Spectrum Sharing Transforms Mobile Broadband Networks Towards Markets

Analysis of Sharing Economy Antecedents for Recent Spectrum Sharing Concepts

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***Abstract*—The exponential growth of wireless services with diversity of devices and applications depending on connectivity has inspired the research community to come up with novel concepts to improve the efficiency of spectrum use. Recently, several spectrum sharing system concepts have been introduced and widely researched to cope with spectrum scarcity, though, to date, only a few have reached the policy and standardization phase. Moreover, only a subset of these concepts has gained industry interest with pre-commercial deployments and lucrative business model characteristics. This paper analyzes sharing economy business antecedent factors of the three topical regulatory approaches for spectrum sharing: global TV White Space (TVWS), Licensed Shared Access (LSA) from Europe, and Citizens Broadband Radio Service (CBRS) from the US. A comparison is made between these concepts to identify similarities and differences for developing a successful scalable sharing concept. Key factors for a sharing economy enabled scalable business model are introduced including platform, reduced need for the ownership, leverage of underutilized assets, adaptability to different policy regimes, trust, and value orientation. The results indicate that all analyzed sharing concepts meet basic requirements to scale, TVWS radically lowering entry barrier, LSA leveraging key existing assets and capabilities of mobile network operators, and CBRS extending the business model dynamics. By reducing the costs of spectrum coordination, spectrum sharing concepts will lead to an overall shift from hierarchies towards more use of markets to coordinate economic activity related to spectrum assets. The Sharing Economy and Markets and Hierarchies frameworks provide a dynamic framework for analyzing and developing the spectrum sharing business models.**

Keywords-business model; cognitive radio; markets and hierarchies; sharing economy; spectrum sharing.

I. INTRODUCTION

We have seen the exponential growth of wireless services, applications and devices, requiring connectivity. Furthermore, the number of mobile broadband (MBB) subscribers and the amount of data consumed is set to grow significantly, leading to increasing spectrum demand discussed in the COCORA 2017 [1]. Both the European Commission (EC) [2] and the US President's Council of Advanced Science & Technology (PCAST) [3] have recently emphasized the need for novel thinking within wireless industry to cope with the growing capacity crunch in spectrum allocation, utilization and management. The prominence of dynamic spectrum access and spectrum sharing has been emphasized in improving the efficiency of the spectrum utilization through balancing across domains with different spectrum dynamics. For any spectrum sharing framework to emerge and scale, close cooperation between research, regulation and across industry domains is essential. The collaboration between research and industry is essential in validating enabling platforms, technologies and innovations. The spectrum regulation and standardization has played a central role in enabling current multibillion business ecosystems: For the MBB via exclusive Quality of Service (QoS) spectrum usage rights, and at the same time for the unlicensed wireless local area network (Wi-Fi) ecosystem drawing from the public spurring innovations. Without sound and sustainable business models for all the key industry stakeholders, new concepts will not become deployed in a large scale.

To date, only few of the Dynamic Spectrum Access (DSA) concepts from research have crossed the threshold into policy domain. Furthermore, several spectrum sharing concepts supported by National Regulatory Authorities (NRA) and standardization have not to date scaled up in the wireless services market, the TV White Space (TVWS) being the latest example. After a decade of profound unlicensed TVWS concept research, standardization and trials in the US [4] and the UK [5] with their key learnings, license and database based sharing models have recently emerged and are under regulatory discussion, standardization and pre-commercial trials. The most prominent novel spectrum sharing concepts are the Licensed Shared Access (LSA) [6] from Europe and the three-tiered Citizens Broadband Radio Service (CBRS) from the US [7].

For all the three spectrum sharing concepts there is no prior work available regarding their business model design comparative analysis. An initial evaluation of the general spectrum sharing concept from the business modeling point of view can be found in [8]. Business modelling for the TVWS network was discussed in [9], and the LSA focused strategy and business model analysis in [10][11]. Business model typology and scalability analysis for the LSA and the CBRS were done in [12]. We extend that work by focusing on analyzing and comparing the viability and attractiveness of all three spectrum sharing concepts using sharing economy [13] antecedent factors and markets and hierarchies analytic framework [14]. This paper investigates:

1) *How do recent spectrum sharing concepts support the antecedents for business model scalability in the sharing economy framework?*
2) *How spectrum sharing concepts can be positioned in the markets and hierarchies analytic framework?*

The rest of the paper is organized as follows. First, the TVWS, the LSA and the CBRS sharing concepts are introduced in Section II. Theoretical backgrounds for the sharing economy and the markets and hierarchies analytic frameworks are introduced in Section III. The business model characteristics and the sharing economy antecedents for the TVWS, the LSA, and the CBRS spectrum sharing concepts are derived and analyzed in Section IV. Implications to ecosystem and market – hierarchy positioning are summarized in Section V. Finally, conclusions are drawn in Section VI.

II. OVERVIEW OF RECENT SPECTRUM SHARING CONCEPTS

This section presents the three prominent spectrum sharing frameworks and system model concepts under discussion in regulatory domain: the TVWS, the LSA and the CBRS. The common intention of the concepts is to improve spectrum usage efficiency by allowing new users to access a spectrum on the space or time basis when not being used by the incumbent system(s) currently holding the spectrum usage rights. Detailed description and the status of the TVWS, the LSA, the CBRS, and the concepts and technologies, under continuous revision can be found for example in [4][5], [15][16], and [17][18], respectively.

A. TV White Space (TVWS)

In this section, the opportunistic TV White Space concept utilizing terrestrial broadcasting Ultra High Frequency (UHF) spectrum is discussed in general level. TVWS standardization is spread to several organizations around the world, and there is no single dominant standard, technology or solution to date. In addition to Wi-Fi IEEE 802.11 standards based technologies focused on in this paper, also other radio technologies like the Long Term Evolution (LTE) and the Worldwide Interoperability for Microwave Access (WiMAX) have been experimented for the TVWS.

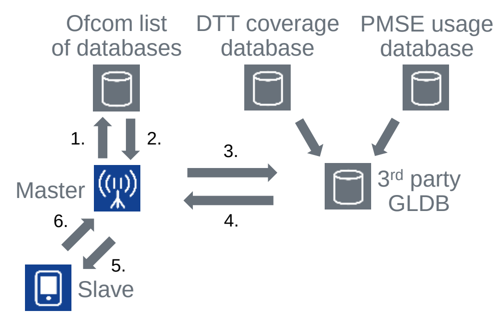

Figure 1. Overview of TV White Spaces framework in the UK.

