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Published in:
2018 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)

DOI:
10.1109/DySPAN.2018.8610409

Published: 01/01/2018

Document Version
Peer-reviewed accepted author manuscript, also known as Final accepted manuscript or Post-print

Please cite the original version:
Matinmikko-Blue, M., Yrjölä, S., Seppänen, V., Ahokangas, P., Hämmäinen, H., & Latva-aho, M. (2018). Analysis of Spectrum Valuation Approaches: The Viewpoint of Local 5G Networks in Shared Spectrum Bands. In *2018 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)* (IEEE International Symposium on Dynamic Spectrum Access Networks). IEEE. https://doi.org/10.1109/DySPAN.2018.8610409

Analysis of Spectrum Valuation Approaches: The Viewpoint of Local 5G Networks in Shared Spectrum Bands

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***Abstract*—Radio spectrum is a scarce natural resource, whose efficient management calls for a thorough understanding of its value. Quite a big number of approaches have emerged for spectrum valuation based on different elements, some with such potentially high uncertainty as future profits, total cost of ownership and societal benefits. Spectrum valuation will be important for the upcoming spectrum decisions by the regulators to deploy 5G networks but will face a new situation, where the use of higher carrier frequencies inherently limits network operations to local areas. This paper analyses the existing spectrum valuation approaches and identifies the key elements to consider, when defining and assessing the value of spectrum especially in the context of future local 5G networks. An important aspect is that the growing pressure to open the mobile market for location specific 5G networks has resulted in new sharing-based models for spectrum access, to allow the emergence of entrant local 5G operators to serve different verticals. We will therefore characterize the identified spectrum valuation elements in the new context of new local 5G networks operating in shared spectrum bands. Our approach considers spectrum valuation for 5G from the perspectives of the different stakeholder roles including regulators, mobile network operators (MNOs) and entrant local 5G operators.**

Keywords—5G; mobile communication market; valuation; spectrum value; spectrum sharing; regulation

I. Introduction

The next generation mobile communication networks known as 5G will expand the range of wireless services and applications to address highly versatile vertical sector use cases with ever increasing quality requirements. 5G is expected to be the key enabler for industrial transformation and allow innovative business models across multiple sectors [1]-[2]. The role of mobile communication networks will thus become increasingly important, forming one of the key infrastructures for the society.

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Spectrum management decisions will play a critical role in meeting the expectations set for the 5G networks. In general, spectrum management aims at maximizing the value of spectrum, its efficient utilization and benefits to the society [3]-[4]. While there is a global commitment to make new spectrum available for 5G, the detailed spectrum allocation and assignment decisions that ultimately determine, who can build and deploy the networks remain a national matter. An overview of spectrum assignment approaches taken in Europe [3] shows the range of approaches adopted nationally. These decisions require a thorough understanding of the value of spectrum, keeping in mind that spectrum valuation is a complicated process that is closely linked to spectrum allocation and assignment.

Traditional approaches to spectrum valuation have considered *engineering value*, *economic value* and *strategic value* as the main value-related elements. Engineering value considers the *cost savings* in the infrastructure that an operator can achieve by gaining access to additional spectrum [5]-[7]. Economic value has a wider perspective and considers the value arising from the services that are provided for use through the availability of the spectrum, in terms of the *predicted future profits* that can be earned by the services offered [8]. Strategic value of spectrum arises from a stakeholder's *control of the market access* through spectrum availability, because the expected market position of one stakeholder depends on spectrum assignments of the others [5].

The spectrum valuation approaches proposed in the research literature make inherent assumptions about the underlying spectrum allocation and assignment models. These have clearly evolved from administrative allocation towards market-based mechanisms and the commons approach [4], [8]. Administrative allocation is typically concerned with rules that minimize harmful interference, without directly considering the economic benefits from the use of a spectrum band [9]-[10]. It is applicable when there is sufficient amount of spectrum to be assigned to those requesting it. On the contrary, market-based mechanisms define spectrum property rights and introduce incentive mechanisms for more efficient spectrum use, by assigning a limited number of spectrum access rights to those, who value them the most [4], [8], [11]. The commons approach has in its turn opened the market for basically an unlimited number of entrants to build and deploy wireless systems that follow regulator approved rules and conditions for sharing

[12]. It has proven to be successful by becoming important for indoor mobile data traffic delivery via wireless local area networks in unlicensed spectrum bands.

It is expected that spectrum sharing will play an increasingly important role in the future, especially to allow entrant 5G networks to be deployed in new spectrum bands that potentially have incumbent spectrum users, whose rights need to be protected [2]. Operations in higher carrier frequencies planned for 5G will change the traditional network deployment models, as radio wave propagation limits the achievable coverage of a base station, when going to higher frequency bands. This development would allow the deployment of potentially a large number of local 5G networks by different stakeholders. As a result, the values of different spectrum bands will be different [13]-[14]. Moreover, and possibly more importantly, the values will be different for different stakeholders [6].

While noting that the upcoming 5G spectrum decisions will have a big societal impact, there is very little prior research on spectrum valuation in the context of 5G networks. This paper aims to address the following research question: *How to value spectrum in the context of local 5G networks in shared spectrum bands*?

The rest of this paper is organized as follows. First, the evolution of spectrum management approaches is reviewed in Section II. The future 5G mobile communication networks are characterized in Section III based on the emerging new local 5G operator models. Section IV includes an analysis of existing spectrum valuation approaches based on research literature and identifies the key elements for spectrum valuation. Spectrum valuation in the context of local 5G networks from the perspectives of the different stakeholder roles is then developed in Chapter V, based on data gathered from a series of expert workshops. Finally, the key findings and future work are presented in Section VI, followed by the conclusions drawn in Section VII.

