for the opposite of the current static spectrum management policy for particular users in particular geographic areas, and has a large potential to become the crucial enabler of the

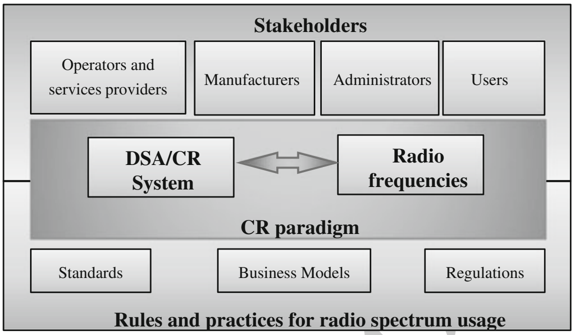


Fig. 4.3 DSA II infrastructure [14]

spectrum reform. Although DSA has broad connotations that encompass various approaches, there are only few ways to get more spectrum: to reallocate it or to allocate unused spectrum for more efficient use, as spectrum is of fixed nature and cannot be grown, manufactured or imported. In this context, DSA could be considered as enabler of R capability to access and transmit in unoccupied spectrum (white spaces) while minimizing interference with other signals in the spectral vicinity [13].

Development of DSA II requires creating a functional techno-economic model, which describes and analyzes the different stakeholders' interrelationships as well as the technologies, policies, and services, as depicted in Fig. 4.3 [14]:

- At the top of Fig. 4.3, possible stakeholders (directly and indirectly impacted by DSA II) and their roles within the wireless telecommunication services, such as: operators and services providers, manufacturers, administrators and users;
- At the bottom of Fig. 4.3, elements which define the rules and practices (principles) for radio spectrum usage, such as: standards, business models and regulations;
- In the centre of Fig. 4.3, the main elements of the CR paradigm, such as: DSA/CR system and its opportunistic access to radio frequencies.

The Fig. 4.4 depicts the potential relationships among different elements of DSA II, for e.g. one of the ways in which relationships between different elements within DSA II could be established is described below:

- direct relationships (wide double arrows) between CR paradigm and radio frequencies, regulations and standards, administrators and operators, service providers. For instance, incorporation of CR technology into existing frequencies, such as TV White Space (TVWS), radar bands, etc.;
- co-dependence (double arrows) between business models and telecommunication operators (e.g. DNA, Elisa, Tele2), service providers (e.g. Wireless Internet Service Providers, WISP), and users (e.g. primary and secondary users), and wireless device manufacturers (e.g. Microsoft, Motorola);

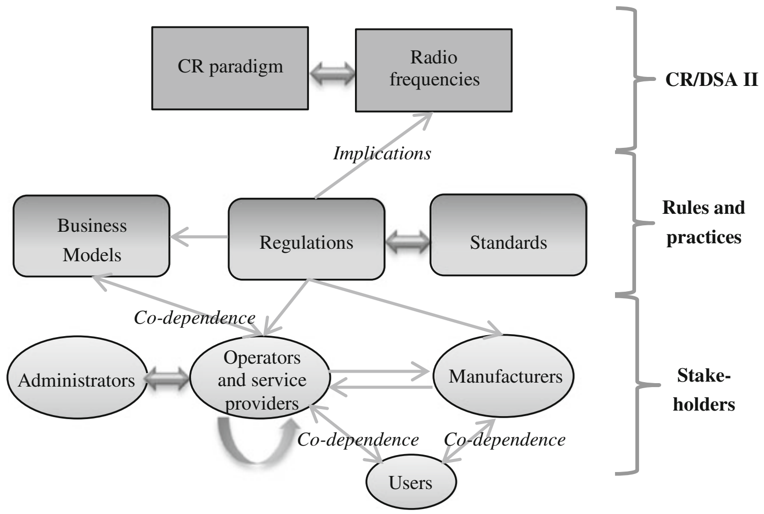


Fig. 4.4 Relationships among different elements of DSA II

- implications of regulations to radio frequencies: the need for the use and assessment of frequencies to be guided by various rules in order not to interfere with services operating on adjacent frequencies. For example, large portions of VHF/UHF TV bands become available on a geographical basis and regulatory entities are already moving towards CR allowance to operate in licensed television spectrum bands but it must not interfere with primary users.

4.2.1.1 Standards and Regulations Within DSA II

In this way, as described above, standards and regulations can be identified as one of the major element of DSA II, as they somehow relate with all other elements of DSA II as shown in Fig. 4.4. This also can be seen in the standardization domain, where three major groups have emerged to work on relevant technologies and architectures [13]:

- IEEE 802.22 and related research that aim to provide DA to vacant TV spectrum;
- SCC41 (formally P1900) working groups;
- ETSI's Reconfigurable Radio Systems Technical Committee on CRs and SDRs.

In general, there are many regulatory bodies that show interest in developing standards or defining norms and regulation for one or another aspect of CR-related telecommunications [15], as reviewed in detail in Sect. 1.4.

4.2.2 The Concept of GDB Within DSA II

Geolocation Database (GDB) access can be defined as the capability of a device to know its geographical position and transmit this information to a database which identifies the suitable channels and transmit powers that the device can use in its current location—other essential element of DSA II [16]. In this way GDB:

- administers principles of spectrum use among regulators, broadcasters, TVWS industry (e.g. TV White Space Devices, TV WSDs), and other users (e.g. Program Making and Special Events, PMSE) in practice.
- controls the frequencies used by TV WSDs and their transmission power so that they do not interfere other wireless communication systems, such as terrestrial TV or radio microphones [17].

Recognizing the importance of the GDB within DSA II (see Table 4.1), business scenarios for GDB for the operation of CR are proposed (Fig. 4.5), as they stand as a basis for further research on DSA and business model related issues (e.g. GDB that is not a big component of the DSA II itself but it is in the center of the market structure), taking into account both technical and business-oriented parameters:

- *Restricted market scenario* (on the top-left corner of Fig. 4.5): it refers to outsource-based business model configuration [18]. The main role here is played by a third party, which is aided by administrator/operator who develops and operates GDBs. It is a solution of generalized GDB that supports all databases.
- *Flexible market scenario* (on the top-right corner of Fig. 4.5): it refers to the user-based and operator-based business model configurations [18]. The main roles here are played by the user and operator, although the available channels are managed by GDB: flexible bands (flexible operators), flexible services (flexible user).
- *Competitive market scenario* (on the bottom-right corner of Fig. 4.5): it refers to the user-based business model configuration [18]. The main role here is played by the users' devices (TV WSDs) in handling available channels. Although it could benefit while introducing the concept of GDB for the operation of CR in TVWS, it could create problem to the existing communication patterns.
- *Hybrid market scenario* (on the bottom-left corner of Fig. 4.5): it refers to the broker-based business model configuration [18]. The main role here is played by TVWS broker by distributing available channels to various service providers.

The business scenarios matrix (Fig. 4.5) is based on two dimensions: technical architecture and industry architecture, (also is relates with previous work [18]):

- *technical architecture* refers to the technology which determines the differences between existing and future architectures: what is the role of GDB in enabling various wireless communication services, how clients/devices of different wireless services will be accessing the same/shared GDB. Based on this parameter GDB scenarios could be split between: centralized technical architecture scenario, and decentralized technical architecture scenario.

Table 4.1 SWOT analysis of GDB

Strengths	Weaknesses
• Interference control • Global view on a radio environment • Followed primary spectrum usage activities • Sufficient computing power to make complex computations • Identification of secondary user's location and available frequency on that location • Lower cost-per-bit	• The changes of the primary spectrum usage have to be updated • Spectrum allocation and radio resource management must be balanced • Band identification, management, control and cost allocation must be standardized to support successful development of CR • Reduced barriers to entry for smaller operators • Higher costs of devices, to validate hardware to meet specific regulatory requirements
Opportunities	**Threats**
• Improved access to wireless services and applications • New market opportunities • Start of commercial utilization of WS • Realization of the CR paradigm for WS in other bands • Greater competition that could lead to value-added services and lower costs • Introduce realization of the CR paradigm for WS in other bands	• Additional information security issues in traditional wireless communication • Lower communication QoS because of possible interference • Reduction in battery life for the new technologies • Market shift from hardware to software manufacturers • More complex regulatory regime

Layout: T1 Standard SC | Book ID: 318863_1_En | Book ISBN: 978-3-319-04021-9
Chapter No.: 4 | Date: 24-12-2013 | Page: 14/74

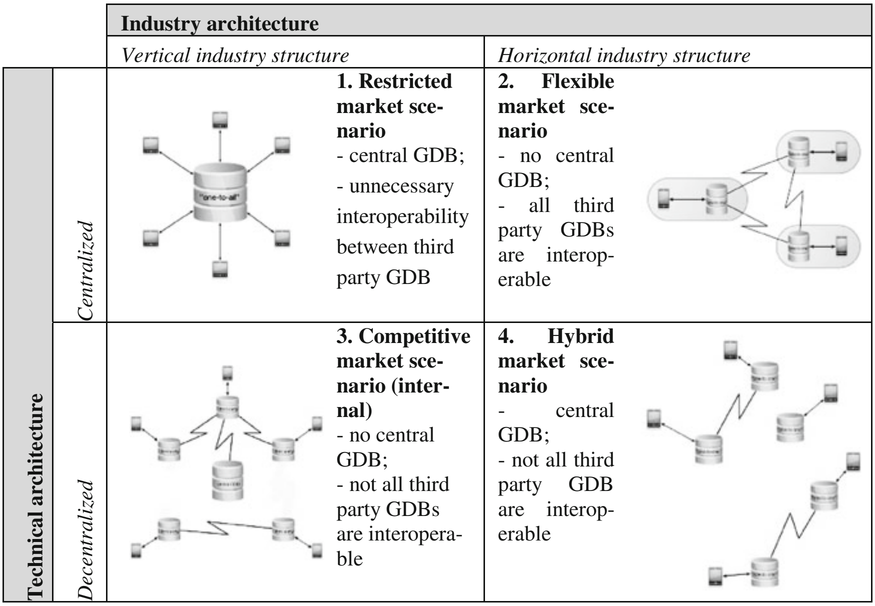


Fig. 4.5 Business scenarios matrix

- *industry architecture* relates to the scope of the GDB in terms of markets and industries in which it competes as well as to the ways in which their roles are combined. The main question here is how GDB business model that would be acceptable/make sense to different stakeholders can be found. Based on this parameter all GDB scenarios could be split between: vertical industry structure scenario, and horizontal industry structure scenario.

Therefore, the *scenarios of* centralized technical architecture refer to the standardized technologies which offer good performance and can scale different use cases and environments there large access network operators are preferred who integrates local area networks into their existing network infrastructure.

On the contrary to scenarios of centralized technical architecture, the *scenarios of* decentralized technical architecture refer to the situation where the access providers may be small and even local. This may lead to the more complex deployments of DSA II.

The scenarios of vertical industry structure refer to the situation when there is one entity (or a group of entities that serve specialized needs to each other) which supports GDB business activity that meets specialized needs of one specific industry, and also is involved in other parts of communication process. This could help eliminating some of the complexity related to the linking of two technologies and business issues related to that technologies, as each generation of technology is as an outcome of tinkering with and meshing together previously unrelated and untried technological combination [19].

Finally, the *scenarios of horizontal industry structure*, by comparison with scenarios of vertical industry structure, are focused on a wider range of GDB business activities of broader range of services and applications grouped according to common requirements to the larger group of customers.

Specific scenarios also encounter specific issues which require specific regulation and standardization as development of DSA II requires creating a functional techno-economic system.

4.2.3 Techno-Economic Studies of Business Scenarios

Techno-economic studies can be conducted using a “bottom-up” approach. This approach firstly focuses on analyzing either new technology architectures (e.g. CR) or industry architectures, from a small group of established stakeholders’ point of view, and then the analysis is expanded to create the whole environment of the new evolving technologies and industry architectures. The purpose of the “bottom-up” paradigm is to express more complex variety of detailed business concepts and problems areas from a set of strictly defined concepts of technology, thus for e.g. firstly technology is chosen and after that deciding how to create the whole environment of new evolving technologies and industry architectures.

In general, techno-economic modelling case studies could be classified into two types [20]:

- *Technology-oriented case studies:* analysis and comparison of emerging technologies (focus on network investments and network related OPEX, and less focus on business models, competition, services);
- *Business model-oriented case studies:* analysis and comparison of alternative business models (focus on value network configurations and revenue sharing models, and less focus on technology as proper business models are essential).

In this light, since DSA II is a highly complex phenomenon, as the starting point in the following paragraphs the techno-economic modelling method is used only for evaluating restricted market scenario from the operator point of view (business model-oriented case studies), where GDB is provided. In this model, the responsibility of protecting incumbent’s users from interference is taken by third parties, while the central GDB operation is kept under surveillance by the administrator/operator who is aided by the regulatory body, as described in ECC Draft report 185 [21]. In this case, each geographical area can be controlled by its own database enabling a distributed operation, as well as allowing specific bands to be tradable under the operating and communications on different CR protocols and standards.

Layout: T1 Standard SC | Book ID: 318863_1_En | Book ISBN: 978-3-319-04021-9
Chapter No.: 4 | Date: 24-12-2013 | Page: 16/74

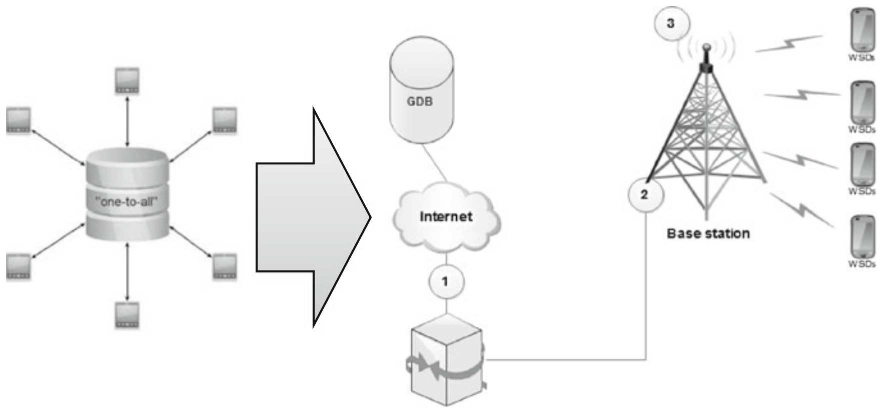


Fig. 4.6 Restricted Market Scenario from the operator point of view

4.2.3.1 The Case of Operator and Service Provider

The main research question is whether operators have direct relationship with the users or not. There is the threat for operators that they may miss their strong position in the market because virtual operators may become real network operators [22]. Due to this, it becomes important to analyze which role has a GDB operator and service provider in the value network. Nevertheless, one thing is clear: the stake of the existing and new operators, as well as service providers, is if they can reach the most positive value through DSA II enabled services that promise a wide range of new opportunities to consumers [14].

To start with, within restricted market scenario (from the operator point of view), there can be two ways (business models) in which GDB exchanges spectrum information with WSDs (see Fig. 4.6):

1. Mobile Network Operators (MNO) offers GDB-based mobile services.
2. GDB operator offers services to end-users utilizing MNO's network.

In the first case, the GDB operator (or spectrum operator) is not a threat to MNO, but instead they are cooperators, because spectrum operator "gives" frequencies to MNO who provides access to WSDs (end-users) in order to get GDB information. In this way, the role of spectrum operator is to connect to the MNO's network for offering GDB services to potential users who are also the current mobile subscribers using services such as voice, messaging, internet based video streaming, voice over IP, value added services and other.

Regarding to the cost of the service, there is no need for end-users to pay directly the spectrum operator, because the MNO could charge the required amount of money through the customer's bill without knowing about buying access to GDB. However, the spectrum operator needs to find the way how to charge the service from MNO and how to offer the new services using mobile network.

In the second case the GDB operator is a threat to the MNO, because when the GDB operator asks to use MNO's infrastructure in order to offer services, the MNO loses some resources. But it becomes too difficult to define the access price to the MNO network because in this way the big fixed provider should charge new players.

In both cases there will be the need for extra investments for upgrading the network (see numbers in Fig. 4.6):

- extra gateway in MNO's network (1);
- base station software upgrade (2);
- base station and antenna system hardware upgrade (3).

All these three points encompass CAPEX for GDB implementation:

- connection to the Internet;
- DB costs (server, database).

In addition, there are also OPEX for deploying GDB, and all these costs need to be covered from MNOs by charging them in some way:

- operation and maintenance (O&M);
- electricity;
- personnel costs;
- transmission line of GDB to Internet, etc.

4.2.4 Conclusion

The purpose of this section is to contribute to the on-going discussion on techno-economic analysis of business scenarios, and on classification of business scenarios and identification for business models for the use of GDB in TVWS by narrowing down from general (different stakeholders) to concrete (one stakeholder) point of view.

The final results of this work will allow applying the GDB business scenarios analysis in the future studies, taking into account the same method for modelling new business scenarios for others groups of established stakeholders' of DSA II and then seeing if there can be any common business model derived from the multitude of different models. The results will lead to a model of cost and revenues in which different GDB architectures (centralized/decentralized, horizontal/vertical) are compared from different point of views in order to get very specific view of impact of CR paradigm to the wireless telecommunication services.

Acknowledgments The authors would like to thank their colleagues from COST Action IC0905 (COST-TERRA) for sharing their ideas and support in developing this work.

The first author extends her special gratitude to prof. Heikki Hämmäinen (Aalto University, Department of Electrical Engineering; Espoo, Finland) for hosting her

visit to the department in March 2013, and to his team of researchers, especially to Thomas Casey, and Arturo Basaure.

4.3 Underlying Market Dynamics in a Cognitive Radio Era

Thomas Casey and Timo Ali-Vehmas

VTT Technical Research Centre and Nokia Corporation, Tampere, Finland

4.3.1 Introduction

This section explores the possibilities of how the value system around wireless networks could be organised in the future and what would be the underlying market dynamics given the introduction of CR and dynamic spectrum access technologies. Using a combination of systems thinking tools and platform theory, four value system configurations around the future radio platform are introduced and the corresponding underlying dynamics are characterised. Based on this a feedback model using system dynamics and agent based modelling is built, configured with historical market data and used to evaluate future evolution possibilities both for GSM based mobile cellular and Wi-Fi based wireless local area radio platform paths. We explore how the value system could continue on established evolution paths but also deal with the transition to a so called complex adaptive system. Furthermore, for policy makers, we discuss threats associated with winner-takes-all and fragmentation type of scenarios, and highlight the possible importance of aligning the underlying market dynamics with the natural allocation and assignment cycle of spectrum frequency bands. This material is based on works published in [23], to where the reader is guided for further information beyond this chapter.

CR and DSA technologies have the potential to disrupt the current value system and usher in a new era in wireless communications. Under the new paradigm the management of radio resources would be decentralised to the edges of wireless networks where devices would together collaborate and provide wireless services [24]. The paradigm shift could potentially direct the market towards a horizontal and open structure enabling many new service applications and entrants [25] and could thus fundamentally change the underlying dynamics of the market as illustrated in Fig. 4.7. However, established path dependencies on current spectrum management models are strong and it is uncertain whether they can, or even should, be broken. Therefore, as it relates to the deployment of CR and DSA, there is a need to understand the underlying dynamics of the market in addition to the technology itself.

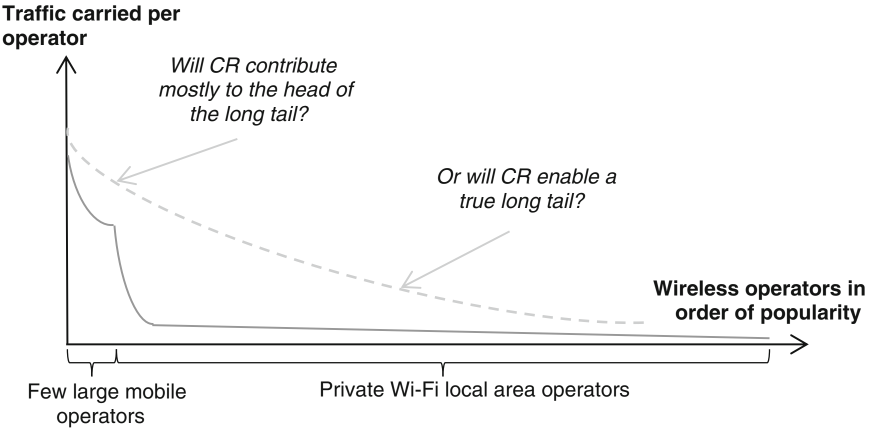


Fig. 4.7 An illustration of the head and long tail of potential application areas and market opportunities enabled by CR/SDR (A long tail results when the tools of production and distribution are democratized and supply and demand are connected [48])

Regarding how actors in the current value system around the radio spectrum resource are organised, one can distinguish different models. Historically, spectrum licenses were given to one actor who was in charge of service provisioning and network deployment and controlled the whole value system from infrastructure to devices (e.g. government monopoly operators) which in turn led to inefficient legacy allocations [25]. Improvements have been made e.g. after telecommunications liberalisation with the introduction of digital cellular mobile communications where licenses have been assigned to a group of operators and where ownership of devices and selection of network (i.e. with the help of SIM-cards) have been given to the end-users [26, 27]. This in turn has fuelled competition between operators and has forced them to use the spectrum resources more efficiently and improve the availability of their networks (both in terms of coverage and capacity). On the other hand, the usage of harmonised technology standards, as was done in Europe following the GSM Memorandum of Understanding of 1987 [28], has enabled large international economies of scale, device circulation and roaming which in turn has been a key ingredient that has enabled the more than six billion mobile subscriptions we currently have in the world. As mobile operators around the world are converging to LTE and LTE-A, CR and DSA technologies could be naturally embedded to this technology path.