The TVWS aims to improve spectrum efficiency through utilizing the unused and underutilized spectrum in space and time based on databases. In this concept, license-exempt *White Space Devices* (WSDs) obtain the available channel information via a certified *Geo-Location Database* (GLDB), which optimizes the effective reuse of the spectrum, and ensures interference free operation for the incumbent licensed users. The GLDB stores and periodically updates TV licensees' Digital Terrestrial TV (DTT) network infrastructure and channel occupancy information, and in the case of the UK, the Program Making and Special Events (PMSE) service usage data. In the operations phase, to access the TVWS spectrum, *WSD base stations* (BS) reports locations to a GLDB, which computes and returns the available TV channels for WSDs. Figure 1 depicts an overview of the TVWS framework, and how access to white spaces based on the GLDB would work in the UK case. In the preparatory phase, the GLDB will deploy the basic operational dataset provided by the Office of Communications (Ofcom) consisting of DTT coexistence data, location agnostic data, PMSE data, and unscheduled adjustments data. A master WSD would first consult a list of DBs provided by Ofcom hosted Website. Then, it would select its preferred GLDB from the list, and send to it its location and device parameters. The GLDB would then return details of the allowed frequencies and power levels [5].

In the US, the FCC has finalized the TVWS regulation [19], followed by the Infocomm Development Authority (IDA) of Singapore [20] in 2014 and Ofcom from the UK in 2015 [5]. The ECC prepared European level technical framework in the European Conference of Postal and Telecommunications (CEPT) FM53 working group [21]. The TVWS regulatory frameworks to date have been unprotected and license-exempt, applicable for deploying the most prominent TVWS Wi-Fi version of IEEE 802.11af [22]. The FCC has temporarily certified several companies including Google, Microsoft, and Spectrum Bridge as geolocation database operators. In UK, Fairspectrum, Nominet UK, Sony Europe, and Spectrum Bridge are qualified to provide database services for the TVWS. The first use cases of the TVWS in the US have been fixed Wireless Internet Service Provisioning (WISP) for rural communities and industry verticals, where another connection technology, typically Wi-Fi, is needed between the User Equipment (UE) and the TVWS Customer Premises Equipment (CPE).

B. *Licensed Shared Access (LSA)*

The EC communication based on an industry initiative promoted spectrum sharing across wireless industry and diverse types of incumbents [23]. In 2013, the Radio Spectrum Policy Group (RSPG) of the EC defined LSA as [2] "*a regulatory approach aiming to facilitate the introduction of radio communication systems operated by a limited number of licensees under an individual licensing regime in a frequency band already assigned or expected to be assigned to one or more incumbent users. Under the LSA framework, the additional users are allowed to use the spectrum (or part of the spectrum) in accordance with sharing rules included in their rights of use of spectrum, thereby allowing all the authorized users, including incumbents, to provide a certain QoS*."

The recent development in policy, standardization and architecture has focused on applying the LSA to leverage scale and harmonization of the Third Generation Partnership Project (3GPP) ecosystem. This would enable MBB systems to gain shared access to additional harmonized spectrum assets not currently available on exclusive basis, particular the 3GPP band 40 (2.3-2.4 GHz) as defined by the CEPT [24]. The European Telecommunications Standards Institute (ETSI) introduced related system reference, requirements and architecture documents [16][25][26] from the standardization perspective. In the LSA concept, the incumbent spectrum user, such as a PMSE video link, a telemetry system, or a fixed link operator, is able to share the spectrum assigned to it with one or several LSA licensee users according to a negotiated *sharing framework* and *sharing agreement*. The LSA model guarantees protection from harmful interference with predictable QoS for both the incumbent and the LSA licensee.

The LSA architecture consists of two new elements to protect the rights of the incumbent, and for managing dynamics of the LSA spectrum availability shown in Figure 2: the *LSA Repository* (LR) and the *LSA Controller* (LC). The LR supports the entry and storage of the information about the availability, protection requirements and usage of spectrum together with operating terms and rules. The LC located in the LSA licensee's domain grants permissions within the mobile network to access the spectrum based on the spectrum resource availability information from the LR. The LC interacts with the licensee's mobile network in order to support the mapping of LSA resource availability information (LSRAI) into appropriate radio transmitter configurations via Operation, Administration and Management (OAM) tools, and to receive the respective confirmations from the network. The LSA system for 2.3-2.4 GHz band has been validated in field trials in Finland, Italy and France. Architecture, implementation and field trial results are presented, e.g., in [27] – [30].

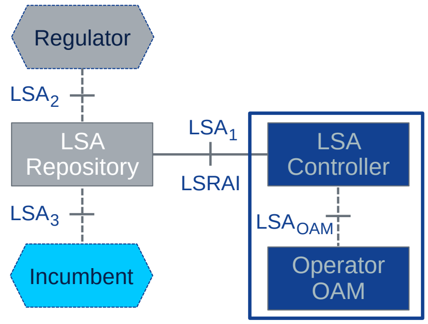

Figure 2. The LSA architecture reference model.

The second use case currently being considered in European regulation is the application of LSA to the 3.6-3.8 GHz band [31]. For this band, the incumbent usage is less dynamic, and the LSA band availability is guaranteed in the license area for a known period. This allows extension to more innovative use cases, such as local networks using small cells, as there is no need for additional frequency resource or existing infrastructure to support dynamic handover. The ETSI Reconfigurable Radio Systems Technical Committee (ETSI RRS) initiated a feasibility study "temporary spectrum access for local high-quality wireless networks" [32] in 2017 to study LSA evolution towards 5G spectrum, localization of spectrum for novel 5G use cases, and to enable horizontal sharing and sub-licensing for efficient use of the spectrum assets.

C. *Citizens Broadband Radio Service (CBRS)*

As the LSA policy discussion started in Europe, in the US the CBRS concept started to gain interest as a complementary spectrum management approach. In the US, the PCAST report [3] in 2012 suggested a dynamic spectrum sharing model as a new tool to the US wireless industry to meet the growing crisis in spectrum allocation, utilization and management. The key policy messages of the document were further strengthened in 2013 with Presidential Memorandum [33] stating *"…we must make available even more spectrum and create new avenues for wireless innovation. One means of doing so is by allowing and encouraging shared access to spectrum that is currently allocated exclusively for Federal use. Where technically and economically feasible, sharing can and should be used to enhance efficiency among all users and expedite commercial access to additional spectrum bands, subject to adequate interference protection for Federal users*."

In Figure 3, the US three-tier authorization framework with the FCC's spectrum access models for 3550-3650MHz and 3650-3700MHz spectrum segments are illustrated. While the general CBRS framework could be applied to any spectrum and between any systems, the current regulatory efforts in the Federal Communications Commission (FCC) are concentrated on the 3550-3700 MHz band as the first use case [7].