As it relates to wireless computer networking, the unlicensed model has diffused widely where access points and base stations can be deployed and services can be provisioned by anybody, provided they follow a simple spectrum etiquette. Wi-Fi certified IEEE 802.11 has become the de-facto standard whose origins can be traced back to FCC's 1985 decision to allow the unlicensed use of spread spectrum techniques on ISM bands [29, 30]. Subsequently, many private enterprises and households have become wireless service providers where the cumulative number of Wi-

Fi chipsets sold has surpassed the one billion mark and the installed base of Wi-Fi access points is already in the order of hundreds of millions.

On the other hand public Wi-Fi has remained somewhat limited where e.g. roaming solutions are still rather fragmented and typically proprietary. Furthermore, given the limitations of the scalability of the IEEE 802.11 MAC protocol the unlicensed model is able to scale and grow in a bottom-up manner only up until a point. Since most of the demand arises from indoor locations [31], more co-ordination and spectrum is needed to enable bottom-up type of growth for which CR and DSA in turn could provide a solution. An example of bottom-up type of infrastructure growth can be observed e.g. with the wide spread diffusion of the Internet Protocol (IP) which has become the generic protocol to interconnect all computers [32]. In a similar manner CR and DSA could enable roaming and mobility between all devices on all possible frequencies which in turn could lead to an open and global network of wirelessly connected devices through which everyone could provide and receive public wireless services on any access point (AP) or device. As it relates to the future of CR and DSA various scenario studies have been conducted [31, 33–36]. In many of these the core question is to what degree the future system (e.g. CR spectrum database structure) is a centralised or decentralised one and to what degree an open (i.e. horizontal) or closed (i.e. vertical) one, a typical pattern that has been identified also on a more generic level [37–39]. However, while static descriptions have been made, the underlying dynamics of these scenarios have not been described. Given the introduction of CR and DSA technologies, the purpose of this paper is to explore the possibilities of how the value system around wireless access provisioning could be organised in the future and what would be the underlying dynamics. Due to the interdependent nature of the problem we take a holistic approach by using a combination of systems thinking tools and platform theory to understand the underlying structures. Based on historical evolution and prior scenario analysis work we introduce four value system configurations around radio platforms and characterise the underlying dynamics for each. Based on this we build a feedback model using qualitative system dynamics and quantitative agent based modelling (ABM), configure it with historical data and use it to evaluate future evolution possibilities both for GSM based mobile cellular and Wi-Fi based wireless local area radio platform paths.

4.3.2 Framework for Underlying Structure of Value Systems

4.3.2.1 Value System Configurations

Systems thinking studies, how things influence one another within a whole, where a core principle is that underlying structure gives rise to observed trends, patterns and events [40]. The structure between actors and their business (and technical) interfaces can be described as a value system [41]. A value system in turn can be characterised as being organised around a mediating technical platform [42–44] operated by a platform manager [45, 46]. Here we define a radio platform (e.g. a mobile network) as being managed by an operator that provides a wireless service and mediates interactions (facilitated e.g. by a database) between two user groups: end-users using devices and entities hosting base stations (BS) (or access points) who both can create affiliations to the platform. The service itself is delivered through technical interfaces and components (devices and access points) and therefore the other side of the platform (e.g. BS host) might not be directly visible to the other (e.g. end-user).

Based on historical evolution and prior scenario analysis work we define four value system configurations around radio platforms. The platform typology follows the closed or open and centralised or decentralised categorisation.

First, in the centralised and closed value system configuration the radio platform is centred around one actor that controls the spectrum resource and the interactions (and signalling) between end-user devices and base station or access point sites, which would e.g. correspond to old government monopoly operators. In such a system there is only one platform manager with whom everyone has to collaborate since there is no other platform to switch to.

Second, in the centralised and open value system configuration the value system consists of a small set of connected radio platforms managed by a small group of platform managers that both collaborate and compete. The platform managers control the spectrum resource and the interactions between end-user devices and BSs or APs (typically operators operate the BSs and site owners only provide horizontal and value system independent resources for site space and electricity etc.). Since a standardised technology is used the platform users can rather easily switch between platforms. This would e.g. correspond to the competition and collaboration model of mobile operators using GSM based technologies where the end-users can use the same device and switch between mobile networks.

Third, in the decentralised and open value system configuration the value system consists of a large set of small connected radio platforms. Anybody can become a radio platform manager and start providing wireless services for other users. There exists a great heterogeneity of technologies and services with plenty of local innovation and competition. However, actors also collaborate, technologies are made interoperable and radio resources are quickly reassigned between platforms so that valuable services that have high demand are able to flexibly scale bottom-up. End-users can freely switch and roam between platforms and can easily become wireless service providers themselves. Such radio systems do not currently exist, although some open Wi-Fi roaming solutions bear some resemblance (e.g. *Eduroam* and *openWTS3*). Still, examples of decentralised and open systems exist in other fields, such as e.g. IP networks in computer networking.

Fourth, in the decentralised and closed value system configuration the value system consists of a large set of small radio platforms that are isolated from each other where all compete over the radio resources and no (or very limited) co-ordination exists. Isolation and intense competition can lead to the erosion of radio resources where nobody is able to scale their services bottom-up. Anybody can start providing wireless services, but typically only for a closed user group. This would e.g. correspond to private Wi-Fi deployments and fragmented roaming and authentication solutions.

4.3.2.2 Underlying Dynamics of Value Systems

Next we will describe the underlying dynamics of each value system configuration using basic concepts from dynamical systems theory [47]. A dynamical system can be characterised with an attractor, whose type can roughly be divided into four groups: fixed point, limit cycle, strange and no attractor.

First, centralised and closed value system can be seen as being directed by a fixed point attractor which evolves towards a static state (like a damped pendulum).

Second, centralised and open value system can be seen as following the dynamics of a limit cycle attractor which produces periodic and somewhat regular change (like a continuously swinging pendulum).

Third, decentralised and open value system can be seen as following the dynamics of a strange attractor which produces deterministic irregular change and functions on the edge of chaos.

Fourth, decentralised and closed value system can be seen as being characterised as a system that does not have an attractor that would give it structure and thus exhibits complete disorder and random behaviour.

The market share of each operator, i.e. radio platform manager, in each value system configuration is depicted in Fig. 4.8. The dynamics are influenced by the adaptation speed of the actors and the system overall, i.e. how often decisions about platform switches are made, how often resources are re-allocated and re-assigned, and how quickly competitors respond to market changes. In a centralised and closed value system configuration following the fixed attractor dynamics, one actor carries all traffic, as was the case with government monopoly operators. The system is very slow to adapt to changes with long resource allocation and assignment delays where users cannot switch to another provider and can overall be seen as corresponding to the inefficient legacy spectrum assignment model.

In a centralised and open value system configuration following the limit cycle attractor dynamics, few actors carry the traffic, as is typically the case with mobile operator competition today. Here the system adapts to changes cyclically where end-users are able to switch to more valuable networks thus inducing competition and more efficient use of resources. Overall the system allocates and assigns resources in a cyclical manner. In a decentralised and open value system configuration following the strange attractor dynamics, traffic is carried by many actors. The value system is quick to adapt to changes with short delays for resource allocation and assignment and low switching costs for end-users. Here actors form a long tail distribution where actors from the tail can quickly grow and reach the top and vice versa. Such a value system corresponds to the observations of Anderson [48] who states that a long tail distribution results when the tools of service production and distribution are democratised and supply and demand are

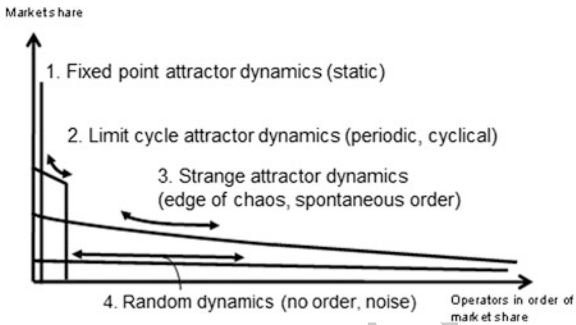


Fig. 4.8 The market share of each operator, i.e. radio platform manager, in each value system configuration

connected. Overall, the value system would correspond to a so called complex adaptive system [49] where large number of agents interact using simple rules and which is characterised by self-organisation, emergence, and scale-free network structures with long tail distributions [50]. This has been observed e.g. in the Internet in terms of routers [51] and web pages [50].

Finally, in a decentralised and closed value system configuration following the no attractor dynamics, traffic is carried by many actors but no actor is able to get ahead of others, get more resources and scale up. There is no delay for resource allocation and assignment (as is the case with the unlicensed spectrum licensing), resources do not accumulate and no structure is formed. Overall the system adapts randomly and seems like noise to an outside observer.

4.3.3 Feedback Model of the Underlying Dynamics of the Value System

The above described underlying dynamics are generated by a large set of actors and encompass a large number of feedback connections. Our next goal is to build a model of these underlying dynamics using two feedback modelling tools: qualitative system dynamic modelling [52] and quantitative agent based modelling [53]. As background for the modelling work eight expert interviews were conducted including representatives of device and network equipment vendors, mobile operators, regulators and academia.

As it relates to the modelling approach, it is important to make a distinction between detailed and dynamic complexity. Simply put, dynamic complexity is modelled with feedback structure, whereas detailed complexity is modelled by increasing the number of variables [40]. System dynamics focuses more on dynamic complexity and can easily encompass a wide range of feedback effects, but typically aggregates agents into a relatively small number of states [53]. Agent based modelling, on the other hand, puts more focus on detailed complexity where individuals and their interactions are explicitly represented, which in turn makes it more difficult to link model behaviour to its structure. Therefore, modellers must trade off disaggregate detail and breadth of boundary [53]. Our goal here is to use a combination of detailed and dynamic complexity, i.e. leverage the strength of both system dynamics and agent-based modelling. We start out by characterising the underlying dynamics of the value system configurations with simple system archetype feedback structures [54] and after that use ABM to assimilate the large number of feedback relationships between individual agents simultaneously, i.e. integrate detailed and dynamic complexity together [40].

4.3.3.1 GSM Evolution Path

We now envisage future mobile cellular networking scenarios. CR spectrum licenses to operate mobile networks will be given to all agents during the CR and DSA introduction period (year 2020). We assume that competitive reaction speed (SC) will remain low since rather long term investments are still needed. Furthermore, we conduct sensitivity analysis by adjusting the resource accumulation speed (SR) which reflects the overall spectrum licensing model. In the base case it will correspond to regulated exclusive licenses, i.e. the currently dominant licensing model with large spectrum bands and long license times. In the first sensitivity case SR will be considerably slower and correspond to license-exempt, i.e. unlicensed spectrum. In the second sensitivity case SR will be only slightly slower and reflect light or secondary licensing, where small bands are assigned dynamically with shorter cycles while ensuring that competition prevents extensive resource accumulation. In the third sensitivity case SR is considerably faster and corresponds to unregulated exclusive licenses where all resources can cumulate or be assigned to one operator and no spectrum caps are enforced.

Figure 4.9 shows the market shares of agents in the base case. As can be observed, after the introduction of CR and DSA technologies and the entrance of new smaller operators, competition between the large operators intensifies and they lose some market share. However overall, the underlying dynamics of the value system continue to follow the limit cycle dynamics, i.e. although some additional competition is present the majority of resources still accumulates to and circulates between the incumbent operators and the strength of the success to successful mechanism between the agents remains rather strong.

Changes in competitive efforts are shown in Fig. 4.10 where before the introduction of CR and DSA the competitive efforts of the three large operators are quite close to one another and evolve cyclically (in the model competitive effort ranges from a minimum of 30 to a maximum of 100). After the introduction of CR and DSA and the entrance of new operators, competitive activity between the large operators increases but still, the value system continues to evolve in a cyclical manner, i.e. it has some positive feedback but is still dominated by negative feedback. Nevertheless, this new competition leads to more efficient use of resources and more value overall. One can also observe that the increased

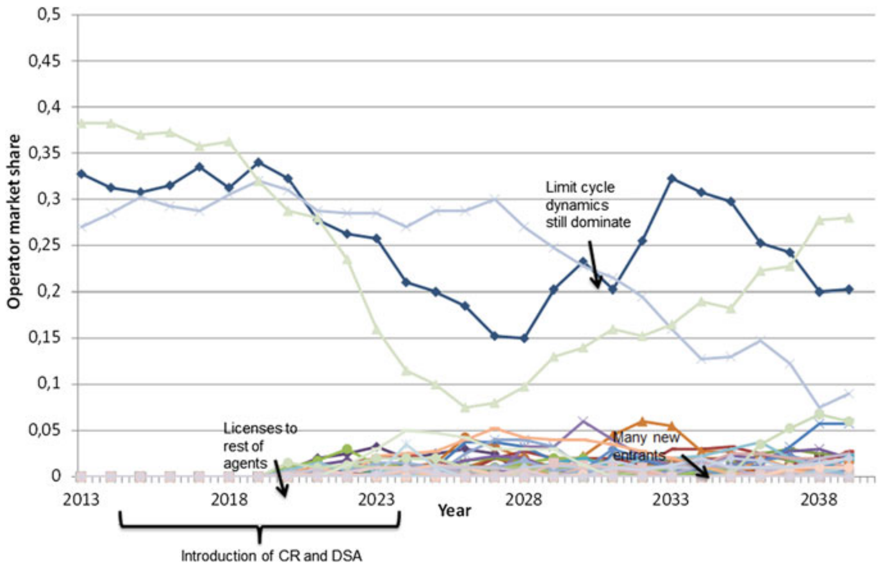


Fig. 4.9 Market share of agents in the base case

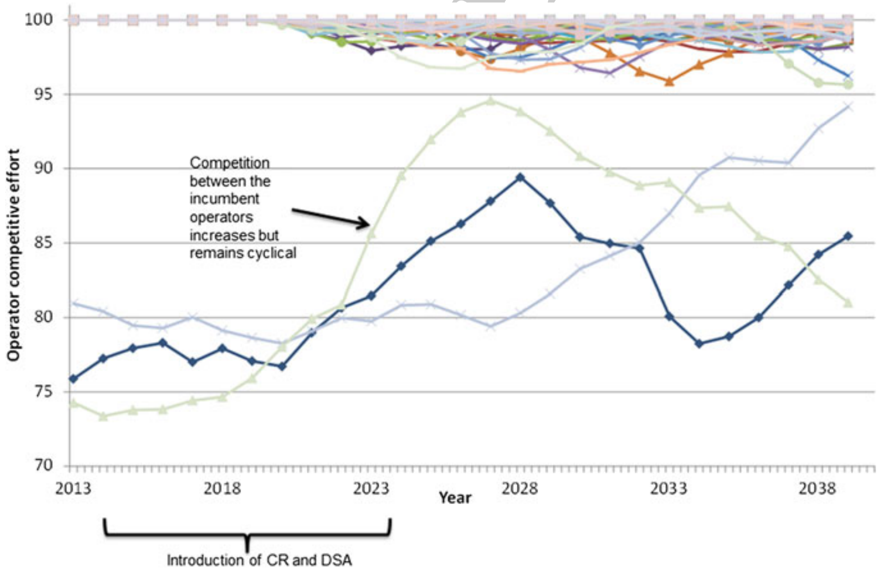


Fig. 4.10 Changes in competitive efforts between agents

possibility for end-users to switch between operator networks increases volatility in the system since the system still remains slow to react to changes.

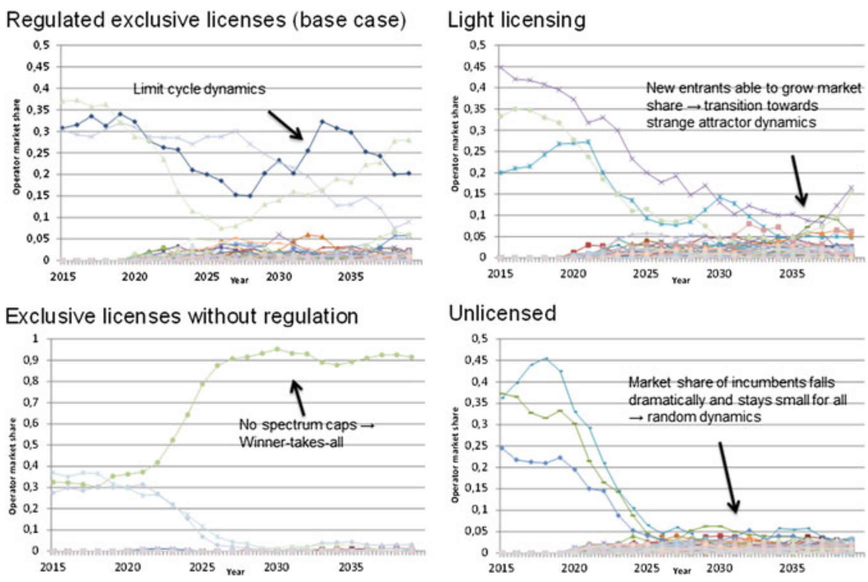


Fig. 4.11 Sensitivity analyses results

Next Fig. 4.11 shows results from the sensitivity analysis. As can be observed, introducing an unlicensed model dramatically reduces the market shares of large operators and leads to a situation where the market share of all operators remains small and thus the value system transitions to follow the no attractor dynamics. With a light licensing model incumbent operators are able to sustain some market share but are joined by new entrants who have been able to grow their market share and thus the value system starts transitioning towards strange attractor dynamics. The use of exclusive licenses without regulation leads to a winner-takes-all situation where all resources accumulate to one actor who starts dominating the whole market and thus the value system transitions to follow the fixed attractor dynamics.

In terms of competition, with the unlicensed model all agents compete fiercely, resources do not accumulate and the individual platforms remain limited in value. With the light licensing model competition is less intense and resources are directed to valuable services which in turn are able to grow and scale up but not enough to gain a significant share of the market. With unregulated exclusive licenses competitive effort by the dominating agent drops to a minimum value and therefore, although it controls almost all of the resources, the value of the platform does not increase.

4.3.3.2 Wi-Fi Evolution Path

We now focus on potential future scenarios involving the evolution of Wi-Fi based wireless local area access. We assume that all agents have the existing unlicensed spectrum resources and that competitive reaction speed (SC) will remain the same

Layout: T1 Standard SC | Book ID: 318863_1_En | Book ISBN: 978-3-319-04021-9
Chapter No.: 4 | Date: 24-12-2013 | Page: 27/74

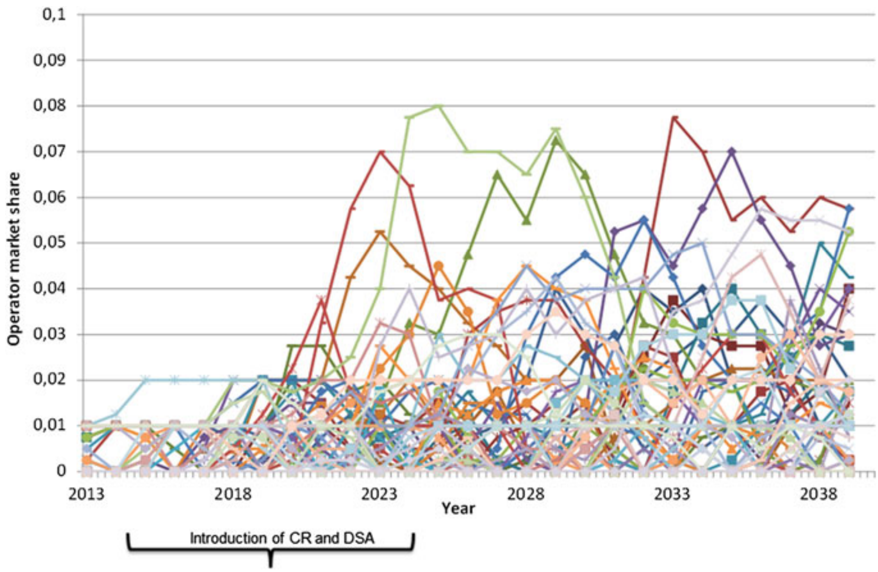


Fig. 4.12 Market shared in the Wi-Fi evolution base case

reflecting local and instantly adaptive behaviour and small scale investments. In terms of the sensitivity analysis the resource accumulation speed (SR), corresponding to the spectrum licensing model, will grow to be somewhat faster in the base case (i.e. light and secondary licensing), and in other sensitivity cases will remain the same (i.e. continuation with the unlicensed model), grow to be still somewhat faster (i.e. regulated exclusive licenses), and considerably faster (i.e. unregulated exclusive licenses).

Figure 4.12 shows the market shares of agents in the base case. As can be observed, after the introduction of CR and DSA technologies and light licensing, some operators with valuable services are able to scale up, get more resources and market share. However, the system adapts quickly to changes and resources are reassigned to wherever new innovations and locally relevant services are created and therefore no single actor or group of actors starts to dominate the value system. Therefore, the value system transitions to follow strange attractor dynamics, where the strength of the success to successful mechanism is low and competition is high. The value system evolves chaotically, i.e. has some negative feedback but is dominated by positive feedback. Overall, the system can be characterised as a complex adaptive system that operates at the edge of chaos.

Changes in competitive effort are illustrated in Fig. 4.13 where one can observe that before CR and DSA, and light licensing are introduced competition between agents is fierce. After the introduction of CR and DSA and light licensing, coordination increases but competition remains still high and fuelling new services and local innovation. However, competition is not so intense that resources erode,

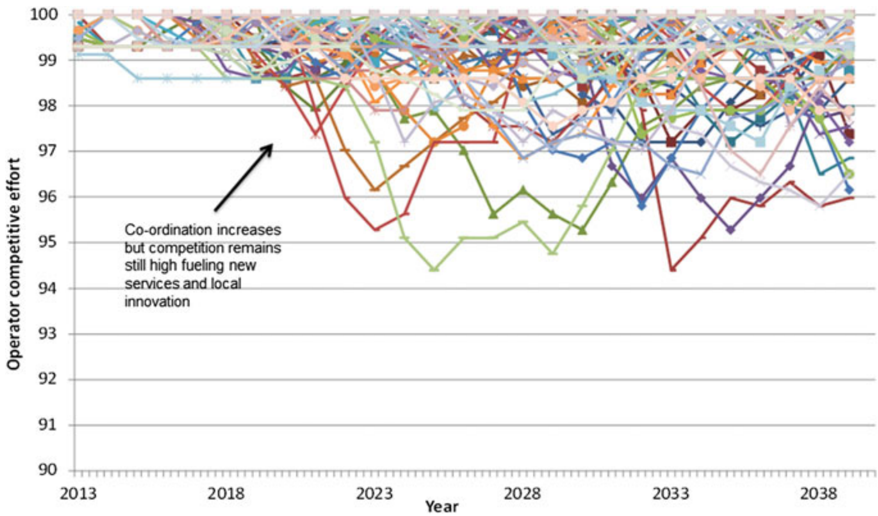


Fig. 4.13 Competitive efforts in the Wi-Fi evolution base case

leading to more efficient use of resources and more value overall as compared to the unlicensed model.

Following Fig. 4.14 shows results from the sensitivity analysis of this case. As can be observed, continuation with an unlicensed model leads to a situation where the market share of all operators remains very small and thus the value system continues to follow the no-attractor dynamics. This would also correspond to the fragmentation of CR technologies and spectrum databases in a similar manner as is the case with Wi-Fi roaming and authentication today.

With a regulated exclusive licensing model, resources accumulate so that two operators start controlling the market and thus the value system transitions to follow the limit cycle dynamics. In the case of unregulated exclusive licenses, resources accumulate to one actor leading to a winner-takes-all situation and fixed attractor dynamics. The dominant actor or actors in both of these cases could come from the group of incumbent mobile operators but could also come from outside the value system e.g. if a large internet player controlled the spectrum database and leveraged network externalities arising from elsewhere.

In terms of competition, with the unlicensed model all agents compete fiercely and the individual platforms remain limited in value, with the regulated exclusive licenses model the two dominant actors that get most of the resources slow down and start competing cyclically and with unregulated exclusive licenses competitive effort by the dominating agent drops to a minimum value. Figure 4.15 shows the top 30 operators in order of market share at the end of the historical simulation (year 2012) and at the end of the simulation in the different sensitivity cases.

When comparing the base case to the historical situation the market shares of wireless service providers especially in the head have increased. With the unlicensed

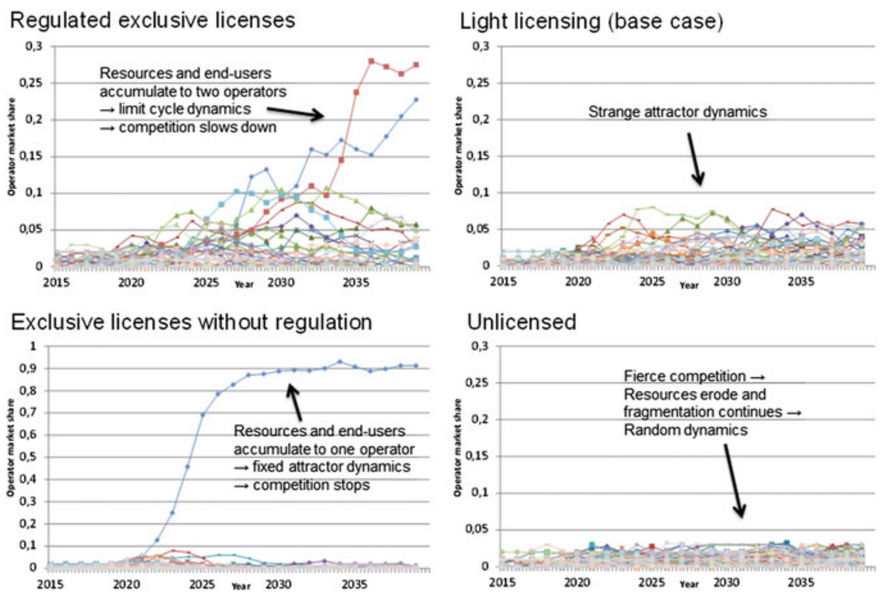


Fig. 4.14 Market shares in the Wi-Fi evolution sensitivity analyses

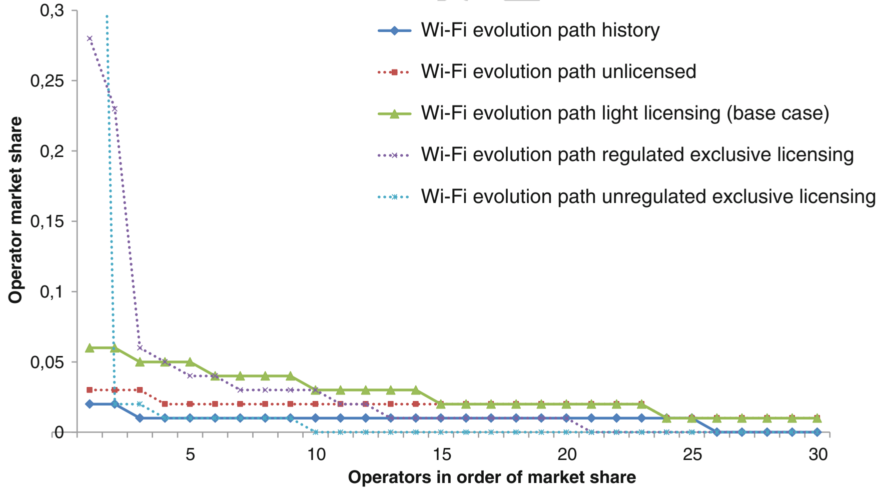


Fig. 4.15 Top 30 operators in order of market share year 2012 and at the end of the simulation in the different Wi-Fi evolution sensitivity cases

model the head has also grown slightly but the tail has become considerably longer than with light licensing and the number of active wireless service providers stabilises to roughly 70 agents. This would correspond e.g. to a situation where most of the agents are operating their smartphones as Wi-Fi access points for themselves. With the regulated exclusive licensing model the two operators in the head have taken most of the market share where the tail in turn has lost market share and most of the operators have become passive. With unregulated exclusive licenses one agent in the head gets all of the traffic and practically no long tail exist.

4.3.4 Discussion

The implications of the underlying dynamics of future CR scenarios and the corresponding spectrum database structure also highlight issues specifically relevant for policy makers. As it relates to the GSM evolutionary path, the value system continues to follow the limit cycle dynamics and to be dominated by few incumbent operators. In such a case CR and DSA technologies are likely to be embedded to the technology standards used by the mobile operators (i.e. LTE-A and its future versions). The possible spectrum databases and indoor sites would also be mostly controlled by mobile operators.

In terms of the Wi-Fi evolutionary path, the value system evolves to a complex adaptive system where the CR and DSA technologies would establish themselves as an independent technology standard enabling roaming and mobility between all devices on many frequency bands. The database infrastructure would follow an open and decentralised architecture (resembling that of IP) and be operated by many entities. Furthermore, as shown in the sensitivity analysis, it is also possible that a collision occurs between the two evolution paths and that the overall value system transitions from a centralised to a decentralised one or vice versa corresponding to the more general level descriptions of [37, 39]. The value system around the mobile cellular network platform could evolve towards strange attractor dynamics (i.e. entrance of many small operators and a diminishing role for incumbent operators) and vice versa the Wi-Fi path could evolve towards limit cycle dynamics (e.g. Wi-Fi access points controlled by incumbent mobile operators or other large actors).

From a policy maker perspective the results also point out future threats. There is a possibility that CR and the corresponding database technologies will become fragmented, much like Wi-Fi roaming and authentication now, and the roles of CR databases will remain very limited, isolated and local. Yet another threat is a winner-takes-all type of situation where one of the existing operators, or another strong player outside the value system, controls the CR database infrastructure and uses closed proprietary technologies which might in turn slow down diffusion overall. The results could also have implications as it relates to different spectrum frequency bands and their characteristics. As discussed by [47], dynamical systems tend to naturally synchronise with one another and transition to follow the same dynamics. For example, roughly put, one can say that low frequency bands propagate far and need more centralised co-ordination and long assignment cycles whereas high bands in turn do not propagate far, remain as a local resource (especially in indoor locations) and thus need less co-ordination. Therefore, one could pose a question whether there is a natural allocation and assignment cycle for the spectrum frequency bands and if so, how would these characteristics relate to the described underlying dynamics. For example in terms of the GSM evolution path, the usage of standardised technologies, cellular network planning and competition following the limit cycle market dynamics has led to rather efficient use of 900 and 1800 MHz bands. Subsequently, one can question, to what degree should CR and DSA technologies even be used to disrupt these underlying dynamics. Still, one can argue that there exists an upper limit for frequencies after which building cellular networks becomes inefficient. Unlicensed private Wi-Fi deployments, on the other hand, have led to rather efficient use of use of the 2.4 GHz ISM band and correspondingly one can question are the unlicensed and light licensing models more naturally aligned with higher spectrum bands and short range sites.

Since the policy maker can influence the underlying dynamics of the market with the spectrum licensing model it could be beneficial if the value system would be orchestrated so that the underlying market dynamics are aligned with the natural allocation and assignment cycle of the radio resources. This would correspond to a few core applications (such as mobile voice, text messages and managed mobile internet connectivity) enabled by mobile cellular technologies and governed by cyclical competition.

Strange attractor dynamics and light and secondary licensing models would be aligned with high spectrum bands and base stations and access points working on sites with short range with instantly adaptive behaviour and small scale investments needed where somewhat unreliable assets, e.g. light or secondary licenses, would be sufficient. This would correspond to many different types of applications, locally relevant public services enabled by CR and DSA technologies and be governed by chaotic competition with just enough co-ordination to ensure system operation. No attractor dynamics and the unlicensed model would be aligned with very high frequency bands and with access points and devices working on very short range sites. This would correspond to private and personal use and applications, enabled by low power levels, simple spectrum etiquette and decentralised medium access protocols with collision avoidance mechanisms (e.g. CSMA/CA) but otherwise isolated governance In reality such alignment is of course difficult (if not impossible) to reach and therefore the dynamics could work on all frequency bands (such as CR devices on TV white spaces) and on all site types. Nevertheless, as a general rule, one can argue that this would be the most natural alignment, which in turn would mean that CR and DSA technologies could reach their highest potential if they were used with short range sites and high spectrum bands.

Furthermore, what is interesting to note is these underlying dynamics might be better aligned with the market characteristics of particular countries. For example the limit cycle dynamics are commonly observed in many European countries with a strong harmonisation legacy, such as e.g. Finland, where only GSM based technologies have been used, three network operators compete using the same technology and SIM-card based post-paid subscriptions are common leading to moderate churn rates (e.g. annualised churn typically above 10 % in Finland [55]).

Markets in countries such as e.g. India are already more decentralised and follow strange (or no) attractor type of dynamics where many operators are present and pre-paid subscriptions and multi-SIM phones are common leading to very high churn rates (e.g. annualised churn roughly 40 % in India [34]) which in turn could make the market better compatible with CR and DSA systems as pointed out by [56].

On the other hand, in countries with vertical market structures, such as e.g. Japan, operators have traditionally had tight control of the technologies deployed, each operator having their own application stack, where the operators can internally be seen as following the fixed attractor dynamics with dedicated operator devices and high switching costs leading to low churn rates (e.g. annualised churn well below 5 % in Japan [55]). Although in our simulations it was assumed that CR and DSA increase device flexibility and the probability of switching between operators, this might not be the case if operators are in a position to limit and control the deployment of CR and DSA technologies in the devices.

Overall, these simulations show that only small changes in some parameters might change the market dynamics significantly. Therefore, as it relates to technology standardisation, it is important to preserve the opportunity to manage the market dynamics during the entire lifetime of the system technology and to avoid undesirable deadlocks and market failures. Since it is not possible to define all the parameters precisely right today it would be beneficial to preserve flexibility and configurability in standards and technologies in order to be able to control and adapt to the market dynamics later. The right architectural technology decisions are therefore very important for CR and DSA technologies.

4.3.5 Conclusion

In this section, we have studied value system evolution around future radio platforms given the introduction of CR and DSA technologies. We have used a combination of systems thinking tools and platform theory to characterise four value system configurations around the future radio platform and the corresponding underlying dynamics and have built a feedback model to evaluate future evolution possibilities both for GSM based mobile cellular and Wi-Fi based wireless local area radio platform paths. The results showed how the value system could continue on established evolution paths but also how it could transition to a so called complex adaptive system. For policy makers, the results have pointed out threats of winner-takes-all and fragmentation type of scenarios. The results also highlighted the possible importance of aligning the underlying market dynamics with the natural allocation and assignment cycle of the spectrum frequency bands, a hypothesis that could be explored more in future research. Furthermore, the overall framework introduced here, could in the future also be used to model the evolution of value systems around other technologies and e.g. explore the relationship of CR and DSA to other ICT technologies, e.g. Internet and cloud computing.

Acknowledgments The authors would like to thank Professor Heikki Hämmäinen and Mr. Ankit Taparia for their contributions. This work has received funding from the EECRT project and has also been conducted under the context of COST-TERRA (COST Action IC0905) research framework.

4.4 Business Scenarios for Spectrum Sensing-Based DSA

Vânia Gonçalves, Simon Delaere and Pieter Ballon

iMinds-SMIT, Vrije Universiteit Brussel, Brussels, Belgium

4.4.1 Introduction

The scarcity of spectrum that is experienced and/or anticipated today, is caused by the ever-growing use of wireless applications and by the way in which spectrum is managed. The long-term allocation of spectrum blocks to specific radio access technologies (RATs), specific services and specific operators is often cited as an inflexible spectrum management mechanism leading to suboptimal results. It is well known that most of these blocks of spectrum are not fully utilised.

Therefore, it is widely expected that measures allowing more efficient use of radio spectrum will include a shift from classic "command-and-control" to more dynamic forms of spectrum management and access will be a crucial part of the future telecommunications [57, 58]. In many markets, significant moves towards such dynamic spectrum management have already been made, including the introduction of selling and leasing of frequencies, collective use of spectrum and technologically neutral spectrum licenses. A technological advance that supports this objective is the development of CR and spectrum sensing prototypes. In its Report on Cognitive Technologies [33], the Radio Spectrum Policy Group defines spectrum sensing as follows: "[Spectrum sensing] provides a real-time 'map' of the radio environment. The main focus is on identifying unused areas in the intended frequency range that can be used by [Cognitive Radios]." The intended frequency range of our concept of spectrum sensing is considered to cover the entire spectrum, resulting in a RF tuning range of 100 Hz to 6 GHz. Furthermore, the spectrum sensing concept used for this research can sense very fast (29.5–88.5 ms) and requires low power amounts (7.8 mJ), making it ideal for implementation in terminals.

Spectrum sensing research often takes as point of departure a limited number of use cases, in order to sketch out a number of typified actors and their interactions. However, it is seldom addressed whether the conclusions drawn from such analysis are valid for other implementations of spectrum sensing. The hypothesis put forward here is that many contexts in which spectrum sensing technologies may be applied are so distinct from a business and regulatory point of view, that the characteristics and viability of one use case cannot be determined from analysing other use cases. It is therefore essential to determine which parameters are critical for distinguishing fundamentally different business scenarios. Four of such fundamental variables are identified and discussed below.

In order to test this hypothesis, the following research questions will be discussed: are there important differences in spectrum sensing scenarios that have to be considered in any business or regulatory analysis? If so, what are the business parameters that explain these differences? Is it possible to construct a business classification based on these business parameters? What added value would such a classification have and who would benefit from it? The results presented here could be used as a starting point for future research and decision-making related to spectrum sensing.

4.4.2 *Business Parameters*

The business parameters proposed below are the main differentiators between distinct classes of spectrum sensing business scenarios. They have been derived from an analysis of the use cases currently outlined in a variety of academic and consultancy research and industry white papers on spectrum sensing (see a.o. the references below). Based on these differences, four fundamental business variables have been derived, namely: ownership, exclusivity, tradability and neutrality.

4.4.2.1 Ownership

The main differentiator between spectrum sensing business scenarios is ownership. The concept of ownership used points out to ownership of a license and thus, the right of use for a given frequency band conferred by a regulatory authority, which still differs from ownership of spectrum. Using this business parameter in the classification, two major groups of business scenarios arise: the *unlicensed* spectrum business scenarios and the *licensed* spectrum business scenarios. The latter ones include every business scenario in which a regulator has issued licenses for a certain band of spectrum, independent of the way it is used and whether or not this license grants exclusivity rights to a dedicated frequency band.

4.4.2.2 Exclusivity

Drilling down within the group of licensed spectrum business scenarios, the exclusivity business parameter addresses the question whether or not frequency bands are exclusively assigned to a licensee. A regulator can decide to assign a specific frequency band for every licensee, thus making the frequency band *exclusive*. If the regulator would decide to group multiple frequency bands in a spectrum pool and make it available for multiple licensees, there would be *no exclusivity*. Note that the concept of exclusivity does not imply that only the licensee can have access to the frequency band. In some cases, users that do not have a license for the specific frequency band can utilise some (or all) of the frequencies in that band. The following business parameter will further discuss this topic.

4.4.2.3 Tradability

A third business parameter that is bound to affect future business models and regulatory consequences is tradability. This business parameter questions whether or not it is permitted for terminals to switch between different operators' frequency bands. If tradability is allowed, an operator can buy or lease a licensee's frequency band. Motivations for an operator to do so could include (but are not limited to) offloading of its own over-utilised bands, better coverage for its clients on the competitor's network, better quality of service, etc. In return, the primary user can be compensated. However, if tradability is either not allowed, or impossible, the use of the frequency band is restricted to the licensee itself.

4.4.2.4 Neutrality

A final differentiator is technology neutrality in licensed spectrum bands. Some frequency bands may be open to a variety of radio access technologies (RATs), while others only allow one specific technology. It is obvious that the latter case limits the efficient use of spectrum, but in terms of regulatory consequences, it can be assumed that a technology neutral frequency band would need to address more issues, such as setting technical conditions to access the band and coordinating the cooperation between multiple technologies.