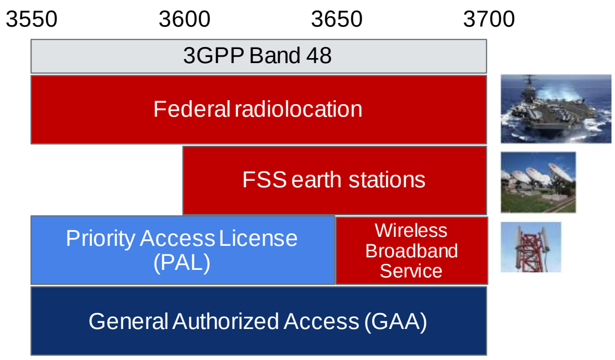

Figure 3. The US 3-tiered CBRS spectrum access model and band plan.

The standardization process for the CBRS is ongoing in the Wireless Innovation Forum (WinnForum) [18], and for the specific spectrum band in the 3GPP [34]. The three tiers depicted in Figure 3 are:

1) *Incumbent Access* (IA) layer consists of the existing primary operations including authorized federal users and Fixed Service Satellite (FSS) earth stations. The IA is protected from harmful interference from the CBRS users by geographic exclusion zones and interference management conducted by the dynamic *Spectrum Access System* (SAS),

2) *Priority Access* (PA) layer includes critical access users like hospitals, utilities, governmental users, and non-critical users, e.g., Mobile Network Operators (MNOs). PA users receive short-term priority authorization (currently, a three-year authorization is considered) to operate within designated geographic census track with Priority Access Licenses (PALs) in 10 MHz unpaired channel. PALs will be awarded with competitive bidding, and with ability to aggregate multiple consecutive PALs and census tracks in order to obtain multi-year rights and to cover larger areas. Any entity eligible to hold a FCC license could apply for a PAL and is protected from harmful interference from the General Authorized Access (GAA) layer.

3) *General Authorized Access* layer users, e.g., residential, business and others, including Internet service providers are entitled to use the spectrum on opportunistic *license-by-rule* regulatory basis without interference protection. In addition to the 50% GAA spectrum availability floor specified to ensure nationwide GAA access availability, the GAA could access unused PA frequencies. GAA channels are dynamically assigned to users by a SAS. The addition of the third tier is intended to maximize spectrum utilization, and to extend usage from centralized managed BSs to stand-alone GAA access points.

The SAS dynamically determines and assigns PAL channels and GAA frequencies at a given geographic location, controls the interference environment, and enforces exclusion zones to protect higher priority users as well as takes care of registration, authentication and identification of user information. In 2016, the FCC finalized rules for CBRS [7], and introduced the *light-touch leasing* process to make the spectrum use rights held by PALs available in secondary markets. Under the light-touch leasing rules, PA Licensees are free to lease any portion of their spectrum or license outside of their *PAL protection area* (PPA) without the need for the FCC oversight required of partitioning and disaggregation. This allows lessees of PALs to provide targeted services to geographic areas or quantities of spectrum without additional administrative burden. Coupled with the minimum availability of 80 MHz GAA spectrum in each license area, these rules will provide the increased flexibility to serve specific or targeted markets. Furthermore, the FCC will let market forces determine the role of a SAS, and as such, stand-alone exchanges or a SAS-managed exchanges are permitted.

The *CBRS devices* (CBSDs) are fixed or portable BSs or access points, or networks of such, and can only operate under the authority and management of a centralized SAS, which could be multiple as shown in Figure 4. Both the PA and the GAA users are obligated to use only certified the FCC approved CBSDs, which must register with a SAS with information required by the rules, e.g., operator identifier, device identification and parameters, and location information. In a typical MNO deployment scenario, the CBSD is a managed network comprising of the *Domain Proxy* (DP) and Network Management System (NMS) functionality. The DP may be a bidirectional information routing engine or a more intelligent mediation function enabling flexible self-control and interference optimizations in such a network. In addition to larger MNO-operated MBB networks, DP enables combining, e.g., the small cells of a shopping mall or sports venue to a virtual BS entity that covers the complete venue. The DP can also provide a translational capability to interface legacy radio equipment in the 3650–3700 MHz band with an SAS to ensure compliance with the FCC rules. A, MNO could utilize a DP and/or operator-specific SAS in protecting commercially sensitive details of their network deployment data. In the dialog between industries [35], the FCC and the main incumbent user, United States Department of Defense (DoD), it is assumed that in addition to informing database approach, there is a need to introduce a Non-Informing Approach, requiring *Environmental Sensing Capability* (ESC).

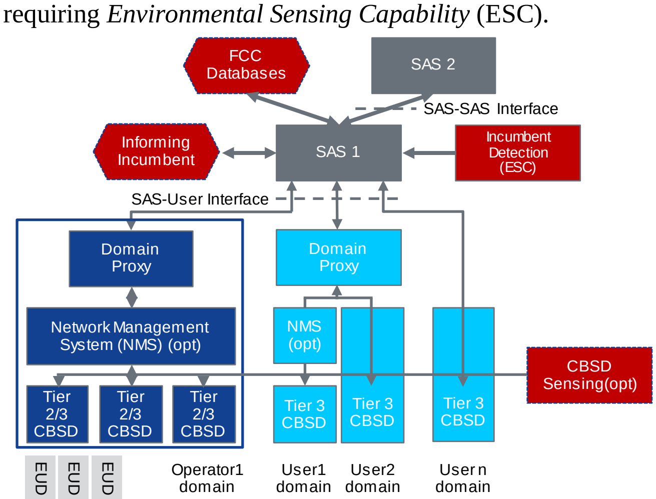

Figure 4. The US 3-tiered 3 CBRS concept and functional architecture.

The ESC architecture and implementation scenarios discussed include a dedicated sensing network for a SAS, collaborative sensing by commercial network BSs, or their combination. According to the FCC rules [7], the SAS must either confirm suspension of the CBSD's operation or its relocation within 300 seconds after the ESC detection communication, or other type of notification from the current federal user of the spectrum band.

The White House aims to expand wireless innovation in spectrum sharing further through identifying an additional 2 GHz of federal owned spectrum below 6 GHz for future commercial sharing [35]. The success of the CBRS is critical to future federal–commercial spectrum sharing. Moreover, the FCC has already proposed the use of the three-tier model and the SAS for 5G in several cmWave and mmWave bands.

III. Business Model and Sharing Economy Antecedents

Development of business models for spectrum sharing can benefit from the previous work on business models in the Internet business domain. Scalable business model analysis has been developed by Amit and Zott [36] as a model of e-business based on four independent dimensions: efficiency, complementarities, lock-in, and novelty. Rappa [37] classified the Web-based business models as brokerage model, advertising model, information-intermediary model, merchant model, manufacturer direct model, affiliate model, community model, subscription model, and utility and hybrid models. Bouwman et al. [38] differentiate in their business model analysis business model effects: organizational structure, services, technology, revenue, and environmental factors: regulation, technology, market. Hallowell [39] stated a scalability paradox that while the reduction of scalability is often caused by human intervention, the competitive advantage based on differentiation is also gained by human intervention. Stampfl identified and categorized the antecedents of business model scalability into five mutually exclusive factors in the explorative business model scalability model [40], which Stephany adapted into his sharing economy definition [41].