4.4.3 Business Classification

Based on the aforementioned parameters, it is possible to derive a variety of distinct spectrum sensing business scenarios as shown in Fig. 4.16. Each category of business scenarios entails different regulatory issues and approaches. Furthermore, different roles and main beneficiaries can be identified in different cases.

This classification differs from other classifications, such as [59] and [60], because (as far as the specific scenarios go) it is focused on spectrum sensing, it is not a technical classification and it uses a very detailed level of scenario groups.

For every class of the proposed classification, an exemplary business scenario has been chosen for discussion. In the following subsections, examples of the Unlicensed business scenario, the Single RAT Pool business scenario, the

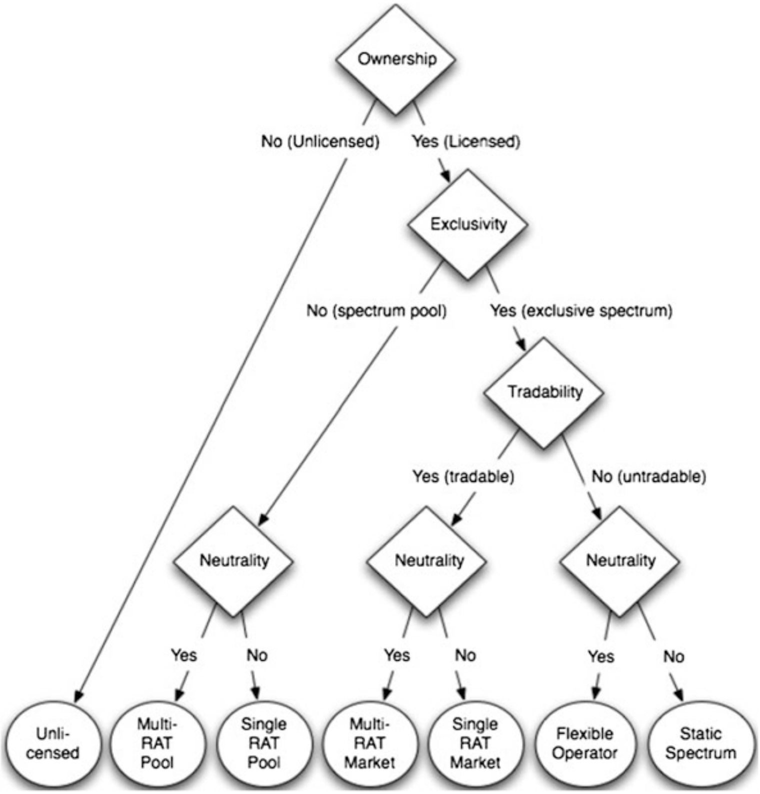


Fig. 4.16 Classification of spectrum sensing business scenarios

Multi-RAT Market business scenario, the Single RAT Market business scenario and the Flexible Operator business scenario will be discussed. The Static spectrum business scenario will not be discussed, as there is no use for spectrum sensing in a frequency band with restricted use for the licensee and one specified technology only. Furthermore, the Multi-RAT Pool business scenario will not be reviewed, as it can be argued that there is presently no realistic scenario in which a frequency band would be awarded in the near future with full flexibility as described by the four business parameters.

4.4.3.1 Unlicensed

The unlicensed case is different from most other business scenarios because there is no ownership of a license involved. Examples of business scenarios are mostly found in the unlicensed bands or ISM bands. Like many other technologies, both Zigbee and Wi-Fi (802.11 g/n) operate in the 2.4 GHz ISM band. This may cause problems of interference, resulting in a failure for the radio access technologies to

Layout: T1 Standard SC | Book ID: 318863_1_En | Book ISBN: 978-3-319-04021-9
Chapter No.: 4 | Date: 24-12-2013 | Page: 37/74

send and receive data. Since Zigbee's data loss is more apparent, it is up to Zigbee to adapt and move to another frequency. In order to choose the optimal frequency or channel, Zigbee can use spectrum sensing. This way, it can dynamically detect the ideal location that provides the least risk of interference. By moving away from the Wi-Fi signals, both technologies are able to coexist.

The main benefit of spectrum sensing for this case is the fact that multiple technologies and users can coexist in the same band. This is achieved by avoiding interference. For unlicensed business scenarios, the most important actors are the unlicensed users and the regulator. The unlicensed users are allowed to share unlicensed spectrum, but they need to comply with certain rules put forward by the regulator. Most importantly, the bands accessible without license are defined by ITU-R and national radio authorities. Additional rules mainly contain technical requirements for the devices, accepted power levels, field strength limits and regulations regarding interference. Every potential unlicensed user should comply with these rules before accessing the ISM band.

The above describes the current workings and regulations for the business scenario. A question that can be asked is whether the implementation of spectrum sensing in unlicensed devices would change this situation. It can be assumed that additional regulations will not be needed. On the contrary, some technological device requirements that have the purpose of limiting and avoiding spectrum could be redeemed by spectrum sensing, since it could by itself solve all interference issues. In order for this to work, however, an additional condition a regulator might set, is that every device that wants to enter the unlicensed band should be equipped with spectrum sensing engines.

Additionally, a regulator might have issues with the fact that spectrum sensing could also lead to frequency hoarding. Since everyone will be able to sense the ISM bands for available frequencies, some users may block all of these frequencies, just in case they might need more bandwidth. If the regulator is aware of this sort of behavior, it is very likely it would act against it.

4.4.3.2 Single RAT Pool

If license ownership is a fact, but no exclusive frequency bands are assigned to every single licensee, then those licensees will have to share spectrum from a spectrum pool. In case different radio access technologies could operate in this spectrum pool, while sensing for appropriate frequencies, spectrum efficiency would theoretically be maximised, although some experts argue that the diversity of technologies and their propagation characteristics would make interference mitigation measures so stringent that parts of the gained spectrum efficiency would again be lost, for example due to excessive 'largest common denominator' guard bands and spectrum masks. This Multi-RAT Pool business scenario is still rather unrealistic at this moment. Therefore, the focus will be on spectrum pool in which all licensees of just one technology share spectrum by sensing the pool and occupying appropriate and available frequencies.

To assess business and regulatory issues, the Open spectrum LTE business scenario has been chosen; in which all LTE licensees share all available LTE bands. If this scenario is compared to the unlicensed one, the huge differences immediately become clear. This is an operator-based scenario, which does not require off the shelf equipment, but expensive industrial scale networks that need to be used more efficiently because of the huge investments. This being said, it is incomparable to most other scenarios. For spectrum sensing, it is important to know that LTE can operate on multiple frequencies, in a variety of frequency bands and even in various slices of bandwidth ranging from 1.4 MHz up to 20 MHz. Considering that this variety of frequency bands is to be found in the spectrum pool, spectrum sensing becomes essential in rapidly finding available frequencies. Furthermore, spectrum sensing could lead to more efficient use of the spectrum pool, by optimally filling it.

One of the apparent downsides of this model comes down to the willingness to fairly share between competitors. Imagine five mobile network operators all utilising the same LTE "spectrum pool". The regulator must guarantee access for all operators and a fair distribution of the spectrum. A first issue to address here is how such a fair distribution could be defined. Among other options, the regulator might take into account the number of mobile subscriptions, and set bandwidth boundaries accordingly.

A second issue the regulator may struggle with is the actual use of frequencies for the right purposes. In other words, how can the regulator control whether or not occupied frequencies are actually used for serving the customers? Furthermore, how can it act if occupied frequencies are not used for serving customers? It is needless to say that these issues still have to be resolved on a regulatory level, before spectrum sensing could ever be implemented in a spectrum pooling business scenario.

4.4.3.3 Multi-RAT Market

In this scenario licenses are issued, specific bands are exclusively assigned to every single licensee and tradability is allowed. In this case secondary users can, under specific conditions, access the licensee's frequency band. Again, this is a very prominent difference with the previously discussed scenarios. Since the context is again entirely different, different conclusions can be drawn from this group of scenarios.

For this scenario, two business cases will be explored below: emergency and public services and TV White Spaces business scenarios.

4.4.3.4 Emergency and Public Services

Every European country has a designated emergency band, for which the emergency operator has an exclusive license. This is the 380–400 MHz band. For routine situations, this band offers more than an adequate amount of frequencies.

However, in crisis situations, the need for bandwidth exceeds the available band. Summarised, the emergency operator usually has excess and occasionally experiences a shortage of spectrum. Obviously, the latter could have serious consequences as all radios would have to queue before being able to communicate.

Spectrum sensing could offer two main benefits to solve these problems. First of all, secondary users could sense the emergency band, looking for available frequencies during routine situations. In return, the emergency operator could receive compensation. Second, the emergency operator itself could sense for available frequencies in other bands during times of crisis, when the need for bandwidth is exceeding the emergency band. Again, the emergency operator would also have to compensate the primary user (licensee) for utilising its frequencies.

Since crisis situations are impossible to predict, it is crucial that in these rare cases, the emergency operator can push all secondary users from its frequency band. The emergency operator would thus require guarantees concerning the availability of spectrum before opening up its band. Even though most agreements are bilateral (between the primary and secondary user), the emergency operator would still want the regulator to be involved. An emergency operator for example, would want the regulator to first check whether the sensing technology works. Second, the emergency operator wants regulatory guarantees that the technology would never fail. Third, the technology for 'pushing' secondary users during crisis situation should be examined, and lastly, the emergency operator would want the regulator to do some research on correct pricing and negotiation platforms.

Even if all these conditions are met, the question of which secondary users would put up with the occasional push, still remains. It is rather unlikely that mobile operators would risk offering a bad quality of service, with a bad reputation as a consequence, for a minor spectrum gain in return.

4.4.3.5 TV White Spaces

The TV White Spaces scenario is distinct from the emergency and public services scenario as the latter is using public spectrum, while this scenario will focus on commercial spectrum. As the context differs, it becomes clear that these scenarios cannot be treated equally.

The analog to digital switch over in television broadcasting has had some positive consequences on spectrum use. As digital signals require less bandwidth to provide the same or even better quality of television, previously occupied frequencies become available. Moreover, in many places empty channels exist between channels used for broadcasting, in order to avoid interference. These so-called TV White Spaces could be used for other, licensed or unlicensed, services. Because they are situated in the lower areas of the radio spectrum, these available channels have very good propagation characteristics, making them well suited for long range broadband access technologies (e.g. WiMax), particularly in areas where fixed broadband access is hard to realise. In order to make use of this potential without refarming the frequencies altogether, the TV band can be opened up to secondary users, which would scan the licensed band, looking for available channels. If the secondary user wants to make use of the available channel, it has to adhere to certain conditions (such as avoiding interference) and possibly compensate the primary user for using its spectrum band. Not only will sensing allow the secondary user to identify available channels, it will also allow the secondary user to (dynamically) avoid interference [61]. In case the license holder starts to make use of frequencies previously lying idle, the secondary user can again detect this through sensing—possibly aided by a database, as in the U.S.—and move away to other, available channels. Summarised, spectrum sensing would enable efficient use of abundant spectrum. In return, the licensee could receive compensation [62].

It can be assumed that the licensee would be willing to open up its band if correct compensation is foreseen and if the broadcasting of its content does not experience any interference. Secondary users, from their side, would be very willing to access the TV band. They could lease the excess frequencies to deploy mobile services, such as last mile broadband city coverage using IP-based Wi-MAX. For many of these secondary users, spectrum sensing is crucial to find available spectrum portions to operate. Without the existence and detection of these available portions, most of these operators would not be able to transmit any data, as they do not have appropriate frequencies or licenses at their disposal.

Given the fact that licensees would trade frequencies with secondary users, this business scenario deals with the secondary market principle. In the RSPG paper [58] it is proposed that the conditions for such a secondary market should be set by the regulator. However, in case there is only one licensee, a "marketplace model" would be unlikely to be deployed in the future. On the contrary, bilateral contractual agreements between the licensee and the secondary users would be more likely to occur. This also implies less control of the regulator over the trade process. The licensee will most likely be the actor deciding on the different conditions, such as compensation, technical requirements and interference issues. However, the current general regulatory framework should always be taken into consideration, even in case of bilateral contractual agreements.

4.4.3.6 Single RAT Market

For this group of scenarios, a *Secondary Market LTE* scenario is discussed. In this business scenario, only the use of LTE is allowed. As opposed to the *Open spectrum LTE* business scenario discussed earlier, this business scenario does not deal with a spectrum pool, but with exclusively assigned frequency bands that can be conditionally accessed by secondary users. As a consequence, this Single RAT Market should also be regarded as a separate group of scenarios.

The rights of spectrum use, acquired by the primary user, can be traded or leased. In other words, the licensee of a frequency band for LTE use would be allowed to be remunerated by a secondary user, in return for opening up a certain portion of its frequency band. The secondary user would sense this band, looking

Layout: T1 Standard SC | Book ID: 318863_1_En | Book ISBN: 978-3-319-04021-9
Chapter No.: 4 | Date: 24-12-2013 | Page: 41/74

for available frequencies. The primary user's motivations would be the compensation it would receive from the secondary user, making up for the high fee paid to acquire the license to operate in the frequency band. The secondary user's objectives could be offloading of its own over-utilised bands, better coverage to its clients on the competitor's network, better quality of service, etc.

On a regulatory note, there has been some discussion about regulatory reform to be able to allow this secondary market. In the RSPG paper [58] it is proclaimed that the national regulator can decide on the conditions for such a secondary market. It is even expected that in the future, a real-time marketplace and negotiation platform could come into place.

Another question that arises in this secondary market model is whether or not this will create new actors in the telecommunications industry. If a marketplace would come into place, who would be in control of this market? Would this be the regulator? Would this be an LTE operator? Or would this even be a third party, acting as a broker? Would there even be a marketplace accessible for all operators, or would the secondary market just exist in bilateral relations, when one operator privately contacts another operator to buy or sell?

In any case, it is believed that the need for a regulator would be less stringent than in the *Open spectrum LTE* business scenario. Contracts not only set the technical conditions for entering the primary user's spectrum between operators, but they also decide on other conditions (such as compensation, duration, interference limits, Quality of Service guarantees, etc.).

4.4.3.7 Flexible Operator

A last business scenario can be situated in the licensed and exclusively assigned bands that are not tradable. In other words, the assigned frequency band can never be accessed by other users. If only one access technology can be used in such a band, spectrum is used in a static way, similar to the situation today. Since spectrum sensing would make no sense in such a business scenario, it is of no use to elaborate on it. However, if multiple technologies can be used, spectrum sensing could do its part. For this case, an LTE—femtocell handover business scenario will be analysed.

Femtocells are smart cellular access point base stations that use the Internet as backhaul. The femtocells are designed to solve the problem of reduced coverage and data rates, when using cellular technology indoors. Multiple femtocell 'heads' connect to a base station controller, which performs the handover (between macrocell and femtocell) and radio resource management. Besides better quality of service (higher data rates and increased coverage), the use of femtocells can be advantageous because they are cheap, in terms of CAPEX and OPEX, and require less power.

Spectrum sensing in mobile phones could be used to connect to better performing networks (femtocells). The network operator would encourage this, because it can offload its macrocell networks. Furthermore, the operator can save

Layout: T1 Standard SC | Book ID: 318863_1_En | Book ISBN: 978-3-319-04021-9
Chapter No.: 4 | Date: 24-12-2013 | Page: 42/74

on OPEX and enjoys customer lock-in, as the bond between end-user and network operator has tightened, considering the purchase of an operator's femtocell. On the other hand, the end-user will enjoy better quality of service, guaranteed coverage and higher data rates, enabling innovative services. Additionally, it could be possible that he has to pay less for service through femtocells.

The most important actors in this business scenario are, without any doubt, the mobile network operator and the end-user. Presumably, the end-user already has a mobile subscription with the mobile network operator.

From a regulatory perspective, not much has to change vis-à-vis the current regulatory framework. The end-user and network operator play by the rules that were agreed in their contract. Still, one consideration can be made: a mobile network operator would want the femtocell to only operate in its own frequency bands. As a consequence, the operator enjoys customer lock-in. This may be in conflict with the general regulatory preference of interoperability. A few years ago, number portability came into place to ensure end-users the freedom to switch between operators. Therefore, it can be assumed that the regulator would want a femtocell to serve not for one operator only, but for all operators in the market.

4.4.4 Conclusion

The idea that a set of spectrum sensing business classes can be distinguished which refer to strongly divergent actors and interactions, and subsequently also to different consequences and conclusions, has been tested in this paper. Four business parameters have been proposed, which are the basis of a business classification of distinct spectrum sensing classes and scenarios. The purpose of such a classification is providing a starting point for future research of spectrum sensing and CR implementation. Furthermore, such a classification could be of value to business actors and regulators, as they could use this classification for further analysis and decision-making.

It is clear that spectrum sensing cannot be managed and regulated as a whole. Because different business scenarios have different actors, roles and consequences, this paper indicates that the proposed scenario groups are fundamentally distinct and incomparable. As a result, conclusions for one set of scenarios should be assumed to be potentially widely different from other spectrum sensing business scenarios. In other words, every scenario should be analysed separately to evaluate its viability and the way spectrum sensing can contribute to this. Future research will further detail and analyse the fundamentally different business and regulatory logics behind the proposed classes and scenarios in real-life cases.

Acknowledgments The findings presented in this paper are based on research performed in the IWT ESSENCES project (Flanders, Belgium). Contributions from colleagues and project partners are here acknowledged, with special contribution from Matthias Barrie.

4.5 Possible Business Opportunities for CR

Peter Anker

Ministry of Economic Affairs and Delft University of Technology, Delft, The Netherlands

It may be assumed that the regulatory regime and the fundamental choices that will have to be made on the use of CR technology will create certain business opportunities and at the same time will pose limitations on other business opportunities for CR and dynamic access to spectrum (see Sect. 5.2 for in-depth discussion on this). There needs to be a fit between the regulatory regime, the fundamental choices on technology and a perceived business opportunity.

Opportunistic spectrum access based on sensing will always have a likelihood of interference and there are no guarantees that an OSA-device can find an opportunity to communicate. This will depend on the amount of OSA-devices and their communication needs in relation to the amount of capacity available. This sets limitations to the use and on the types of applications that can be supported. Since there is no need to build infrastructure there is a match with a device oriented open access regime of a commons. OSA based on sensing is expected to be restricted to low-end applications involving low power devices.

Opportunistic spectrum access can be used to share bands between licensed users and unlicensed short-range devices in bands that were difficult in the classic scenario. A good example of this is the use of the 5 GHz band. RLANs use sensing to detect and avoid incumbent radar systems.

OSA is also of interest to military users but for a completely different reason. A true OSA-device acts solitary without the need for coordination with the outside world. This makes it possible to communicate without making the whereabouts and communication needs of the military radios known to others. This will make their communications less vulnerable.

Since sensing is in its present form is not reliable enough, regulators around the world have turned their focus from sensing towards a GDB. This will require investments in a database and related infrastructure that need to be recouped. Entrepreneurs will only invest in this infrastructure if there is long-term assurance for access to spectrum and willingness to pay from customers. This shifts the orientation from a device centric approach to a service centric approach. Such a business case is better supported by a regulatory regime based on property rights.

A possibility to ease the problem of the (un)reliability of sensing is to focus sensing in a band that is not too-wide in a completely unlicensed environment to create a true commons for short range devices. The regulator should pinpoint a band for dynamic spectrum access in cooperation with industry. To reach economies of scale this band could be designated on a regional level, for example on a European level.

A very promising application for a true commons whereby unlicensed devices pool their spectrum is in-house networking. An in-house network is an ad-hoc network by its very nature. No two in-house networks are exactly alike and devices are turned on and off during the day, new devices are brought in, devices leave the house and the neighbouring houses have the same ad-hoc way of working. The number of wireless devices in a household is rising while the users want to have new equipment that is "plug and play". A new device that is put into service should be able to find its own possibilities to communicate within the in-house network. OSA can be used to realise this goal. A new OSA device senses its environment and coordinates its use within the local in-house network. A possible band to start is e.g. the 60 GHz band.

A second example of ad-hoc networking is the radio network between vehicles as part of Intelligent Transportation Systems (ITS). Restricting access to the pool for certain applications with a polite cognitive protocol, may alleviate the tragedy of the commons. In that case, the number of devices outnumbers the available spectrum in such amount that the spectrum is of no use to all. However, even if a polite cognitive protocol is used and the band is restricted to a certain type of applications, the amount of spectrum that is made available must be enough to cater for the intended business case.

Another possibility is to use sensing in a more controlled environment between licensed users. This will give more control over the environment, because the users are known. This type of sharing could be used to broaden the amount of accessible spectrum for temporarily users who need a guaranteed Quality of Service. This makes this type of sharing a perfect fit for e.g. Electronic News Gathering and other Programme Making and Special Events services. Electronic News Gathering only requires spectrum for short periods of time and for a restricted local area but it requires guaranteed access during the operation.

Another service that needs guaranteed access to spectrum but only in a very local area and for a short period of time is public safety. Public safety organisations have their own network for day-to-day operations. However during an emergency situation they have a huge demand for communications on the spot [63]. A public safety organisation might make an agreement to alleviate their urgent local needs with other frequency users. In the agreement sharing arrangements are covered but the actual spectrum usage can be based on the local conditions and spectrum sensing of the local use of the primary user.

A good opportunity to start this form of sharing is in bands of the military. The military already have a longstanding practice of sharing with both the ENG community and public safety organisations. This may raise the level of trust to a level that is high enough to start an experiment.

In a true property rights regime dynamic access to spectrum is obtained through buying, leasing or renting access rights from the owners of the spectrum. This regime provides the possibility for active coordination between the incumbent user and the cognitive user about the likelihood of interference, and on guarantees about access to spectrum. If the barriers to instant trading are removed, the opportunity to buy and sell rights to access spectrum can be based on the actual demand for spectrum. This creates the opportunity to use DSA systems for higher valued services, such as mobile telephony, and for a spot market to be introduced.

A spot market is a perfect means to acquire or sell rights to spectrum access based on the actual demand at any given moment in time.

This property rights regime can be used among operators to pool the spectrum in such a way that the rights to spectrum access are based on the actual demand for spectrum by their respective users. One of the suggested implementation scenarios is that mobile operators use a part of their spectrum to provide the basic services to their respective customers and pool the rest of their spectrum to facilitate temporarily high demands for spectrum. However, cooperation between mobile operators that are in direct competition to each other is not likely to happen [64].

This kind of sharing spectrum might be a more viable option for implementation in border areas to ease the problem of border coordination. Nowadays the use of spectrum in border areas is based on an equal split of the use of spectrum between neighbouring countries through the definition of preferential rights. However, there is no relationship with the actual demand for spectrum at either side of the border. A prerequisite is that the spectrum market is introduced at both sides of the border or in a region, e.g. the European Union.

Pooling spectrum between different services that are not in direct competition to each other might be a more promising approach. A property rights regime can help to make licensed spectrum that is not fully used available to others users. In this case access to spectrum is based on an negotiable acceptable level of interference, instead of the worst case scenarios based on harmful interference that are used by regulators to introduce a new service in an already used band. This may open bands for alternative use which might otherwise be kept closed. The incumbent licensee may now have an incentive to open its spectrum for other, secondary, users. The incumbent licensee is in full control because it can earn money with unused spectrum, whilst the access to its spectrum of the secondary user is on the incumbents own conditions.

Licensed owners of spectrum can also grant access to parts of their spectrum that they do not need in a certain geographic area and/or for a certain period of time to secondary devices. These devices can get access to this spectrum after an explicit request for permission to the owner of the spectrum. The owner will need a mechanism to facilitate requests from secondary devices for permission to use spectrum. Cellular operators can use their existing infrastructure to handle these requests. E.g. a mobile operator can set aside a mobile channel for this purpose. The owner of the spectrum and the secondary user can negotiate their own terms under which the secondary user may have access to spectrum. This provides possibilities for active coordination between the incumbent and the secondary user about the acceptable level of interference and guarantees to access spectrum.

A spectrum market can only function if information about the actual ownership of the spectrum property rights is readily available to facilitate trading. The regulator is ideally positioned to perform the task to keep a record of the ownership of these rights. Inclusion of monitoring information about actual usage of spectrum can further facilitate trading by giving more insights in the possibilities for secondary usage.

A second incentive might be to introduce easements in spectrum property rights. In other words, if a spectrum owner is in possession of spectrum that (s)he actually does not use, everybody is entitled to use this spectrum in an opportunistic way as long as the transmissions of the rightful owner are not subject to interference from this opportunistic spectrum access. This is an incentive which might prevent market players from hoarding spectrum [65].

A special case of licensed spectrum pooling is pooling whereby a single operator who is the exclusive owner of the spectrum uses CR technology to perform a flexible redistribution of resources among different radio access technologies within its own licensed frequency bands to maximize the overall traffic by an optimum use of spatial and temporal variations of the demand. This could be used by mobile operators to realise a flexible spectrum allocation to the various radio access technologies in use or to have an optimal distribution of spectrum between the different hierarchical layers of the network. For example to realise an optimal allocation of spectrum to femto-cells that takes account of the actual user demand without affecting the macro network. The prime requisite for such a scenario is that the license from the operator is flexible enough and is technology neutral.

4.5.1 Conclusion

CR holds an interesting promise for improved utilisation of the radio spectrum. However, there is a considerable degree of uncertainty regarding the potential application of CR. In addressing these uncertainties the business case for the CR is to be considered as centre point.

Both the regulatory regime under which the CR will operate and the specific characteristics of the CR technology will pose limitations to the business opportunities for the CR. Successful introduction of CR will require alignment between the characteristics of the CR and the regulatory regime under which the CR will operate. This is further discussed in Chap. 5.

4.6 Value of TVWS Spectrum and Analysis of Business Feasibility of CR for Mobile Broadband Services

Jan Markendahl[1] and Bengt G. Mölleryd[2]

[1]Royal Institute of Technology (KTH), Stockholm, Sweden
[2]Postal and Telecommunications Administration (PTS), Stockholm, Sweden

In this section we present an overview of approaches for valuation of spectrum and describe characteristics and differences between valuation of licensed and non-licensed spectrum. Cost and cost structure for CR are introduced. The impact of deployment costs and spectrum prices on total costs are illustrated for a number of business scenarios where deployment using CR is compared to conventional mobile broadband. Finally we look into uncertainty and risk in terms of control of spectrum and availability of CR equipment.

4.6.1 Value of Licensed Spectrum and Approaches for Valuation of Spectrum

4.6.1.1 Introduction: Industry Transition Push Up Demand for Spectrum

The on-going transition from a voice to a data centric business is challenging for mobile operators as it undermines the established business model. This could be illustrated by the fact that mobile voice generates the equivalent of EUR 240 per GB while mobile data generates around EUR 5 per GB. This forces operators' to launch efficiency programs, cut operational expenditures, like network operational cost. However, in order to cope with the steep traffic growth and capacity constrains operators are forced to continue investing despite declining revenues (Fig. 4.17).

In order to increase capacity spectrum is essential, as spectrum could be seen as a substitute to additional sites, and secondary spectrum, like CR, could potentially provide operator with a cost efficient addition of capacity.

4.6.1.2 Valuation of Spectrum and Network Deployment

The necessity to release more spectrum is at the heart of the most countries digital agendas. However, Plum Consulting[1] underscores that the majority of spectrum suitable for mobile communications have been allocated which implies that it is required to transfer it from other applications in order to make it available for mobile communications. In order to make these decisions valuation of spectrum is essential. Consequently, the area of valuation of spectrum generates a growing interest from industry, operators, consultants, academia, regulators and governments.

Plum presents a review of the value of spectrum licenses, model values based on expected revenues and costs for a hypothetical operator [66]. The Australian government (ACMA) applies an opportunity cost modeling, which it defines as the highest value alternative forgone, but underscores that the opportunity cost pricing differs according to circumstances [67]. Doyle state that it is necessary to take account of the opportunity cost values associated with alternative uses and across different frequency bands used by different users [68]. Yeo estimates spectrum

[1] Plum Insight, August 2013, available at: http://www.plumconsulting.co.uk/pdfs/Plum_Insight_August_2013_The_role_of_spectrum_valuation.pdf

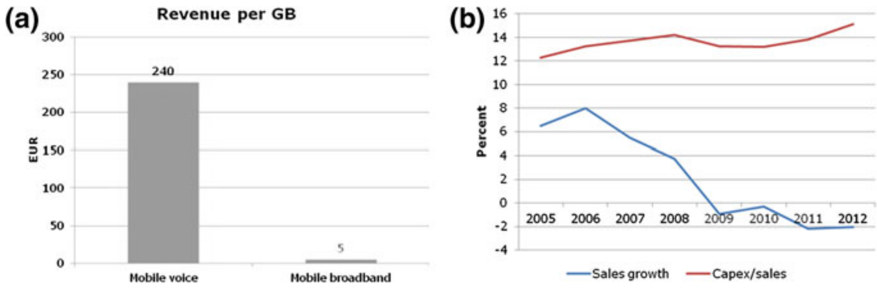


Fig. 4.17 **a** Revenue per GB for mobile in Sweden 2012; **b** Average CAPEX-to-sales and sales growth for European operators 2005–2012, based on an average on company ratios for operators: BT, DT, FT, KPN, Swisscom, Telefonica, and TeliaSonera. **a** *Source* PTS statistics and authors calculation **b** *Source* Bloomberg

values based on calculations from auction data and with an analysis of observed bidding behavior through an econometric model [69].

Ard-Paru captures the value of spectrum commons in Thailand through a cost and benefit analysis, in combination with an engineering valuation which could be used as an indicator for the regulator to decide to license spectrum or not [70]. ITU presents an approach to valuation of spectrum in order to facilitate for spectrum regulators to determine reasonable expectations on market-based revenues for the spectrum in beauty contest or administrative distribution processes, and for spectrum auctions to determine reserve prices [71].

Altogether, the valuation of spectrum could be based on the opportunity cost approach as it builds on the fundamental idea to capture the value of the alternative use, or expressed as what have to be forgone when one alternative is chosen rather than another one [72]. Moreover, Doyle [68] underscores that it is challenging to calculate opportunity cost values of spectrum and that it will generate a wide range of estimates.

Given that the value of spectrum is a function of network capacity as spectrum and base stations sites could be regarded as substitutes it is motivated to highlight the fundamentals for network deployment, which is followed in the next section.

4.6.1.3 Coverage, Capacity and Cost

Capacity in mobile networks can be increased by replacing existing radio equipment with more efficient technology, by deploying new base stations or by adding more radio equipment to existing base station sites using additional spectrum. The relation between network costs, capacity, bandwidth and service area has been established by Zander [73], which stipulates that for a specific amount of spectrum and for a specific radio access technology the following relation holds for capacity limited systems: *"the deployment of N times more capacity requires N times more base stations"*.

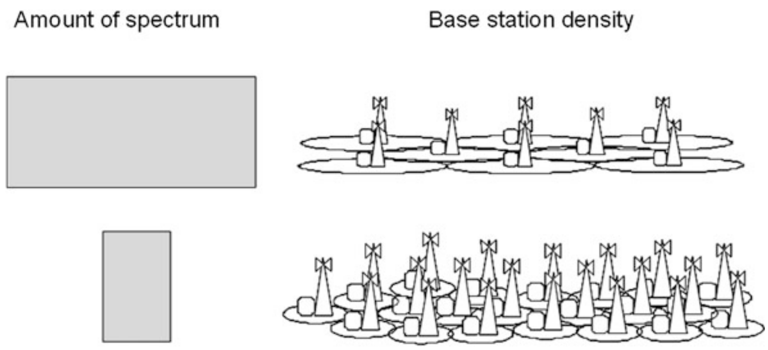


Fig. 4.18 Higher capacity can be provided by more sites or with a larger amount of spectrum

Operators that are unable to obtain additional spectrum are forced to deploy more base stations which require more investments compared to competitors who can add more spectrum and re-use existing base stations sites. Zander describes basic relationships that can be used for comparing different network deployment options [9]. For example, if a mobile operator with a 3G network at 2.1 GHz wants to expand the capacity one option is to build a denser network using the 2.1 GHz band. Another option is to acquire new frequencies in the 1.8 or 2.6 GHz band and reuse existing sites. This is feasible since these bands have almost similar propagation characteristics. Analysis of network deployment and sharing strategies for operators with different amount of spectrum and existing number of base stations are presented in [74, 75] (Fig. 4.18).

4.6.1.4 Cost Structure Modeling and Analysis

For macro cellular network deployment the main components in the cost structure of the Radio Access Network (RAN) are the base station sites, the radio equipment and transmission. It is, however, not the cost of radio equipment that is the dominating component in the cost structure. The largest costs are associated with the base station sites, including costs for towers, masts, non-telecom equipment, power, installations and site leases [76].

When 3G and HSPA system was deployed the costs for the radio equipment (and the capacity) were comparable with the site costs. The fierce competition among equipment manufactures in combination with technology advancement has pressed down prices on network equipment during the last decade, improving the cost-capacity ratio significantly. This enables operators to replace existing radio equipment with new equipment (LTE) for approximately EUR 10K per base station. This can be compared to typical costs of EUR 100K in Europe for deployment of a new site and EUR 20–30K for upgrading an existing site with fiber connection [75], see Fig. 4.19 for a comparison of site capacity and costs. The most recent base station equipment supports three sectors, bandwidths up to 20 MHz and multi-standard solutions, e.g. GSM, WCDMA and LTE.

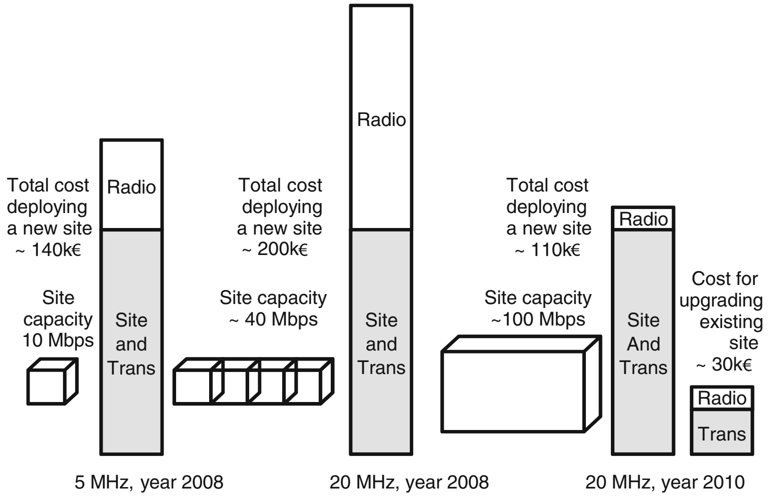


Fig. 4.19 Site capacity and costs illustrating cost reduction by re-use of existing sites [75]

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

4.6.1.5 The Overall Approach

The estimation of the opportunity cost of spectrum is based on an analysis of network capacity and cost for different network deployment options which use different amounts of spectrum. The cost comparison is the basis of the opportunity cost of spectrum and represented by the cost savings facilitated by additional spectrum bands compared to building out existing networks that provide the same capacity as the network with additional spectrum. The approach applied below, which is a high system level analysis, builds on [77–79].

The approach has been explored in several papers [80–83] and the applied analysis consists of three steps: (1) Selection of the network deployment and spectrum allocation cases to compare, (2) Analysis of the deployment cases including user demand, capacity and cost structure, and (3) Comparison of network costs for the options resulting in the opportunity cost.

If operators do not obtain additional spectrum they need to deploy a denser network in order to enhance capacity in areas with capacity constraints. The operators' strategies for network deployment and spectrum portfolio management are vital parts of overall business strategies, which varies between operators depending upon regulatory and market conditions and operators' market position.

4.6.1.6 Calculation of Opportunity Cost

The user demand expressed as capacity per area unit (Mbps per km^2) is based on user density and the data usage per subscriber. It is based on monthly user demand (GB/month) and an approximation on how the usage is spread out over the day. For example, a usage of 5 GB per month spread out over 8 h per day is equal to a continuous demand of 0.05 Mbps per user.[2] By calculating the demand of all users in the area an estimate is obtained of the total area demand (Mbps per km^2). This is compared with the capacity per area unit provided by the base stations, calculated as follows:

Site capacity = *bandwidth* (MHz) * *spectral efficiency* (bps/Hz) * *number of cells/sectors per site*.

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

Total investments to deploy a mobile network are calculated by taking the capital expenditures (CAPEX) for electronics and civil works per site multiplied with the total number of sites. The total cost per site for the active equipment (electronics, radio) is currently around EUR 10K. The cost for civil works is depending upon cost for material and labour implying that the CAPEX is determined by national cost levels. The opportunity cost of spectrum is estimated by analyzing substitution between spectrum and base station sites, and calculating cost savings provided by additional spectrum bands compared to increase the number of sites. The basis is operators' current spectrum holding, and the geographical coverage of the network. It is followed by an estimation of the number of existing sites, and the range of the cell radius. The spectral efficiency gives the basis to calculate network capacity for the different deployment options providing the similar amount of capacity per km^2.

4.6.2 *Aspects and Approaches for Valuation of Non-licensed Spectrum*

The objective of this section is to highlight the differences between the valuation of licensed and non-licensed spectrum as the "valuation logic" differs substantially. Basically, it makes no sense to apply the opportunity cost approach if the non-licensed spectrum is the only type of spectrum that an actor has. On the other hand it is relevant if the actor has other types of spectrum.

[2] The estimate of 0.05 Mbps per user is based on a usage of 5 GB per month: 5 * 1024 * 1024 * 8 = 4194304000/30 = (1398101333/24/3600) * 24/8 = 49 kbps.

4.6.2.1 Key Differences in Valuation of Licensed and Non-licensed Spectrum

The valuation of licensed spectrum is based on the opportunity cost approach where the key idea is substitution between spectrum and base station sites. The basic assumption is that the value of the alternative use, or expressed as what have to be forgone when one alternative is chosen rather than another one [72]. The used assumption is that the resulting capacity and availability of spectrum is well defined and stable, this is the case considering licensed spectrum.

If there is just one type of spectrum used, no opportunity cost analysis is possible. If the actor can use more than one type of non-licensed spectrum a modified opportunity cost approach based on substitution between sites and spectrum could be used. For example TV white space spectrum can be used as replacement or complement to a LTE wide area network or to a WiFi network, i.e. instead of deploying a denser LTE or WiFi network. Estimation the value of non-licensed spectrum applying the opportunity cost approach makes sense if other spectrum resources are available for the operator under study.

With just one single type of non-licensed spectrum, open access (like WiFi), secondary access (like TV WS) and shared access (some type of LSA), the value is that it enables operators to offer services "at all". Hence the value of the non-licensed spectrum depends on potential revenues in relation to the costs for exploiting the non-licensed spectrum bands. The costs are both related to the network deployment and to the overall business. Network costs are e.g. to build base station sites and transmission, to rent space in exiting sites, to buy and install CR equipment and maybe to develop CR solutions. The overall costs are those typical for an operators business, e.g. to build up and maintain a customer base (i.e. marketing & sales, CRM) and to provide service and billing platforms.

For the cases where the approach with opportunity costs and substitution of sites and amount of spectrum can be used another type of aspect needs to be considered—different types of uncertainties. Unlike licensed spectrum the use of non-licensed spectrum is uncertain in many aspects, availability, interference level and resulting quality for end-users. In addition, the complexity and implications for cost of the CR equipment is associated with large uncertainties. For LTE base station equipment both the performance and costs are well known, see Fig. 4.20 for a comparison.

4.6.2.2 How to Estimate Spectrum Value for Non-licensed Spectrum Bands?

In order to estimate value of non-licensed bands different approaches are used depending on what kind of actor we consider and if that actor can make use of other types of spectrum resources. In the rest of this section we will discuss this situation considering mobile broadband (MBB) services using licensed band and

Layout: T1 Standard SC | Book ID: 318863_1_En | Book ISBN: 978-3-319-04021-9
Chapter No.: 4 | Date: 24-12-2013 | Page: 53/74

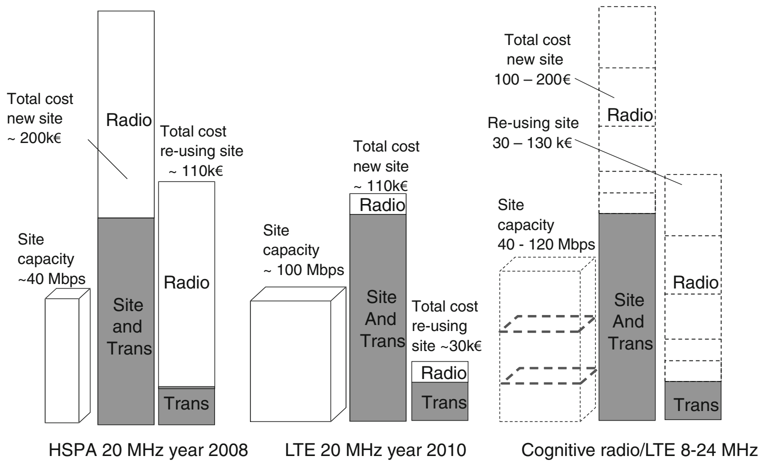


Fig. 4.20 Example of capacity and cost structure for different types of radio access technologies (For the CR solution the indicated variations for capacity and radio costs depend on the amount of available bandwidth and uncertainty about radio complexity and implementation, picture modified from [88])

conventional LTE systems and compare this to a system using TV white space spectrum and CR equipment.