Next, the theoretical frameworks used to analyze how business models and their key elements could evolve and scale in response to novel spectrum sharing models are introduced.

A. Business Models and Ecosystems

Business models in general are built to exploit a business opportunity [42], in connection with the company and its external business environment [43]. In order to gain and sustain competitive advantage, companies must continuously develop and renew their business models. In the development of any new spectrum sharing concept, it is essential to consider the underlying business opportunities and the business model elements that are attractive and feasible for all the key stakeholders. Authors in [44] define business model in general as a framework across three analytical building blocks: a) focus of the business (activities that provide the basis for value creation and capture), b) locus of the business (i.e., defining the potential and scalability of business), and c) modus of business (simplicity and dynamism of business). The discussed spectrum sharing concepts confront the MBB and the wireless industry with strategic environmental changes, such as emerging competitive market structures, policy and regulatory changes as well as technology complexity, which all require companies to adapt or reinvent one or more aspects of their business model designs within their ecosystem.

Ecosystems [45] are created and emerge around synergistic value co-creating and co-capturing activity-systems between stakeholders. Based on the ideas of Moore [45], stakeholders of the ICT specific businesses have started to discuss digital business ecosystems that comprise the converged information and communications technology networks, social networks and knowledge networks. Contemporary research on digital business ecosystems is mostly technology and platform focused, but authors in [46] argued that software components, applications and services could be regarded as digital "species" in global competitive selection process. Regulation, technology and business co-evolve within ecosystemic settings.

B. Business Model Saclability

Potential for scalability is an important aspect when developing a business model, and synchronizing it to the respective business opportunity is crucial. The scalability of the business model and its key elements has been shown to be the primary driver for the venture growth [47], and the attractor towards venture capital investments [48]. Vertical scalability approach scales-up a system by adding more resources into the system nodes, while the horizontal scale-out approach adds more nodes to the complete system. Stampfl [40] identified and categorized the antecedents of business model scalability into five mutually exclusive factors in the explorative business model scalability model: technology, cost and revenue structure, adaptability to different legal regimes, network effects, and user orientation.

The emerging *sharing economy framework* has leveraged these scalability factors with focus on resource efficiency and on-demand platform [49]. Through studying recent early adopters of the framework, Stephany [41] defined sharing economy as "*the value in taking the underutilized assets and making them accessible online to a community, leading to a reduced need for ownership of those assets*." Furthermore, the framework originated from collaborative individual peer-to-peer community consumption has lately evolved to corporations and governments participating the ecosystem as buyers, sellers or lenders [50]. Proposed sharing economy antecedent factors used in assessing business model characteristics of the spectrum sharing concepts are:

a) Platform for online, on-demand accessibility,

b) Reduced need for the ownership,

c) Utilization of underutilized assets,

d) Adaptability to different legal and policy regimes,

e) Communities and trust, and

f) Value creation and user orientation.

Each of these antecedent factors relate to the specificities of the focus, locus and modus of the business in question.

C. Market and Hierarchies

The basis of all business activities is the transformation of resources and capabilities into goods and services. The goods dominant logic views services in terms of a type of intangible goods whereas the service-dominant logic considers service – a process of using one's resources for the benefit of and in conjunction with another party – as the fundamental purpose of economic exchange. Value creation in service dominant logic stems from the use of internal and external resources and overcoming the internal and external resistance for co-creating and co-capturing value in exchange. The service dominant logic together with the resources/capabilities discussion extends nicely to future mobile broadband businesses in large that are characterized with increasing sharing of resources from spectrum to infrastructure with various business models.

Economies have traditionally considered to have two basic mechanisms for coordinating the flow of assets or services through adjacent steps in the value chain: markets and hierarchies, depicted in Figure 5 [14].

Malone [14] studied the change in how firms and markets organize flow of goods and services. He defines *hierarchies* as "Visible Hand" that coordinate the flow of goods through adjacent steps by controlling and directing it at higher level in the managerial hierarchy within a firm and its value chain. Typically, in hierarchies, production costs are relatively high, and *coordination costs* low. These coordination costs consider the costs of gathering information, negotiating contracts, and protecting against the risks of "opportunistic" bargaining [52]. Coordination costs are a part of the *transaction costs* that cover all costs that are involved in making and carrying out a transaction between two parties or more [53]. On the other hand, *markets* can be defined as "Invisible Hand" coordinating the flow through supply and demand forces and external transactions between firms and individuals.

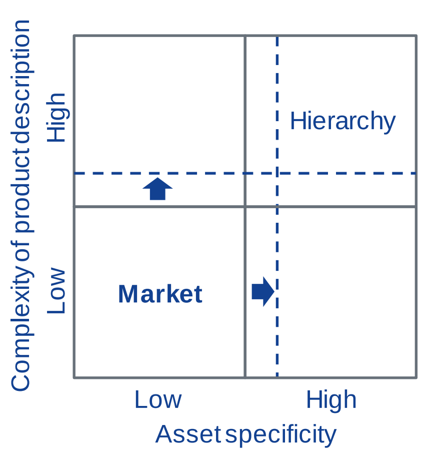

Figure 5. Communication, brokerage, and process & service integration transform spectrum licensing towards markets.

Coordination cost of the markets are relatively high, and production costs low. Naturally, variants of the two pure relationships exist, but can usually be categorized as primarily one or the other.

Figure 5 illustrates Malone's Market-Hierarchy analytic framework [14]. *Complexity of product description* can be defined as amount of information needed to specify the attributes of a product in enough detail to allow a buyer to make a selection. Because highly complex product description requires more information exchange, they also increase coordination cost advantage of hierarchies over markets. *Asset specificity* measures the extent to which investments made to support a particular transaction have a higher value to that transaction than would have if they were redeployed for any other purpose. Specificity relates, e.g., to single function, location, skills, time or lengthy process of development in close collaboration with suppliers.

IV. Analysis of the Spectrum Sharing Concepts

The three spectrum sharing models, the TVWS, the LSA, and the CBRS, introduced and discussed in Section II are next analyzed and compared against the sharing economy criteria presented in Section III. The summary of the sharing economy antecedent analysis is given in Table I.

A. Platform

Sharing economy business models are hosted through platforms and automatized processes across connectivity, content, context and commerce layers that enable a more precise, real-time measurement of available capacity, and the ability to dynamically making that capacity accessible. From commerce perspective, platform is a business based on enabling value-creating interactions between external producers and consumers. Platform provides an open, participative infrastructure for these interactions and sets governance conditions for them.