The analysis approach is outlined in Fig. 4.21. It is applicable to both actors with licensed spectrum, i.e. mobile operators, and actors with making use of non-licensed spectrum only. The first steps are common and include: (i) estimation of spectrum availability, (ii) estimation of capacity that can be provided for a specified type of deployment and inter-site distance, and (iii) a check if the supplied capacity can meet the estimated demand. If not, another (larger) site density needs to be applied. When the demand is satisfied the analysis is split into two branches depending on what actor that is considered.

For an actor with just non-licensed spectrum the next step is to estimate the willingness to pay by end-users. The resulting revenues are then compared with the estimated investments for networks and for other components in the operator overall cost structure.

For a mobile operator with licensed spectrum the opportunity cots approach can be used. The two following build out approaches are compared:

1. Build new sites using existing LTE technology and licensed spectrum
2. Re-use exiting sites and deploy new (CR) radio technology using non-licensed spectrum

Below we will in more detail describe the approach in Fig. 4.21 with focus on the common steps and how a mobile network operator can exploit TV WS. For a new actor the spectrum value depends on the potential revenues and the overall business case, this is beyond the scope of the section.

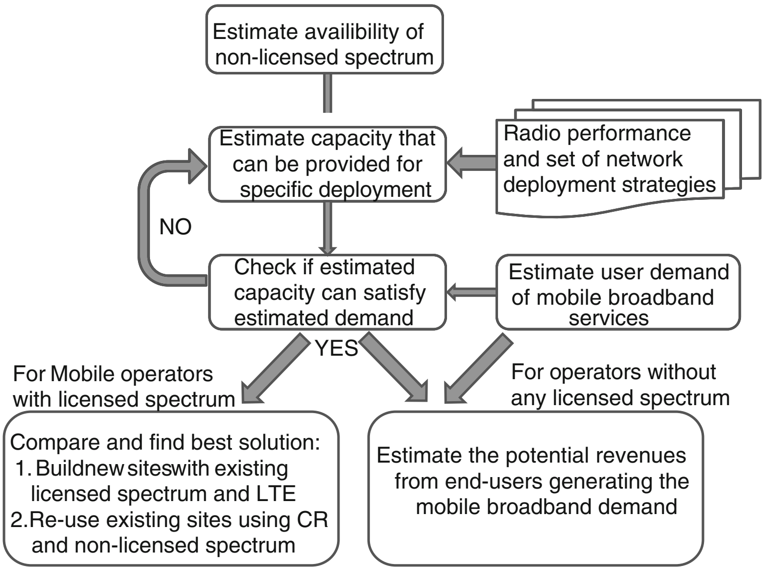


Fig. 4.21 Overall work flow for estimation of value of non-licensed spectrum

4.6.2.3 Network and Capacity Modeling and Analysis

Radio access technology

In order to see if the use of TV WS is feasible we need to do some general modeling of capacity. In this case where we consider "cellular use" of TV white spaces (TV WS) we mean mobile broadband access (MBBA) services. One motivation for this choice is the increasing demand for MBBA services and the relatively low amount of bandwidth that is currently allocated to mobile operators in the 800 or 900 MHz band. For mobile operators TV WS can be used as a complement to licensed spectrum possibly offering improved cost-efficiency. In the 800 and 900 MHz bands TV WS could be used as complement to or as replacement for licensed spectrum.

We assume that the MBBA service will be provided by a radio access technology like LTE with varying system bandwidth up to 20 MHz. We will compare the deployment of networks using the TV WS with deployment of MBBA using LTE in the 800 MHz band. In the analysis we consider cases with a relatively low number of available TV channels, 1–4 TV channels corresponding to a bandwidth of approximately 8–32 MHz.

Availability of TV white space spectrum

In the Quasar project[3] the number of available TV channels has been estimated for a number of countries. The number of "un-used" TV channels is very low in most part the country. "Many" TV channels are available in rural areas in northern Sweden, areas where the population density (and demand) is low [84–86].

Please note that the availability of spectrum for secondary use depends on the type of services and the type of network deployment that is used. By using macro base stations with high towers the mobile broad band will cause interference over large distances, hence the spectrum availability is low. If the spectrum is used for indoor deployment using low power base stations then the secondary usage will cause interference in limited area and hence the number of "available" TV channels will be much larger.

For Sweden less than five channels are available in most parts of the country [85]. Only in some rural areas in northern Sweden more than 20 channels are available, in these areas the demand is very low. One and four TV channels correspond to in total 8 and 32 MHz respectively. This can be compared with the spectrum allocation for the frequency bands intended for LTE in Sweden.

- At 800 MHz the operators have 10 MHz (downlink and uplink);
- At 2.6 GHz the operators have 10–20 MHz (downlink and uplink).

Offered capacity

The offered capacity for the mobile broadband access service depends on the available bandwidth and the spectral efficiency. The offered cell capacity in Mbps equals bandwidth (MHz) * spectral efficiency (bps per Hz). The bandwidth depends on the number of TV channels available for secondary access, the spectral efficiency depends on the network deployment and interference from other secondary users. In our estimates we will use cell average values although we know that the spectral efficiency for MBBA depends on the location of the end-user. In Fig. 4.22 the ITU target data rates are shown for the peak, average and cell border values.

The estimated capacity for a base station site with three sectors is 3 * the spectral efficiency * the bandwidth (3 * SE * BW). Both the spectral efficiency and the bandwidth in terms of number of TV channels can vary according to Fig. 4.23. With this model the key parameter is the product SE * BW with the dimension "bits per second".

The parameter set {SE = 1; BW = 8} gives the same results as {SE = 0.50; BW = 16} and {SE = 0.25; BW = 32}. The impact of interference and different cell sizes can be reflected in the spectral efficiency. For deployment in urban and rural areas we can assume spectral efficiency values in the range 0.50–2.0 and 0.25–0.50 bps per Hz respectively. The lower spectral efficiency for deployment in rural areas combined with a larger bandwidth (more available TV channels) results in values of the product "SE * BW" in the same range as for urban deployment.

[3] http://www.quasarspectrum.eu/

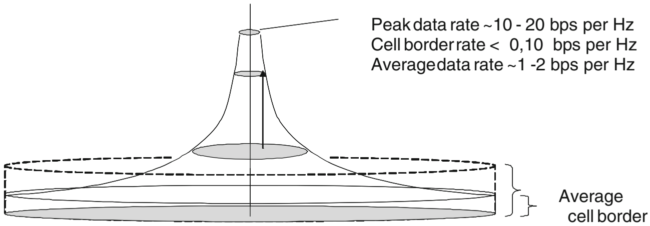


Fig. 4.22 Spectral efficiency target values for LTE

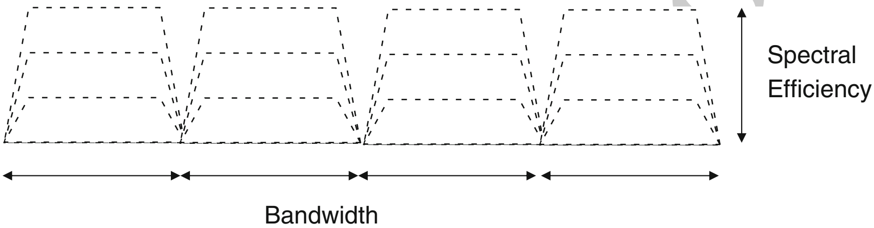


Fig. 4.23 Bandwidth and spectral efficiency

Modeling of user demand

For dimensioning of mobile broadband access we define the user demand as the capacity needed per area unit expressed as Mbps per km^2. This equals the average usage per user times the number of users per area unit. Mobile data usage is the amount of data sent and received per user during one month and usually expressed in GB. For Europe the smartphone users typically consume 0.1–1 GB per month and laptop users with dongle consume 1–10 GB. The usage needs to be expressed in terms of data rates. Assuming that the data is consumed during 8 h per day all days a monthly demand of 10.8 GB corresponds to an average data rate of 0.1 Mbps. Hence, a monthly usage of 0.1 GB, 1 GB and 10 GB per month roughly corresponds to 1, 10 and 100 kbps respectively.

In order to estimate the demand per area unit we need to consider the population density and the penetration of the service offered by the provider. The orders of magnitude of the area demand are illustrated in Table 4.2.

The demand is shown for different "user" densities and for users with different demand levels. The dimensioning means that these demand numbers need to be matched by the offered capacity.

Analysis of demand and offered capacity

We consider cases where quite few TV channels are available. One and four TV channels correspond to 8 and 32 MHz which can be compared to the deployment of 800 MHz networks with bandwidth in the range of 5 MHz–20 MHz.

In Table 4.2 we presented examples of the user demand depending on the number of users per area unit and the usage level per user. The user demand in

Table 4.2 Examples of required capacity as function of number of users and usage level

Geotype	Users per km^2	Area demand for different usage levels (Mbps/km^2)		
		0.1 GB/month	1 GB/month	10 GB/month
Rural	10	0.01	0.1	1.0
Suburban	100	0.1	1.0	10
Urban	1,000	1	10	100
Metro	10,000	10	100	1,000

Table 4.3 Examples of user demand and offered capacity per area unit assuming different coverage areas per site and spectral efficiency * bandwidth (SE * BW)

	Number of users per km^2	Area demand (Mbps/km^2)	Coverage area per site (km^2)	Capacity (Mbps/km^2) for varying SE * BW		
				2	8	32
Rural	10	0.1–1.0	100	0.06	0.24	0.96
Suburban	100	1.0–10	10	0.60	2.4	9.60
Urban	1,000	10–100	1.0	6.0	24	96
Metro	10,000	100–1,000	0.1	60	240	960

these scenarios, expressed as Mbps per km^2, is compared to the offered capacity. The assumed bandwidth (BW) is in the range one to four TV channels and the spectral efficiency (SE) is in the range 0.25–1.0. As mentioned elsewhere, the key parameter for the capacity estimates is the product SE * BW, see Table 4.3. We have assumed deployment scenarios where the cell size differ an order of magnitude when it comes to coverage area.

The comparison indicates that for the assumed usage and user densities and coverage areas of sites the demand can reasonably well be met with bandwidth corresponding to a few TV channels. With 32 MHz quite high demand levels can be met. When demand and supply can be matched the deployment strategy needs to be examined in more depth. The cell size and the site density need to be considered from a cost perspective.

The conclusion of this analysis is that since the offered capacity can meet the estimated demand the assumed type of deployment can be used for further assessment. The actor using on TV WS needs to look into revenues and the overall business cases. A mobile network operator needs to investigate what deployment options that is best, to make use of the TV WS spectrum re-using existing sites or to build a denser network using licensed bands. This is to be discussed next.

4.6.2.4 A Trade-Off for Mobile Operators: To Build a Denser Network or to Use More Spectrum

For addition of more capacity mobile operators have two main options. To use more spectrum and upgrade existing base stations sites with new radio equipment or to use existing spectrum bands and to build a more dense network, i.e. to add

Layout: T1 Standard SC | Book ID: 318863_1_En | Book ISBN: 978-3-319-04021-9
Chapter No.: 4 | Date: 24-12-2013 | Page: 58/74

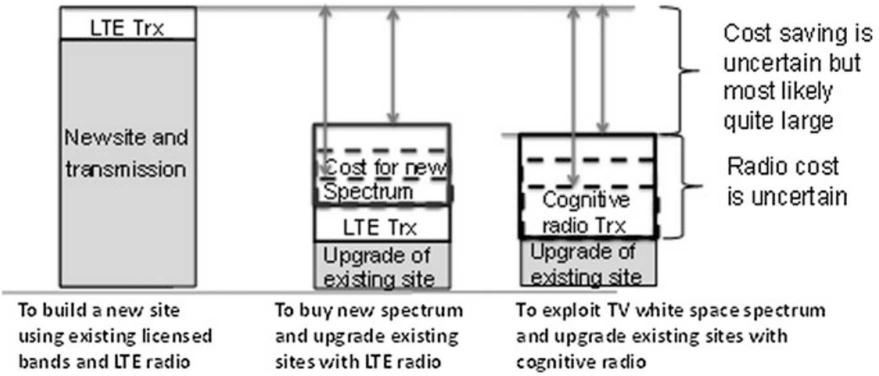


Fig. 4.24 Illustration of cost relations for mobile operators that want to add more capacity using existing licensed spectrum, new licensed bands or TV white space bands

more base station sites. As an alternative to buying licensed spectrum operators may use secondary spectrum access and hence some type of CR.

To add more sites are more costly since towers etc. dominates the cost structure of base station sites. The value of more spectrum in general is illustrated in Fig. 4.24. The price of licensed spectrum can vary a lot [81]. For cases in Europe en estimated “spectrum cost per site” is equal to or less than the cost of the radio equipment. Hence, operators can make substantial cost savings by using more spectrum, no matter if it licensed bands or bands exploiting secondary access are used.

Also for use of secondary access to spectrum the major cost savings result from the fact that no new base station sites are needed. It is not the zero spectrum costs that it is the main issue even if this has a larger impact for cases where the spectrum prices are very high. The costs for CR equipment are uncertain but anyway costs savings can be substantial as illustrated in Fig. 6.18. The use of secondary access would be interesting for mobile operators for another reason. This type of added capacity is used as complement to licensed spectrum bands. Actors using secondary access to spectrum as the only resources are much more vulnerable. On the other hand mobile operators may hesitate to include yet another type of solution and technology, this will be discussed more below in the section investments and risk.

The impact of network deployment and spectrum costs will be illustrated in the next section. The total network costs are studied both for fixed used demand and varying amount of spectrum as well as for fixed amount of spectrum and varying user demand.

4.6.3 Case: Impact of Deployment Costs and Spectrum Prices on the Business Viability of Mobile Broadband Using TVWS

In this subsection spectrum valuation will be illustrated by looking into the business feasibility of mobile broadband access services using secondary access of spectrum in the TV bands. The capacity-cost analysis considers costs for radio equipment, base station sites and radio spectrum comparing network deployment by a market entrant and an existing mobile operator using either licensed spectrum or TV white spaces. In addition, the impact of high and low spectrum prices is considered. The analysis shows that market entrants will be in a more difficult position than the established actors. No matter the cost-capacity performance of CR equipment, a new operator needs to invest in a new infrastructure with sites and transmission. Only for cases where the spectrum costs are "high" (compared to other cost components) use of TW white spaces turn out to be more cost efficient for both existing operators and new operators [87].

4.6.3.1 Case Description, Models and Assumptions

We consider cases for urban and rural network deployment were we compare the overall network costs for a market entrant and an existing mobile operator using either licensed spectrum or TV white spaces. The impact of spectrum prices is illustrated using examples from Europe and India.

Spectrum costs

It is often claimed that one driver for secondary use of spectrum is that the cost of spectrum can be avoided. This is only partly true; it depends on the spectrum price in relation to other network costs. Comparing recent auctions in different countries we can identify large differences. The spectrum cost per site for the Swedish case is in the same range as the radio equipment whereas in India the spectrum cost per site is as large as the costs for base station sites, see Table 4.4.

4.6.3.2 Coverage and Capacity of Base Station Sites

The assumptions regarding coverage are shown in Table 4.5. The user demand is satisfied by adding sufficient capacity to each site. When the demand cannot be met with the available amount of spectrum new sites need to be deployed, i.e. the more bandwidth the fewer number of sites. In the analysis we will show how the overall network cost depends on: (i) the amount of available spectrum (for a fixed demand) and (ii) the user demand (for a fixed amount of spectrum). For both the licensed spectrum and the TV white spectrum we assume that we use a LTE type

Table 4.4 Example of spectrum prices, data from [84]

Case	Bandwidth (MHz)	Spectrum price (€/MHz/pop)	Cost/Site (k€)
Germany 2.6 GHz	20	~0.05	~1
Sweden 800 MHz	10	~0.50	~10
India metro areas 2.1 GHz	5	~5	~100

Table 4.5 Network assumptions

	Urban environment	Rural environment
(Coverage Area [km^2], Radius [km])	(1; 0.56)	(100; 5.65)
Sectors/base station site	3	3
Bandwidth [MHz]	20	20

Table 4.6 Assumptions of user demand

	Urban area Sweden/India	Rural area Sweden/India
#Users/km^2	2,000/20,000	100/1,000
Usage GB/month/user	10/1	10/1
Demand (Mbps/km^2)	200/200	10/10

of radio access technology with an average spectral efficiency of 1 bps per Hz. For the capacity estimates we assume three-sector sites and a re-use factor of 1.

User demand

The dimensioning is based on the estimated user demand per area unit (Mbps/km^2). We assume that the data is "consumed" during 8 (equally) busy hours 30 days per month, see Table 4.6.

Costs for radio equipment and base station sites

We can compare mobile broadband systems using TV white space with deployment in the 800 MHz band. Although the uncertainty is high when estimating costs for CR equipment, some insights can be gained if we consider the overall cost structure for the network deployment. In Fig. 4.25 we consider two main components of the cost structure for a radio access network; the radio equipment and "the sites and transmission". In Sweden the cost for deployment of a macro base station site is typically in the range 50–200 k€, we assume a cost of 100 k€ for deployment of a new site. According to Telenor the cost for upgrading existing sites with a fibre connection is estimated to 20 k€ per site [75].

The cost-capacity ratio of commercial radio equipment has improved more than 20 times the last few years. This is illustrated in Fig. 4.25 where HSPA and LTE are compared. For CR we still do not have any cost numbers, in then analysis we assume twice the cost for the same spectral efficiency as LTE, i.e. 20 k€. Factors that may drive costs for CR are: large system bandwidth, additional systems for sensing, interference management, need to add data bases, and no large scale production. Even if the cost for CR equipment would be the same as for standard

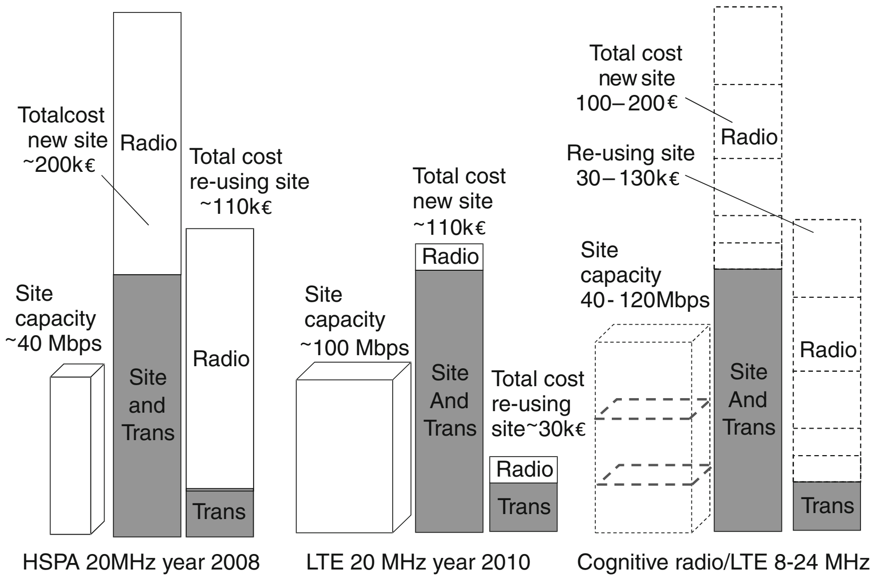


Fig. 4.25 Example of capacity and cost structure for different radio access technologies, for the CR the variations for capacity and radio costs depends on the amount of available bandwidth and uncertainty about radio complexity and implementation, from [87]

LTE base stations, the key issue is if new sites need to be deployed or not. In this case the problem is mostly a matter of market entry. In addition to deploying a totally new infrastructure, a new actor needs to invest in and build up marketing, customer base, service and billing platforms.

4.6.3.3 Performance Analysis: Impact of Cost Structure

We have assumed scenarios where a Greenfield and an Incumbent operator deploy networks in order to provide mobile broadband services. Two options are available for the operators; first, it is to run their networks by using licensed spectrum (this means to acquire new spectrum licenses) and second, to use TVWS and only upgrade the network sites with CR equipment. Assuming a fixed demand and varying the amount of bandwidth that each operator gets, we show the impact of this additional spectrum bandwidth on deployment costs.

The more spectrum the less sites are needed. Hence the costs decrease with increasing bandwidth, this is clearly visible for low bandwidths. The impact of spectrum price can be seen for higher levels of bandwidth, see Fig. 4.26. For the low spectrum price levels (European case) a small increase can be observed but for the high price levels (India case) the networks costs increase dramatically. With the used assumption there is minimum for a specific amount of licensed spectrum.

Besides the costs for sites, radio equipment and spectrum the result depends on the demand levels and the assumed coverage areas. Hence, we present a sensitivity

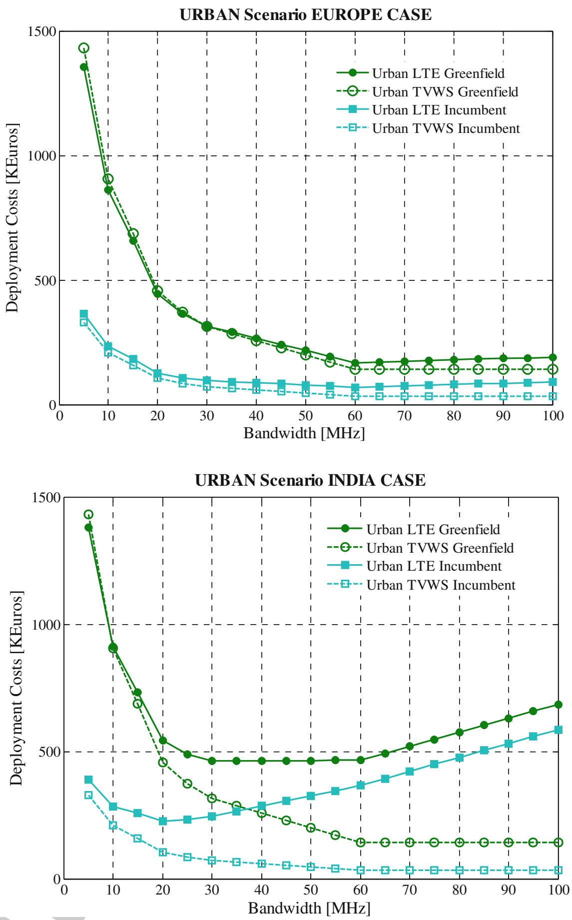


Fig. 4.26 The costs are shown as a function of system bandwidth assuming *low* and *high* spectrum prices (Europe and India respectively) and an urban environment with demand of 200 Mbps/km^2 and a base station coverage area of 1 km^2

analysis where we vary the user demand and the base station coverage. In Fig. 4.27 we illustrate the impact of lower demand and here the same cost minimum can be observed. In Fig. 4.28 we show the cost assuming a smaller coverage area for "high" spectrum prices. In this case a large number of sites are needed and hence the site cost is dominating. For lower spectrum prices, the graphs with lower demand levels and smaller coverage areas are similar to Fig. 4.28.

Now we will vary the demand for a fixed bandwidth of 20 MHz. The costs will increase with demand but the interesting thing is to identify the differences between the deployment cases. Figure 4.29 illustrates how a Greenfield operator building up its network from scratch has higher costs than the incumbent operator. The difference is largest for the low demand levels where the incumbent can make use of existing sites. For the assumed levels of site costs, radio costs and spectrum price the Greenfield operator always has higher network costs, even when CR and TV white spaces are used. For the case where the spectrum prices are "high", the situation is different, see Fig. 4.30. Use of TV white spaces (no spectrum cost)

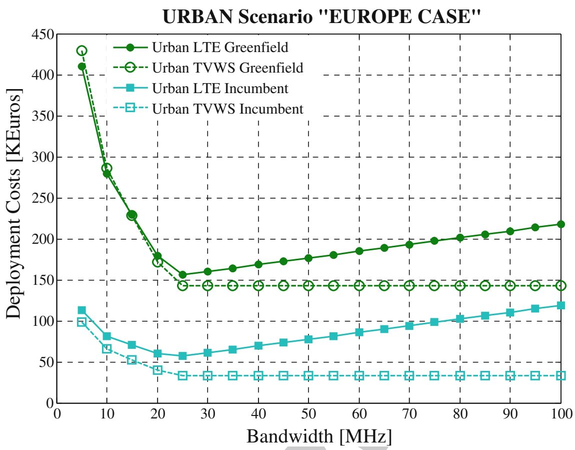


Fig. 4.27 Examples of deployment costs illustrating "Fixed demand and varying amount of spectrum", The costs are shown as function of system bandwidth assuming *low* spectrum prices (Europe) and an urban environment with demand of 50 Mbps/km^2 and *large* base station coverage area (1.0 km^2)

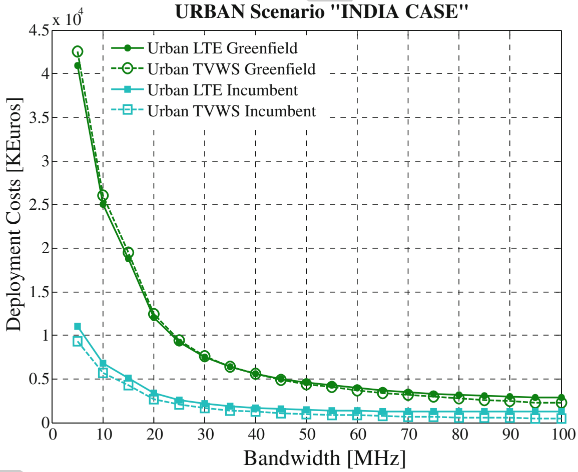


Fig. 4.28 Examples of deployment costs illustrating "Fixed demand and varying amount of spectrum". The costs are shown as function of system bandwidth assuming *high* spectrum prices (India) and an urban environment with demand of 50 Mbps/km^2 and a *small* base station coverage area (0.2 km^2)

results in lower costs for both the incumbent and the Greenfield operator but the incumbent has lower costs.

4.6.4 Uncertainties and Risks

This subsection elaborates on risk and uncertainties in the deployment of new technologies, such as CR. The perspective is techno-economic implying that all parts of the system have to be available in order for the system to function. This is illustrated by the introduction of new standards and the significance of investments in terminals for how it influences the development of the mobile technology system.

Layout: T1 Standard SC | Book ID: 318863_1_En | Book ISBN: 978-3-319-04021-9
Chapter No.: 4 | Date: 24-12-2013 | Page: 64/74

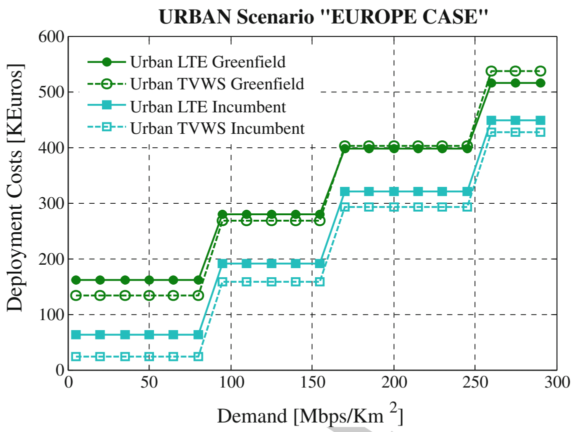


Fig. 4.29 Examples of deployment costs illustrating "Fixed amount of spectrum and varying demand". Network costs as a function of a varying demand in an urban environment assuming *low* level of spectrum cost, 20 MHz of spectrum and coverage area of 1 km^2 per site

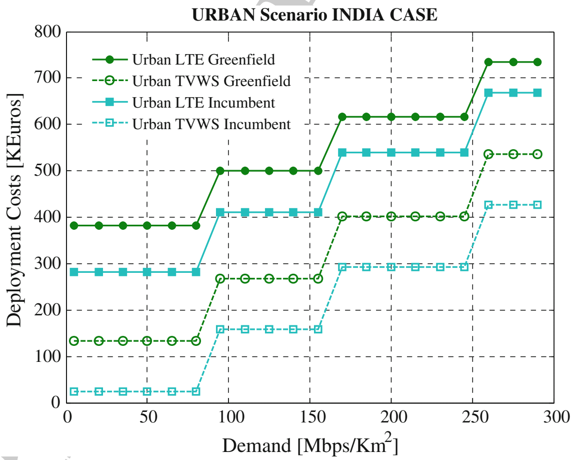


Fig. 4.30 Examples of deployment costs illustrating "Fixed amount of spectrum and varying demand". Network costs as a function of a varying demand in an urban environment assuming the *high* Indian level of spectrum cost, 20 MHz of spectrum and coverage area of 1 km^2 per site

4.6.4.1 It Takes Time to Establish New Mobile Standards on the Market

As mobile communication is a network technology it consists of a number of subsystems. Focus is predominately on network equipment, provided by equipment manufacturers, which have transferred specifications of radio technology standards into the equipment that are manufactured. The advancement of the technology has facilitated multi-band radio enabling operators to easily migrate to new system technologies. But the commercial migration to new technologies requires that end customers have access to appropriate terminals. The historical development of mobile communication has demonstrated that it takes time for new technologies to be established on the market, see Fig. 4.31.

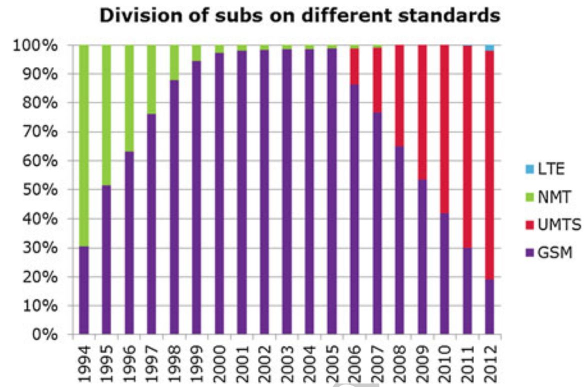


Fig. 4.31 Distribution of the total mobile subscriber base in Sweden. *Source* Svensk telemarknad, PTS

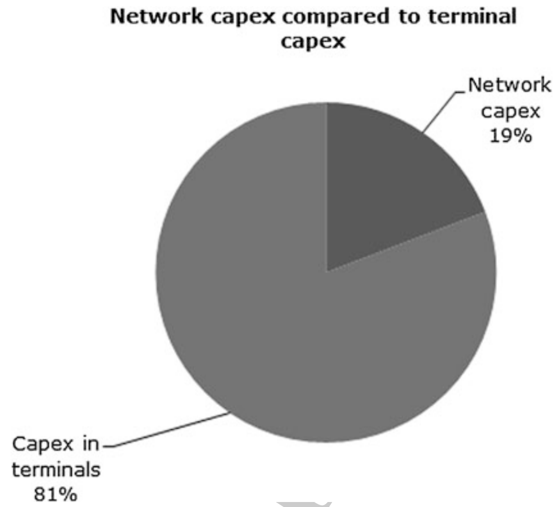
An illustration of this is that NMT, the analogue Nordic Mobile Telephone system, which was launched in the 1980's had its peak in 1995, 3 years after the official launch of GSM. But as handsets for GSM were not available in commercial volumes when GSM networks were completed it took another couple of years before GSM took off.

UMTS (3G) was initially planned to be launched in Europe in 2001, but the lack of terminals delayed the market introduction and the sales of GSM terminals peaked in 2005. The fact is that it was not until 2009–2010 that 3G made up more than half of the handset market in Sweden. Moreover, TeliaSonera was among the first operators in world to launch LTE when it opened its network in December 2009, but the inflow of 4G subscribers was minimal due to limited availability of dongles and terminals was an issue for the future .

The initial growth of 4G in Sweden has been slow, although TeliaSonera got competition on 4G in 2012 when a new network opened, and the total share of 4G subscribers where 0.2 % 2011 and 1.9 % 2012.

Although the major focus is on investments (capital expenditures) made by operators the requirement on end-customers is that they have to purchase new terminals in order for a new technology to be established on the market. Based on reported CAPEX made by operator during 2012 and the value of the terminal market, which is derived from the number of sold handsets in Sweden multiplied with the average selling price we can relate these numbers it is possible to obtain the figure for the total investments. The comparison demonstrates that the consumers' investments in terminals surpass CAPEX provided by operator with four times, see Fig. 4.32. Altogether, the data illustrates that the implementation of new standards is commonly a stretched out process impacted by the introduction of terminals, and determined by the end consumers' willingness to pay for new equipment.

Fig. 4.32 Comparison between network CAPEX and consumers investments of terminals 2012. *Source* operator reports, authors calculations and MTB, the mobile telephone industry



4.6.4.2 Four Factors that Have Implications on CR

Although mobile communication is a technology driven industry investment decisions taken by operators is nowadays governed by financial targets and scrutinized by investment committees and top management in order to safeguard appropriate return on investments. This means that investments and thereby deployment of CR face a number of challenges of which we have identified four factors which we analyse in the following.

Factor 1—It takes time to establish new standards on the market
The introduction of mobile standards, such as GSM, WCDMA, LTE, takes time and the migration from older to newer standards is a stretched out process as the life cycle for older technologies often is prolonged and reach its peak after the new technology has been introduced, as elaborated in the previous section. Given that the mobile industry has matured and operators nowadays are managed with financial targets as a key priority it would be challenging to persuade management to invest and launch CR.

Factor 2—Multiple standards increase complexity
Operators in Europe are currently operating networks with at least three parallel standards—GSM, WCDMA and LTE—which are not optimal for an efficient operator. Although CR could contribute with additional capacity it would add more complexity rather than to streamline the current operation. It also requires a long-term commitment as history show that it takes long time to establish a new standard on the market. This implies that management has to see the merits in CR and be determined that it could contribute with something that the other standards are not able to, which is a challenging task.

Layout: T1 Standard SC | Book ID: 318863_1_En | Book ISBN: 978-3-319-04021-9
Chapter No.: 4 | Date: 24-12-2013 | Page: 67/74

Factor 3—Financial commitments calling for additional CAPEX

It requires a financial commitment for operators to deploy a new technology demanding extensive capital expenditures over a number of years. Investments into a new network are irreversible and thereby sunk which implies that management has to be convinced that investments in CR will pay off and deliver a return of investments in line with the financial targets. With declining revenues operators are scrutinizing their investments decision very carefully and make prioritizations meaning that investments in CR come on top of other investments.

The price deflation on network equipment, which has been driven by competition, technology advancement and economy scale, facilitates for operators to acquire network equipment for the established standards for around EUR 10K per site. The cost for civil works and passive infrastructure makes up the larger part of CAPEX budgets. Given the uncertainty for the volumes of equipment for CR it would rather cost more compared to standardized equipment. This implies that CAPEX budgets has to be extended and accepted in investment committees, which could be challenging as management would rather see higher cash flow than to explore new technologies and increase CAPEX budgets.

Factor 4—Consumers' are the biggest investors

The operator business of today is characterised by standardised products, marketing of services and competition on attracting new customers. The basic principle is to have a large and growing customer base in order to generate a cash flow. The previous section has demonstrated that the end customers' investment in terminals represents the majority of the total investments for mobile systems.

This implies that operators have to persuade the end-customers to not only sign up as subscribers but also to pay for terminals. Although operators could provide various financing options for the acquisition of terminals the end customers has to be convinced by the merits of the offers. The global smartphone trend has demonstrated that economy of scale is essential as its offers customers' good value and enables them to reach internet and unlimited amount of applications while being on the move.

Altogether, this underscores that terminals play a decisive role in the mobile communications system and the availability of terminals that could handle CR is a prerequisite for establishing a business case for the new technology. But given that it will take time before economy of scale could be reached the case for CR could be difficult as end-customers have to be persuaded to pay substantially more for CR terminals compared to standardised smartphones, which are now falling in price.

4.6.4.3 Concluding with an Example

We illustrate the reasoning with a case where we have two operators, of which one is using licensed spectrum and the other is using CR. The case concerns a network for a country with 10 million inhabitants, a mobile penetration rate of 90 % and

Layout: T1 Standard SC Book ID: 318863_1_En Book ISBN: 978-3-319-04021-9
Chapter No.: 4 Date: 24-12-2013 Page: 68/74

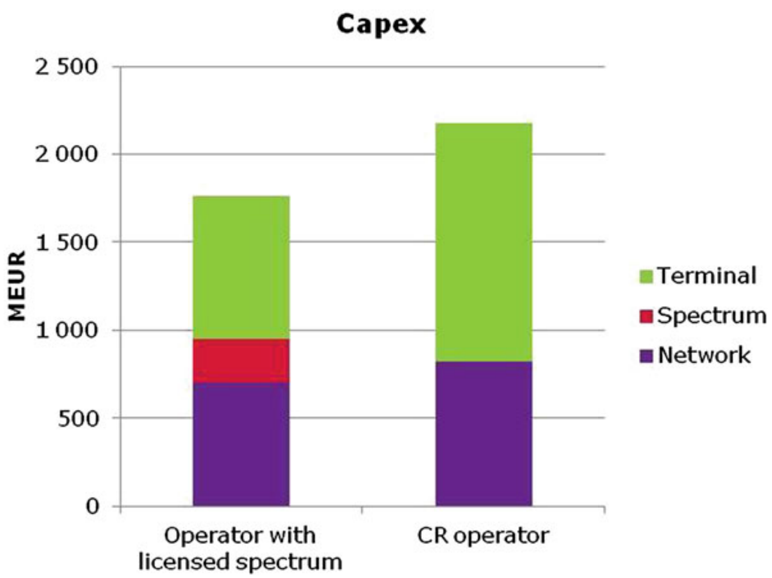


Fig. 4.33 CAPEX for standardized mobile network compared with an operator with CR

Table 4.7 Summary of different spectrum access options, selection building on [89]

Aspect	Access using licensed bands	Unlicensed open access	Secondary spectrum access	Licensed shared access
Availability for use	Full	Good	Varying	Full
Radio complexity	LTE type	WiFi type	>LTE	=LTE
Radio cost	LTE type	WiFi Type	>LTE	=LTE
Availability of base station equipment	Standardized, available	Standardized, available	Unclear, low availability	Standardized, available
Availability of user devices/equipment	Standardized, available	Standardized, available	Not available	Standardized, availability
Risk for operators	Low	Medium	High	Quite low

market share of 30 % for the operator, where the operator using exclusively allocated spectrum has paid the equivalent of EUR 0.50 per MHz/pop for 2 × 50 MHz, while the operator with CR has no cost for spectrum. We calculate with 10K sites where half is green field sites and the other half is using existing sites.

Capex for the green field sites is EUR 100K, while the CAPEX for radio equipment is EUR 10K for the standardised radio and EUR 20K for CR. Moreover, we estimate the cost for smartphones to be in the mid of the range of EUR 200–400 while the range for CR capable smartphones is estimated to be EUR 400–800 for smartphones for CR. The aggregated CAPEX is EUR 1760 m for the operator with licensed spectrum and EUR 2175 m for the CR operator (Fig. 4.33).

Altogether, this reinforces the conclusion that the cost for spectrum make up the least part of the CAPEX budget while the cost for terminals is majority of the total investment. This underscores that the success of CR really has to contribute to the consumers benefits and they have to be persuaded that the standardised smartphone is not sufficient and that they rather should choose terminals that have a CR capability. This requires that the price points make sense for the end-consumers and that are persuaded to invest more than what they otherwise would have done. This will be very challenging as the end customers as well as operators are prioritising low cost and low risks.

4.6.5 Summary Assessment of Spectrum Access Options

When we summarize the business feasibility characteristics for CR solutions the result is not that encouraging. The cost of CR currently would be larger than similar commercial LTE or WiFi systems due to larger complexity. In addition the low level of usage and availability of CR equipment contribute to higher risk for operators using this technology. Other solutions for use of non-licensed spectrum band, WiFi and Licensed Shared Access (LSA), make use of existing technology and hence mean lower risk for operators, see Table 4.7.

We can also see that that the value and the usefulness of CR solutions are different for different types of actors. Existing mobile operators (with licensed spectrum too) that use secondary access and CR have an advantage over new actors. First, exiting operators can re-use the existing base station sites whereas a new actor needs to deploy a new infrastructure. Second, a mobile operator using secondary spectrum access as a complementing resource, new actors using CR usually only the secondary access as the main spectrum resources and hence are more vulnerable.

Although a mobile operator may see potential savings in overall network costs a number of potential drawbacks can be identified. The mobile operator may hesitate to include a new type of technology in the networks. The option to use an existing standard (e.g. LTE) in another licensed band may see as a more straight-forward in order reduce the number of standards. In addition, new user terminals and devices with CR need to be developed marketed and adopted by consumers. Since CR equipment is more complex and produced in smaller quantities than existing radio technologies the products will be more expensive which would be a major obstacle.