At the connectivity layer, this dynamic adaptability to short-term changes, and automatic configuration of radio infrastructure and user equipment is the key differentiator to static sharing concepts, e.g., in the Industrial, Scientific and Medical (ISM) spectrum bands. The global 3GPP ecosystem with scale and harmonization will be the common technology scalability factor for the LSA and the CBRS approaches, while the TVWS has heritage on the Institute of Electrical and Electronics Engineers (IEEE) Wi-Fi ecosystem at the ISM bands.

Compared to the LSA and the CBRS, regulatory and standardization actions for the TVWS have been concluded. However, to date the TVWS platform has not reached a tipping point, despite support from several major IT companies providing the GLDB. Interference constraints and strict technical requirements entail dedicated radio designs. Furthermore, radio ecosystem has not scaled due to scattered standardizations, lack of mobile operators' interest, and the lack of certainty for the long-term availability of white spaces.

TABLE I. SPECTRUM SHARING BUSINESS MODEL ANTECEDENT FACTORS.

Antecedents	**Sharing model**		
	TVWS	***LSA***	***CBRS***
a) Platform	+ Technology platform standardized and may thus be adopted quickly - Based on evolving technologies scores on flexibility, but may lack scale and harmonization - Interference constraints and strict technical requirements requires specialized radios - Uncertainty of spectrum assets has limited interest of major technology vendors and MNOs.	+ Utilizes existing 3GPP ecosystem assets and scale + Network management system automatization based spectrum control function (LC) + Simple repository function (LR) fullfills static and semi-static use cases + Protects and leverages MNOs infrastructure investments	+ Extend 3GPP ecosystem to unlicensed and standalone LTE unlicensed + Dense urban deployments have additional utility and infra assets to share, e.g., fixed optical infra - Requires new intelligent and near real time SAS and ESC sensing functions. - New capabilities in big data & spectrum analytics needed to manage horizontal interference, co-existence and transactions - New spectrum band and introduced dynamism impacts BS and UE radios
b) Reduced need for the ownership	+ Offers access to practically free spectrum + Scores well in terms of efficiency of frequency bands utilization and rapidity of access - Unlimited number of users administratively imposed, rather than voluntarily chosen	+ Enables faster access to lower cost capacity spectrum without coverage obligations + Protects the turf on existing MNO infra with radio upgrades +/- Based on traditional exclusive licensing model with relatively high up front license payment + Expands sharing into other assets, e.g., with local venue owners	+ Unbundles investment in spectrum, network infrastructure and services + Spectrum access with low initial annuity payments + Access to local spectrum driven by business needs, when and where + Expands sharing into other assets, e.g., with local venue owners.
c) Utilization of underutilized assets	- Future availability of the shared UHF spectrum assets is uncertain particularly in dense urban areas - Heterogeneous incumbent users and TV channels properties - Non-guaranteed QoS may limit scope of services	+ Availability of spectrum assets dependent on regulation, currently LSA considerd for 2.3 GHz and 3.6 GHz spectrum band. + MNO connectivity model as is + Differentiation through extra data capacity and high speed enabling QoS and QoE pricing + Option to expand to capacity wholesale service	+ For MNOs low cost offloading + Nomadic Wi-Fi type of Internet access on dense urban environment hot spots + PAL – GAA tier flexibility + Spectrum and small cell hosted solution (SCaaS) + Enables new vertical segments: IoT - Concerns over the QoS predictability particularly with and at GAA layer and neighboring users across census tracks - Transaction costs increase in early development with increased complexity
d) Adaptability to different legal and policy regimes	+/- Regulated and standardized the US and Europe / UK with variants, e.g., in Singapore and Canada. + Low administrative burden + Low entry barrier enables quick access to the market	+ Legal certainty and security with existing regulatory framework + Requires a harmonized framework in regional standardization and regulation in order to reach economies of scale + Initial European focus but very generic concept adaptable to other regimes - National regulation with incumbent ecosystem	+ Low administrative burden with low entry barrier on GAA - Uncertainty with short PA license term and GAA with opportunistic access only - Need regulation and standardization with incumbent ecosystem (DoD) - Initially US federal specific, need adaptability to other regimes
e) Communities and trust	+ Geo-location database is trust vehicle to protect incumbent users' QoS - Heterogeneous GLDB operators in terms of services and business models - Rules out the possibility of decentralized agreement over accepted interference levels - The tragedy of the commons - Business model uncertainty limits incentives to invest	+ Trust in predictability of QoS and pragmatic incumbent protection build on binary agreements and implemented in LR. + Protection of LSA licensee business critical information quaranteed + Use existing consumer ownership on connectivity with existing known services for lock-in + Small cell ecosystem could introduce new players & shared asset opportunities	+ Trust implemented using the SAS + Internet giants 'innovation' ecosystems to trigger communities + Customer data ownership on apps and services for customer lock-in + Small cell ecosystem introduces new players and shared asset opportunities +/- Complemented by sensing as defense incumbents lack of trust in GLDB - Protection of MNOs business sensitive information assets in SAS uncertain - DoD OPSEC requirements
f) Value and user orientation	+ Main current use case is to provide Internet to rural unserved areas + Free spectrum facilitates local niche services, e.g., for various IoT vertical start-ups +/- Spectrum market related new value-added service opportunity for database providers utilizing positive network externality - Unlicensed users' QoS not protected - Requires special user equipment	+ Clear business model as is + Additional capacity to serve customers with improved QoS and QoE + Customer experience management as a tool for value differentiation + Can open the market to new players with local licenses	+ Flexible regulatory framework allows facilitates introduction of innovative local business model designs + Local and Internet players offer differentiation based on user knowledge. + Enables heterogeneous segments, e.g., consumers, enterprises, IoT + Introduces new roles: SAS admin, broker and sensing + Local services, e.g., media broadcasting and advertisement

The deployment of the LSA system will require relatively minor changes to the existing mobile broadband infrastructure. MNOs can utilize existing network off-the-shelf, and build additional LSA controller as an added Self Organizing Network (SON) functionality on top of the OAM system. In the LSA system, envisaged for the 2.3-2.4 GHz band, spectrum control is inside the MNO domain, and diffusion towards cognitive networks, in large, could be retained within MNOs control. Furthermore, the LR has low complexity compared other sharing concepts as sharing will be static or semi-static and binary between the incumbent and the licensee.