References

1. Kibilda, J., Nolan, K., Tallon, J., DaSilva, L.A.: Whitespace networks relying on dynamic control channels. In: Proceedings of the 2013 8th International Conference on Cognitive Radio Oriented Wireless Networks (CROWNCOM) (2013)
2. Thanki, R.: The economic significance of licence-exempt spectrum to the future of the internet. Technical report (2012)

3. Cisco Visual Networking Index. Global mobile datatraffic forecast update, 2011–2016. http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/white_paper_c11-520862.pdf (2011)
4. Mancuso, A., Probasco, S., Patil, B.: (draft) Protocol to access white space (PAWS) database: use cases and requirements, Internet Engineering Task Force (IETF) Std., Rev. 09. http://tools.ietf.org/html/draft-ietf-paws-problem-stmt-usecases-rqmts-09 (2012)
5. ECC REPORT 159. Technical and operational requirements for the possible operation of cognitive radio systems in the "white spaces" of the frequency band 470–790 MHz. Electronic Communications Committee (ECC), Technical report. http://www.erodocdb.dk/Docs/doc98/official/pdf/ECCREP159.PDF (2011)
6. Federal Communications Commission (FCC). Unlicensed operation in the TV broadcast bands, ET docket No. 04-186 and 02-380; FCC 10-174, Federal Register vol. 75, No. 233. Federal Communications Commission (FCC), Technical report (2010)
7. Haykin, S.: Cognitive radio: brain-empowered wireless communications. IEEE J. Sel. Areas Commun. **23**(2), 201–220 (2006). http://dx.doi.org/10.1109/JSAC.2004.839380
8. Bahl, P. Chandra, R. Moscibroda,T., Murty, R. Welsh, M.: White space networking with Wi-Fi like connectivity. ACM SIGCOMM Comput. Commun. Rev. **39**(4), 27–38 (2009). http://doi.acm.org/10.1145/1594977.1592573
9. Gur, G., Bayhan, S., Alagoz, F.: Cognitive femtocell networks: an overlay architecture for localized dynamic spectrum access [dynamic spectrum management]. IEEE Wirel. Commun. Mag. **17**(4), 62–70 (2010)
10. Sen, S., Zhang, T., Buddhikot, M.M., Banerjee, S., Samardzija, D., Walker, S.: Dual technology femto cell architecture for robust communication using whitespaces. In: IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN) (2012)
11. Murty, R., Chandra, R., Moscibroda, T., Bahl, P.: SenseLess: a database-driven white spaces network. IEEE Trans. Mob. Comput. **11**(2), 189–203 (2012)
12. Tallon, J., Forde, T., Doyle, L.: Dynamic spectrum access networks: independent coalition formation. IEEE Veh. Technol. Mag. **7**(2), 69–76 (2012)
13. Wyglinski, A.M., Nekovee, M., Hou, T.: Cognitive Radio Communications and Networks: Principles and Practice. Elsiever Inc. (2010) AQ6
14. Sukarevičienė, G., Fomin V.V.: Analysis and modelling of dynamic spectrum access information infractructure (DSA II). In: The Proceedings of the XVIII International Master and Ph.D. Students Conference on Information Society and University Studies (IVUS 2013). Kaunas, Lithuania (2013a)
15. Sukarevičienė, G., Fomin, V.V.: Modeling dynamic spectrum access infrastructure, development as a techno-econimic system. In: The Proceedings of 18th EURAS Annual Standardization Conference, Brussels, Belgium (2013b)
16. EBU Technology fact Sheet. White space devices. Operating Eurovision and Euroradio (2013)
17. Kokkinen, H.: Fairspectrum provides TV white space database for Europe's first geolocation radio license. Press release. Helsinki, Finland (2012)
18. Sukarevičienė, G.: Developing business model for GDB for the operation of cognitive radio in the TV white space bands. Master thesis. Kaunas, Lithuania (2012)
19. Lyytinen, K., Fomin, V.V.: Achieving high momentum in the evolution of wireless infrastructures: the battle over the 1G solutions. Telecommun. Policy **26**, 149–170 (2002)
20. Smura, T.: Techno-econimic modelling of wireless network and industry architectures. Doctoral dissertation for the degree of Doctor of Science in Technology. Espoo, Finland (2012)
21. ECC Report 185. Further definition of technical and operational requirements for the operation of white space devices in the band 470–790 MHz
22. Gianmarco, B., et al.: The evolution of cognitive radio technology in Europe: regulatory and standardization aspects. Telecommun. Policy **37**, 96–107 (2013)
23. Casey, T.R., Ali-Vehmas, T.: Value system evolution towards a cognitive radio era: implications of underlying market dynamics. In: Proceedings of the 2012 IEEE International Symposium on Dynamic Spectrum Access Networks (2012)

24. Mitola, J., Maguire, G.Q.: Cognitive radio: making software radios more personal. IEEE Pers. Commun. **6**(4), 13–18 (1999)
25. Chapin, J.M., Lehr, W.H.: Cognitive radios for dynamic spectrum access—the path to market success for dynamic spectrum access technology. IEEE Commun. Mag. **45**(5), 96–103 (2007)
26. Manninen, A.T.: Elaboration of NMT and GSM standards: from idea to market. Ph.D. thesis, University of Jyväskylä (2002)
27. Steinbock, D.: Globalization of wireless value system: from geographic to strategic advantages. Telecommun. Policy **27**(3–4), 207–235 (2003)
28. Hillebrand, F.: GSM and UMTS: the creation of global mobile communication. Wiley, New York (2002)
29. Lemstra, W., Hayes, V., Groenewegen, J.: The Innovation Journey of Wi-Fi: The Road to Global Success. Cambridge University Press, Cambridge (2010)
30. Negus, K.J., Petrick, A.: History of wireless local area networks (WLANs) in the unlicensed bands. J. Policy Regul. Strat. Telecommun. Inf. Media **11**(5), 36–56 (2009)
31. Smura, T., Sorri, A.: Future scenarios for local area access: industry structure and access fragmentation. In: Proceedings of the Eight International Conference on Mobile Business, pp. 57–63. Dalian, China (2009)
32. Leiner, B.M., Cerf, V.G., Clark, D.D., Kahn, R.E., Kleinrock, L., Lynch, D.C., Postel, J., Roberts, L.G., Wolf, S.: A brief history of the internet. ACM SIGCOMM Comput. Commun. Rev. **39**(5), 22–31 (2009)
33. Ballon, P., Delaere, S.: Flexible spectrum and future business models for the mobile industry. Telematics Inform. **26**(3), 249–258 (2009)
34. Casey, T.: Analysis of radio spectrum market evolution possibilities. Commun. Strat. **75**, 109–130 (2009)
35. Barrie, M., Delaere, S., Ballon P.: Classification of business scenarios for spectrum sensing. In: Proceedings of the 21st International Symposium on Personal Indoor and Mobile Radio Communications, pp. 2626–2631. Instanbul, Turkey (2010)
36. Medeisis, A., Delaere, S.: High-level scenarios for the future of cognitive radio business. In: Proceedings of the 22nd International Symposium on Personal Indoor and Mobile Radio Communications, pp. 2330–2334, Toronto, Canada (2011)
37. Anderson, P., Tushman, M.L.: Technological discontinuities and dominant designs: a cyclical model of technological change. Adm. Sci. Q. **35**(4), 604–633 (1990)
38. Arthur, W.B.: Positive feedbacks in the economy. Sci. Am. **262**, 92–99 (1990)
39. Fine, C.H.: Clockspeed-based strategies for supply chain design. Prod. Oper. Manage. **9**(3), 213–221 (2000)
40. Senge, P.: The Fifth Discipline: the Art and Practice of the Learning Organization. Doubleday, New York (1990)
41. Porter, M.E.: Competitive Advantage: Creating and Sustaining Superior Performance. Free Press, New York (1985)
42. Stabell, C.B., Fjeldstad, Ø.D.: Configuring value for competitive advantage: on chains, shops, and networks. Strateg. Manag. J. **19**(5), 413–437 (1998)
43. Jacobides, M.G., Knudsen, T., Augier, M.: Benefiting from innovation: value creation, value appropriation and the role of industry architectures. Res. Policy **35**(8), 1200–1221 (2006)
44. Iansiti, M., Levien, R.: Strategy as ecology. Harvard Bus. Rev. **82**(3), 68–81 (2004)
45. Eisenmann, T., Parker, G., Van Alstyne, M.W.: Strategies for two-sided markets. Harvard Bus. Rev. **84**(10), 92–101 (2006)
46. Gawer, A., Cusumano, M.A.: How companies become platform leaders. MIT Sloan Manage. Rev. **49**(2), 28–35 (2008)
47. Strogatz, S.H.: Exploring complex networks. Nature **410**(6825), 268–276 (2001)
48. Anderson, C.: The Long Tail: Why the Future of Business is Selling Less of More. Hyperion Books, New York (2008)
49. Arthur, W.B.: Complexity and the economy. Science **284**(5411), 107–109 (1999)
50. Barabási, A.L., Bonabeau, E.: Scale-free networks. Sci. Am. **288**(5), 50–59 (2003)

51. Faloutsos, M., Faloutsos, P., Faloutsos, C.: On power-law relationships of the Internet topology. ACM SIGCOMM Comput. Commun. Rev. **29**(4), 251–262 (1999)
52. Sterman, J.D.: Business Dynamics: Systems Thinking and Modeling for a Complex World. McGraw-Hill, New York (2000)
53. Rahmandad, H., Sterman, J.: Heterogeneity and network structure in the dynamics of diffusion: comparing agent-based and differential equation models. Manage. Sci. **54**(5), 998–1014 (2010)
54. Wolstenholme, E.: Using generic system archetypes to support thinking and modelling. System Dyn. Rev. **20**(4), 341–356 (2004)
55. Riikonen, A., Kitahara, T., Hämmäinen, H.: Comparison of mobile internet usage and industry structure: Japan vs. Finland. In: 18th Biennial Conference of the International Telecommunications Society. Tokyo, Japan (2010)
56. V. Sridhar., Casey, T., Hämmäinen, H.: Flexible spectrum management for mobile broadband services: how does it vary across advanced and emerging markets? Telecommun. Policy (2012, in press)
57. European Commission. Radio spectrum, a vital resource in a wireless world. http://ec.europa.eu/information_society/policy/ecomm/radio_spectrum/index_en.htm AQ7
58. Radio Spectrum Policy Group. On cognitive technologies. European Commission, Brussels, 25 Jan 2010
59. Lehr, W. Chapin, J.: Role of cognitive radio in the evolution toward converged future networks. In: Second Joint IBBT-MIT Workshop on Cognitive Radio Standardization and Markets, Brussels, 11 Dec 2009
60. Freyens, B.P., Loney, M., Poole. M.: Wireless regulations and dynamic spectrum access in Australia. In: Paper presented at Dyspan (2010)
61. Gonçalves, V., Pollin, S.: The value of sensing for TV white spaces. In: 2011 IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN), pp. 231–241 (2011)
62. FCC. FCC adopts rules for unlicensed use of television white spaces. Washington D.C., 14 Nov 2008
63. Pawelczak, P., Venkatesha Prasad, R., Xia, L., Niemegeers, I.G.M.M.: Cognitive radio emergency networks-requirements and design. In: 2005 First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005, pp. 601–606. IEEE (2005)
64. Bourse, D., Agusti, R., Ballon, P., Cordier, P., Delaere, S., Deschamps, B., Grandblaise, D., et al.: The E2R II flexible spectrum management (FSM) framework and cognitive pilot channel (CPC) concept—technical and business analysis and recommendations.In: E2R II White Paper (2007)
65. Anker, P.: Does cognitive radio need policy innovation? Competition Regul. Netw. Ind. **11**(1), 2–26 (2010)
66. Plum Consulting. Valuation of public mobile spectrum at 825–845 MHz and 870–890 MHz. In: A report to the department of broadband communications and the digital economy, 15 Sept 2011
67. Australian Communications and Media Authority (ACMA). Opportunity cost pricing of spectrum. Public consultation on administrative pricing for spectrum based on opportunity cost. http://www.acma.gov.au/webwr/_assets/main/lib310867/ifc12-09_final_opportunity_cost_pricing_of_spectrum.pdf (2009)
68. Doyle, C.: The pricing of radio spectrum, using incentive mechanisms to achieve efficiency, centre for management under regulation, Warwick Business School (2007)
69. Yeo, J.: Valuations in an FCC spectrum auction. University of Minnesota (2009)
70. Ard-Paru, N.: Spectrum assignment policy: towards an evaluation of spectrum, commons in Thailand. Department of Technology. Management and Economics, Division of Technology and Society, Chalmers University of Technology, Gothenburg, Sweden (2010)
71. International Telecommunication Union (ITU). Exploring the value and economic valuation of spectrum. Broadband Series (2012)

72. Buchanan, J.M.: Opportunity cost. In: Durlauf, S.N. Blume, L.E. (eds.) The New Palgrave Dictionary of Economics Online, 2nd edn. Palgrave Macmillan. 03 June 2009. doi:10.1057/9780230226203.1222. http://www.dictionaryofeconomics.com/article?id=pde2008_O000029 (2008)
73. Zander, J.: On the cost structure of future wireless networks. In: Proceedings of IEEE VTC'97. Phoenix, AZ, 5–7 May 1997
74. Markendahl, J., Mölleryd, B.G., Mäkitalo, Ö., Werding, J.: Business innovation strategies to reduce the revenue gap for wireless broadband services. Commun. Strat. **75**(3rd quarter), 35 (2009) AQ8
75. Markendahl, J.: Mobile network operators and cooperation—a tele-economic study of infrastructure sharing and mobile payments services. Ph.D. dissertation, Royal Institute of Technology, Stockholm. http://www.impgroup.org/dissertations.php (2011)
76. Johansson, K.: Cost effective deployment strategies for heterogeneous wireless networks. Ph.D. dissertation, Royal Institute of Technology, Stockholm (2007)
77. Marks P., Viehoff, I., Saadat, U., Webb, W.: Study into the use of spectrum pricing. Appendices 1 and 2: Case Studies, Prepared by NERA & Smith for the Radiocommunications Agency. http://www.ofcom.org.uk/static/archive/ra/topics/spectrumprice/documents/smith/smith1.htm (1996)
78. Sweet, R.I., Viehoff, D., Linardatosc, N., Kalouptsidis. C.: Marginal value-based pricing of additional spectrum assigned to cellular telephony operators. Inf. Econ. Policy **14**(3), 371–384 (2002)
79. Marks, P., Pearson, K., Williamson, B., Hansell, P., Burns, J.: Estimating the commercial trading value of spectrum. A Ofcom report by Plum Consulting. www.plumconsulting.co.uk/pdfs/Plum_July09_Commercial_trading_value_of_spectrum.pdf (2009)
80. Mölleryd, B.G., Markendahl, J., Mäkitalo, Ö.: Spectrum valuation derived from network deployment and strategic positioning with different levels of spectrum in 800 MHz. In: Proceedings of 8th Biennial and Silver Anniversary ITS Conference. Tokyo (2010)
81. Mölleryd, B.G., Markendahl, J.: Valuation of spectrum for mobile broadband services—engineering value versus willingness to pay. In: Presented at 22nd European Regional ITS Conference Budapest. http://www.econstor.eu/bitstream/10419/52146/1/672544792.pdf, 18–21 Sept 2011
82. Markendahl, J., Mölleryd B.G.: Mobile broadband expansion calls for more spectrum or base stations—analysis of the value of spectrum and the role of spectrum aggregation. Int. J. Manage. Netw. Econ. **2**(2), 115–134 (2011) AQ9
83. Mölleryd, B.G., Markendahl, J.: Valuation of spectrum for mobile broadband services—the case of India and Sweden. Submitted to Telecommun. Policy (2013)
84. Kronander, J., Nekovee, M., Sung, K.W., Zander, J., Kim, S.-L., Achtzehn, A.: QUASAR scenarios for white space assessments and exploitation. In: URSI EMC Conference. Worclaw (2010)
85. Zander, J., et al.: On the scalability of cognitive radio: assessing the commercial viability of secondary spectrum access. IEEE Wirel. Commun. Mag. **20**(2), 28–35 (2013)
86. Quasar deliverable D5.1. Model integration and spectrum assessment methodology AQ10
87. Markendahl, J., Gonzalez-Sanchez, P., Mölleryd, B.G.: Impact of deployment costs and spectrum prices on the business viability of mobile broadband using TV white space. In: 7th International Conference on Cognitive Radio Oriented Wireless Networks (Crowncom) (2012)
88. Markendahl, J., Mäkitalo, Ö.: Analysis of business opportunities of secondary use of spectrum, the case of TV white space for mobile broadband access. In: 22nd European ITS Conference (2011)
89. Zander, J., Mähönen, P.: Riding the data tsunami in the cloud—myths and challenges in future wireless access. IEEE Commun. Mag. **51**(3), 145–151 (2013)
90. Sutton, P., Nolan, K., Doyle, L.: Cyclostationary signatures for rendezvous in OFDM-based dynamic spectrum access networks. In: 2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2007), pp. 220–231 (2007)
91. Sutton, P.D., Nolan, K.E., Doyle L.E.: Cyclostationary signatures in practical cognitive radio applications. IEEE J. Sel. Areas Commun. **26**(1), 13–24 (2008)

92. Sutton, P., Lotze, J., Lahlou, H., Fahmy, S., Nolan, K., Ozgul, B., Rondeau, T., Noguera, J., Doyle, L.: Iris: an architecture for cognitive radio networking testbeds. IEEE Commun. Mag. **48**(9), 114–122 (2010)
93. Gummadi, R., Wetherall, D., Greenstein, B., Seshan, S.: Understanding and mitigating the impact of RF interference on 802.11 networks. ACM SIGCOMM Comput. Commun. Rev. **37**(4), 385–396 (2007). http://doi.acm.org/10.1145/1282427.1282424
94. Reed, J.H., Bostian. C.W.: Understanding the issues in software defined radios. Virginia Tech (unpublished) AQ11

Author Query Form

Book ID :	**318863_1_En**
Chapter No.:	**4**

Springer
the language of science

Please ensure you fill out your response to the queries raised below and return this form along with your corrections

Dear Author
During the process of typesetting your chapter, the following queries have arisen. Please check your typeset proof carefully against the queries listed below and mark the necessary changes either directly on the proof/online grid or in the 'Author's response' area provided below

Query Refs.	Details Required	Author's Response
AQ1	Please confirm the corresponding author is correctly identified and amend if necessary.	
AQ2	Please confirm the section heading levels are correctly identified.	
AQ3	Please check and confirm that the inserted city in the affiliation for authors have been correctly identified and amend if necessary.	
AQ4	Please provide high resolution for Figs. 4.11 and 4.24.	
AQ5	Please check and confirm the inserted citation of Figs. 4.17, 4.18 and 4.33 are correct. If not, please suggest an alternate citation.	
AQ6	Please provide publisher location for the reference no. [13].	
AQ7	Please provide year for this reference no. [57].	
AQ8	Please check and confirm the edit made in the reference no. [74].	
AQ9	Please check and confirm the inserted page no. for this reference no. [82].	
AQ10	Please update this references no. [56, 83, 86, 94].	
AQ11	References [90–94] are given in list but not cited in text. Please cite in text or delete from list.	

MARKED PROOF

Please correct and return this set

Please use the proof correction marks shown below for all alterations and corrections. If you wish to return your proof by fax you should ensure that all amendments are written clearly in dark ink and are made well within the page margins.

Instruction to printer	*Textual mark*	*Marginal mark*
Leave unchanged	• • • under matter to remain	
Insert in text the matter indicated in the margin		New matter followed by or
Delete	/ through single character, rule or underline or through all characters to be deleted	or
Substitute character or substitute part of one or more word(s)	/ through letter or through characters	new character / or new characters /
Change to italics	under matter to be changed	
Change to capitals	under matter to be changed	
Change to small capitals	under matter to be changed	
Change to bold type	under matter to be changed	
Change to bold italic	under matter to be changed	
Change to lower case	Encircle matter to be changed	
Change italic to upright type	(As above)	
Change bold to non-bold type	(As above)	
Insert 'superior' character	/ through character or where required	or under character e.g. or
Insert 'inferior' character	(As above)	over character e.g.
Insert full stop	(As above)	⊙
Insert comma	(As above)	,
Insert single quotation marks	(As above)	or and/or or
Insert double quotation marks	(As above)	or and/or or
Insert hyphen	(As above)	
Start new paragraph		
No new paragraph		
Transpose		
Close up	linking characters	
Insert or substitute space between characters or words	/ through character or where required	
Reduce space between characters or words	between characters or words affected	