In the CBRS model with higher dynamics, the third opportunistic GAA layer and sensing function will require a more complex SAS system. In managing a higher volume of dynamic transactions, big data analytics capabilities of Internet players could become of need and bring competitive advantage. In the radio access side, higher dynamics in the spectrum control across the PA and the GAA layers and operator service areas will necessitate advanced spectrum analytics and horizontal co-existence management. Furthermore, with tight response time requirements this could also affect radio design of BSs. On the other hand, the PAL and the GAA layers with the common SAS will offer opportunities to common markets for licensed and licensed-by-rule equipment, and services across customer segments. Higher frequency and the small cell focus layer enables CBRS operators to utilize their fixed optical infra assets in backhauling. In addition to this, the GAA layer has an optimal opportunity to leverage emerging LTE unlicensed and Wi-Fi ecosystems to scale and complement LTE operator and stand-alone solutions.

B. *Reduced Need for Ownership*

The second factor deals with the superior value proposition and transactions that offer access over ownership, and ability to realize more choices with rapidity and lower initial costs. Sharing economy are spawning a variety of efficient new as-a-service (aaS) business models.

In the unlicensed TVWS concept, only device authorization is needed before starting operations on practically free spectrum, which radically lowers the entry barrier compared to two other concepts. Unlimited number of users are administratively imposed, rather than voluntarily chosen. Concept scores well in terms of efficiency of frequency bands utilization and rapidity of access. In the UK TVWS concept, the unlicensed approach is complemented with a licensed option for devices that must be manually configured.

The LSA concept offers lower cost spectrum without coverage obligations, with QoS guaranteed by licensing. For a greenfield operator, the up-front investment in spectrum license combined with needed infrastructure continues to set an entry barrier. Therefore, the second use case of LSA on the band 3.6-3.8 GHz envisaged for more local licenses and deployment without need for existing mobile infrastructure or specific network management tools provides opportunities that are more prominent for new entrants. Extra capacity could in addition offer a scale-out opportunity with a wholesale service. The PAL operator in the CBRS could deploy similar kind of business model designs.

The CBRS three-tiered regulatory approach can disruptively unbundle investment in spectrum, network infrastructure and services, and transform spectrum sharing further towards markets. Access to low cost spectrum with lower initial annuity payments for spectrum rights enables local 'pro-competitive' deployments, and further expands sharing mechanism for infra resources between operators. Furthermore, the light-touch leasing process will make the spectrum use rights held by a PA licensee available in secondary markets. The CBRS concept has potential on a longer term to reduce the need for parallel network infrastructure when spectrum, and related radio access infra assets are tradable, and hosted and shared on-demand and as-a-Service.

C. *Utilization of Underutilized Assets*

Access and deployment of the underutilized assets on-demand is essential to generate continuous revenue early. The value of the shared spectrum resources is highly dependent on the availability, liquidity and predictability.

Future availability of the shared TVWS spectrum assets is uncertain particularly in the dense urban areas. In rural area, TVWS operators are optimally positioned to create revenues from savings in spectrum costs, extended coverage and increased relative capacity. Coverage has potential to extend the customer base, while capacity could increase the Average Revenue Per User (ARPU). On the other hand, non-guaranteed QoS, heterogeneous incumbent users, and TV channel properties limit usability and the scope of services of the shared resources.

In the LSA approach, a sharing framework and binary sharing agreement negotiated between regulator, incumbent and licensee guarantee QoS and statistically known availability in advance. The LSA sharing framework could be initiated on a voluntary basis, but the regulator also may impose it. Availability of spectrum assets is highly dependent on the regulation, and the LSA was studied in the context of 2.3 GHz spectrum band as the starting point. The second use case currently under discussion is the 3.6-3.8 GHz band, in which case the predictability of spectrum availability is even higher, as dynamic changes in spectrum availability do not occur. Similar predictability is possible for the second tier PAL operator in the CBRS. Utilizing extra capacity established MNOs could create differentiating value proposition around QoS and Quality of Experience (QoE), and have option to expand to capacity wholesale and hosting services.

While the third opportunistic GAA layer offers the unlicensed Wi-Fi ecosystem type innovation environment, the availability, and particularly the QoS is not guaranteed. This has limited MNOs interest, based on traditional business models with need for the high upfront investments. On the other hand, both traditional MNOs and alternative operators could use the GAA layer with free spectrum resource for offloading and nomadic Wi-Fi type of Internet access. On dense urban environment, new business model designs and revenue structures could emerge combining spectrum with other shared assets, e.g., small cell hosted solution as-a-service (SCaaS), advertisement & transaction based models, and enabling new vertical segments within Internet of Things (IoT). Furthermore, the three-tier model offers network operators unprecedented flexibility and scalability through the ability for to move between the PA and the GAA tiers. This allows for the use of much shorter leasing periods, one to three years, without requiring a lessee to forgo their investment if their lease does not renew via simply converting from PA to GAA tier. For a new market entrant, this enables to try out their new service utilizing the GAA tier without having to invest in spectrum with future option to choose to buy a PA license when / where needed depending on the market and interference protection needs. In the system level, this flexibility and scalability between tiers combined with the secondary market provisions will improve spectrum efficiency in capacity, and particularly in value as spectrum can be regularly re-allocated to the most valuable use. The complexity of the CBRS introduces new independent or integrated roles to the ecosystem related to SAS administration, sensing operator and future spectrum broker that could increase deployment costs in early development. New technology introduction should be continuously assessed in relation with added complexity and deployment costs.

D. Adaptability to Different Legal and Policy Regimes

The harmonization of spectrum management is indispensable to unlock a wide range of positive externalities throughout the entire value chain. Scalability of all sharing concepts could be limited by fragmented national incumbent use cases, related different incumbent protection mechanisms, and regulatory differences affecting repository/database and spectrum management system architectures and implementations.

The TVWS concept is regulated and standardized the US and Europe / the UK with variants, e.g., in Singapore and Canada. While having a negative impact on the platform scale, the low administrative burden approach of the TVWS offers low entry barrier to the market.

Existing European LSA regulatory framework offers legal certainty and security with relatively high initial administrative burden. This protects the turf for established players, but limits the scalability through high entry barrier during the early macro deployments on the 2.3 GHz band. While the LSA offers visibility and predictability needed for high up-front investments in spectrum and infrastructure, both the CBRS and the TVWS regulatory approaches are pro-competitive targeting to lower administrative burden and entry barrier. The higher frequency small cell use cases of the LSA envisage opportunities that are more prominent for new entrants, and similar kind of business model designs than the PAL layer in the CBRS.

The CBRS will have advantage on leveraging the common US market. Sharing concepts in Europe require a harmonized framework in regional standardization and regulation to reach economies of scale. The regulatory and standardization actions needed with regulated or highly political incumbents' ecosystem (like defense, media and broadcasting) will potentially limit the scalability of all the frameworks. Uncertainty is introduced with the short PA licensing terms, and the GAA with opportunistic access only.

E. Communities and Trust

Making spectrum accessible is not enough; the underutilized assets need to move within the community. The trust is the trigger of collaborative shared consumption that makes the system grow and scale. The creation of a critical mass ecosystem with positive network effects is important for all three approaches with new context model based spectrum administrator and broker roles.

The TVWS concept rules out the possibility of decentralized agreement over accepted interference levels and is prone to the *tragedy of the commons* as number of competitive users grows. Heterogeneous GLDB operators in terms of services and business models may have additional negative impact to the community and the trust factor.

The repository or database is the vehicle to accomplish trust in all the models. Trust in the predictability of QoS and pragmatic incumbent protection is built on binary agreements and implemented in LSA Repository. In the CBRS, the database approach is complemented by the ESC for defense incumbents. Additional challenge for the CBRS is protection of MNOs business critical information assets in a SAS, and to meet stringent DoD's Operational Security (OPSEC) requirements.

In network externalities, business model designs represent a co-opetitive situation between MBB, wireless Internet and Internet domains. TVWS operators leverage their niche through tailoring according to local customer segment they serve benefiting of extended coverage. Furthermore, particularly in rural use cases, communication bit rates could be increased to level that enables access to Internet and media services to new user group.

In case LSA licensees have existing infrastructure and dedicated resources in other mobile bands, they can utilize their connectivity scale and customer base to achieve instant critical mass, and use existing consumer ownership on connectivity for lock-in. New entrants in the case of LSA and CBRS could build their critical mass and lock-ins using Internet 'innovation' ecosystems, and consumer and customer data ownership on apps and services.

Shared spectrum local small cell deployments in all the sharing concepts scale out ecosystems from legal and real estate aspects to radio planning and site camouflaging, as small cells will attach to structures and building assets not owned by traditional operator. This creates additional opportunities for sharing and collaboration between operators and various specialist companies like infrastructure owners and providers, real estate and street furniture owners, utility service companies and backhaul providers.

F. Value Creation and User Orientation

Sharing economy platforms create reciprocal economic value. Simplicity of the offer built around user knowledge driven 'demand pull' is critical in differentiating with existing service, as well as in scaling new spectrum sharing enabled services.

In the TVWS concept, unlicensed users' QoS is not protected. To date, the primary commercial 'niche' use case has been the non-competitive Fixed Wireless Access (FWA) WISP, in which a single GLDB serves a set of unlicensed WSDs belonging to local WISP providing Internet access to unserved rural areas. Free spectrum facilitates local niche services, e.g., for various IoT vertical start-ups. FWA use cases need specialized devices seen as extra complexity by users.

MNOs could utilize the surplus LSA spectrum in strengthening customer satisfaction through fulfilling existing need pull with familiar services and simplicity of the offer built on existing customer data via customer experience management tools. In general, spectrum sharing technologies should only be visible to end user through benefits offered in availability, coverage, capacity, data rates, or as decreased service costs. Both the LSA and the CBRS can also facilitate introduction of innovative local business model designs. For MNOs, they enable differentiation opportunities in serving more heterogeneous customer segments, e.g., consumers and enterprises, and for alternative type operators like Internet players faster efficient access to new systems and services. Local and Internet players are uniquely positioned to offer differentiation around existence of their extensive user knowledge. On one hand, operators prefer specialized services, or enhanced QoS traffic delivery for a fee to content, application, or over-the-top service providers. New entrants from Internet domain, in particular, on the GAA layer would like to see broadband as a utility, transparent and non-exclusive basis.

In addition to providing mandatory spectrum availability information brokerage, the LSA repository, the SAS, and the GLDB administrators can capture value through selling advanced information regarding the quality of the shared spectrum based on information from both the incumbents and other sharing users. These value-added services will be framed by regulatory action, and their value will increase with the number of service users, creating a positive network externality. On the other hand, for operators the added complexity of the spectrum management can be seen as increased transaction and opportunity costs.

V. Implication: Toward Markets for Spectrum Sharing Business Evolution

In this section, the analysis of spectrum sharing concepts discussed in Section IV are summarized using the markets and hierarchies analytic framework, presented in Section III. The summary of the anticipated changes into the mobile broadband ecosystem is depicted in Figure 6 and market-hierarchy positioning in Figure 7.

A. Value Creation and Capture Mechanism Transformation in the Ecosystem

As a continuation to the sharing economy analysis, we used the concepts of ecosystems and business model to provide a framework regarding the resources, business model, value and trust, shown in Figure 6. Specific attention in the framework is paid to value creation and capture mechanisms and their evolution over time.

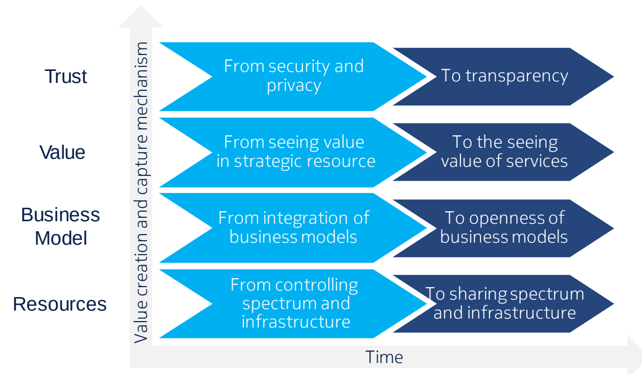

Figure 6. Value creation and capture mechanism transformation in the ecosystem.

At resource level, a clear transition from controlling spectrum and infrastructure toward sharing of spectrum and infrastructure assets can be observed. At the business model level, it could be expected that that the role of openness in business models would gain in importance. Regarding value, the spectrum sharing appears to conform more the "value from service" -approach than what traditionally has been the case in the industry. In the value creation process, firms may work as an integrator, collaborator, transaction broker or bridge provider, and correspondingly take care of resource configuration microprocesses like streamlining, sorting, resource crowdsourcing or continuous testing. The theme trust was seen to play a crucial role in the spectrum sharing and future 5G business ecosystem in large. The security and privacy concerns remain in providing services from the customers' perspective, but the role of transparency within the ecosystem was seen as becoming more pronounced.

There can be seen two developmental processes ongoing towards spectrum sharing and 5G. On one hand, MNOs are striving for technologies that enable more efficient use of existing spectrum assets, such as Carrier Aggregation (CA), Multiple-Input and Multiple-Output (MIMO) antenna technologies, and LTE on unlicensed spectrum concepts. On the other hand, regulators on their part strive to increase the amount of available spectrum. Both streams of action influence the value of spectrum, either from technological cost perspective or through new stakeholders entering the ecosystem. From conceptual perspective, these aforementioned developmental processes give us a layered view on value creation and capture. Accepting that business models are the devices for creating and capturing value, both *openness* and *integration* of business models are essential elements for understanding the ongoing dynamics toward 5G. Sharing of resources, whether spectrum or infrastructure, influences both integration of different players' business models and the required degree and type of openness of these business models, and in turn having an impact of the value creation and capture achieved within the ecosystem. At the second layer, where regulators strive to increase the amount of available spectrum for 5G, also the different types of operators such as existing MNOs or upcoming micro-operators [53] that could offer local services, influence value creation. However, the creation of trust, that also influences value creation and capture, is a more multifaceted issue as it cannot only be created through regulative control: it requires also a certain level of openness that needs to be adopted within the future 5G ecosystems.

B. Positioning of the Spectrum Sharing Concepts in the Markets and Hierarchies Analytic Framework

As discussed in Section III, there are three major forces transforming industries towards markets through reducing asset specificity and complexity of product description: communication, brokerage, and integration [14]. Based on the recent platform economy research [55], spectrum sharing markets can be seen to provide the several benefits compared to hierarchies in the communication and IT domain. Markets scale more efficiently by eliminating gatekeepers and utilizing network effects, unlocking new sources of value creation and supply, and providing superior marginal economics of production and distribution. Moreover, commerce platforms de-links ownership of assets from the value it creates, and aggregates unorganized markets with lower transaction costs.

We used the concepts of sharing economy and markets and hierarchies to provide a framework regarding the positioning of the spectrum sharing concepts as depicted in Figure 7. We argue that all the six sharing economy antecedent factors have positive effect in transforming towards markets. Complexity of product description is seen to be lowered particularly by platform, adaptability and value creation and user orientation antecedents. Assets specificity, on the other hand, is impacted by reduced need for the ownership, utilization of underutilized assets, and communities and trust. As a summary, resulted positioning of the analyzed spectrum sharing concepts is depicted in the Figure 7. In *asset specificity*, the high site specificity of the TVWS concepts impacts it's low score. For the LSA, the time specificity of the availability of the spectrum limits it's market characteristics. On the other hand, the CBRS score well due to scalable and flexible three-tiered model, fine-grained spectrum allocation in time and location, and the sub-leasing option that enables vertical disintegration.

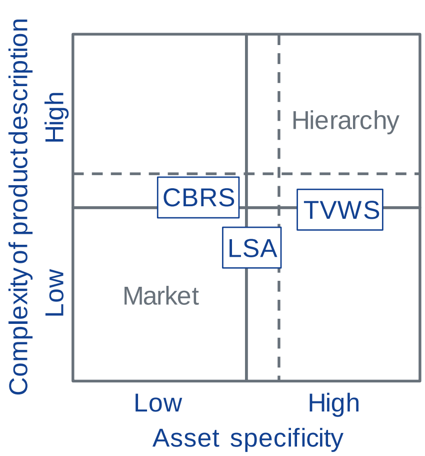

Figure 7. The positioning of the spectrum sharing concepts in the markets and hierarchies analytic framework.

Low *complexity* of product description favors the LSA, which builds on existing licensing regulatory regime with guaranteed QoS, predictability and legal certainty. TVWS on the other hand, stems from most mature regulatory and standardization landscape globally, and the simplicity of offer to specific niche use case. The CBRS extends the offer to heterogeneous local use cases and service providers. Though, the flexibility and dynamism of the CBRS result in increased system complexity at early deployment phase.

VI. Conclusion and Future Work

Recently, several spectrum sharing system concepts have been introduced and widely studied to cope with spectrum scarcity, though to date only a few has developed into pre-commercial deployments. This paper discussed business model characteristics and sharing economy scalability criteria, and evaluated recent spectrum sharing concepts, the TV Whites Space, the European Licensed Shared Access and the US Citizens Broadband Radio Service, with respect to these criteria.

For a spectrum sharing concept to be adopted, it is essential not just to develop technology enablers to meet regulatory criteria but also to provide a scalable business model design for all the stakeholders. Harmonization and scalability of the platform and automation of processes will drive economies of scale and trigger early market opening. The model must be able to offer superior value proposition that offer access over ownership and ability to realize more choices with lower initial transactions costs compared to exclusive models. Value of the shared spectrum resources are highly dependent on its availability, liquidity and the predictability. Access, resource orchestration and configuration of the underutilized assets on-demand is essential to generate continuous revenue early. Scalability of all sharing concepts could be highly impacted by fragmented national incumbent use cases, related different incumbent protection mechanisms and regulatory differences. Trust is the trigger of all collaborative shared consumption that makes system grow and scale. The creation of a critical mass ecosystem with positive network effects is important for all three approaches with new database spectrum administrator and broker roles. Simplicity of the offer built around user knowledge driven 'demand pull' is critical in value differentiation for existing services as well as in scaling new spectrum sharing enabled services.

By reducing the costs of spectrum coordination, spectrum sharing concepts will lead to an overall shift from hierarchies towards more use of markets to coordinate economic activity related to spectrum assets. This transition is triggered by communication, brokerage, and integration enablers from technology, policy and business domains that reduce asset specificity and complexity of product description.

The analysis indicates that the TVWS concept actively promoted by the US and the UK administrations, benefits from practically free spectrum and low entry barrier. However, to date the level of market acceptance has remained low mainly due to uncertainties related to the available spectrum assets, platform scale, and predictability. Moreover, unlicensed non-guaranteed QoS has limited the scope of services and business model designs. The LSA provides high predictability and certainty for both the incumbent and the LSA licensee, leverages existing platforms and capabilities, and preserves low impact to the ecosystem and business models. The opportunistic third tier of the CBRS concept lowers entry barrier to new alternative operators, scale out ecosystem with new roles, and foster service innovation particularly. Similarly, the higher frequency small cell use cases of the LSA envisages more flexible and scalable opportunities for new entrants, and novel business model designs. On the other hand, introduced dynamism will increase system complexity, and requires novel technology enablers in building trust and ensuring pragmatic predictability in the spectrum management platform while minimizing additional transaction costs.

At resource level, a clear transition from controlling spectrum and infrastructure toward sharing of spectrum and infrastructure assets can be observed. At the business model level, it could be expected that that the role of openness in business models would gain in importance, and the spectrum sharing appears to conform more the “value from service” -approach than what traditionally has been the case in the industry. We argue that all the six sharing economy antecedent factors have positive effect in transforming towards markets. Complexity of product description is seen to be lowered particularly by platform, adaptability and value creation and user orientation antecedents. Assets specificity, on the other hand, is impacted by reduced need for the ownership, utilization of underutilized assets, and communities and trust.

The sharing economy and market and hierarchies analytic theories provide a dynamic framework for analyzing and developing the spectrum sharing business models. In the future, spectrum sharing concept business modelling studies will need to be expanded to cover novel ecosystem roles and stakeholders in resource orchestration and configuration. In particular, co-operative business model with traditional mobile network operators and local alternative micro-operators will be an important aspect to research.

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