II. EVOLUTION OF SPECTRUM MANAGEMENT APPROACHES

Spectrum regulators in general aim at maximizing the value of spectrum in their spectrum management decisions, when allocating spectrum among different radio communication services and assigning access rights to those requesting them. This is a complex process with several types of inputs with potentially a high level of uncertainty. There are many classifications for spectrum management approaches and in this paper, we distinguish between administrative allocation, market-based mechanisms and the commons approach. To understand different approaches to spectrum valuation, in the following we first consider how spectrum management approaches have evolved from administrative allocation towards market-based mechanisms and the commons approach.

A. Administrative Allocation

Administrative allocation or the hierarchical command and control approach was the dominant method used by regulators to assign spectrum access rights through beauty contests or direct awards for decades. It is still in use for many radio communication services by many national regulatory authorities. The main criterion in administrative allocation is to create rules that minimize harmful interference between the different wireless systems and protect incumbent spectrum users' rights [11]. It considers harmful interference merely through engineering parameters, without trade-offs between the costs of harmful interference for one application and the benefits of additional activities of another application, which would reflect economic values [11].

To gain access rights to spectrum under administrative allocation, competing entrants must prove that they will advance the public interest, while the incumbent spectrum users enjoy financial incentives to oppose their requests [11]. This can lead to a decrease in competition as well as to inefficient spectrum use as there are no true incentives for efficiency. Once granted the access rights, the entrants can enjoy predictable quality levels through well-defined criteria for interference protection. Administrative allocation has received growing criticism over time [9], [10], [15]. However, it has also been applicable as a simple means for spectrum assignment without excessive byrocracy, when spectrum demand does not exceed spectrum supply [16].

B. Market-Based Mechanisms

Market-based mechanisms have replaced administrative allocation in many countries in assigning access rights for the provisioning of commercial wireless services. Market-based mechanisms define spectrum property rights in the form of licenses granted to a limited number of applicants through some market mechanisms. These mechanisms take the value of spectrum into account and replace case-by-case administrative rules by defining spectrum property rights that incentivize more efficient spectrum use [11]. They often allow secondary markets for spectrum, where the original spectrum property rights can be traded or leased in whole or in part by geography, bandwidth or by both for a given duration [4], [17]. Spectrum trading [18] aims at increasing the efficiency of spectrum use and social welfare by introducing more flexibility to spectrum access rights, as spectrum demand changes across locations, times and user groups. Its success depends on transaction costs that need to stay low for spectrum trades to occur.

Spectrum auctions [19] have become the most common market-based mechanism for spectrum allocation and assignment, when granting rights to deploy cellular mobile communication networks such as 3G and 4G. Those who have gained access rights through auctions often have the rights for post-auction trading, which further promotes innovative business models. However, several studies have assessed the use of auctions as a market-based mechanism for mobile communications through various welfare analyses [16], [20]-[23] indicating the importance of careful design of auction mechanisms and related parameters. While the overall trend is from administrative allocation towards market-based mechanisms, these studies have identified several challenges in auctions. They do not always produce superior market outcomes and regulators should recognize the complex relationship between spectrum management and market outcomes [23]. Authors in [24] state that auctions work only when licenses are liquid, i.e. when there are enough buyers and sellers. It is reasonable to assume that the number of buyers is relatively small in vertical and enterprise licensing cases, because licenses are local and benefit only a few buyers. For example, if a factory or a harbor wanting to deploy a local network to its own property, there would not necessarily be any other buyers, because the property is only used or controlled by the facility owner. In those cases, simple spectrum assignment methods that are closer to administrative allocation than market-based mechanisms can be applicable. Finally, because spectrum trades occur quite seldom, it is complicated to collect a sufficiently large dataset for valuation analysis to help in the design of market-based mechanisms [8].

C. Commons Approach

An alternative to administrative allocation and the market-based mechanisms is the commons approach that puts the spectrum access into the hands of many, through allowing unlicensed access for low-power wireless devices. The most typical solution is to allow unlicensed devices to operate under regulator defined rules and conditions [12], [25]. The value of unlicensed spectrum under the commons approach arises from making spectrum access possible to several different type of usages and stakeholders, which has resulted in new profits, as well as from its capability to promote innovation and competition. The commons approach also allows faster time to market, as entrants do not need to wait for license awarding decisions. However, it does not result in guaranteed quality. The most notable example of the success of the commons approach is the use of wireless local area networks (WLAN) in unlicensed bands by various stakeholders for mobile data delivery especially indoors [12], [25].

D. Role of Spectrum Sharing

Spectrum sharing refers to the situation where two or more radio systems operate in the same frequency band. While spectrum sharing in general has been present in many bands for a long time, the role of spectrum sharing is becoming increasingly important in spectrum management to allow access to new bands especially for mobile communication networks, while protecting the incumbents and assigning access rights among multiple entrants. The vast development of technical approaches in the recent years is making it more feasible for wireless systems to share the same spectrum bands.

Figure 1 summarizes different spectrum management approaches, including the role of spectrum sharing in them. Administrative allocation did not traditionally promote spectrum sharing, as it aims at minimizing harmful interference, which often means clearing the band from incumbent use and assigning non-tradable exclusive access rights with high margins for interference protection. On the other hand, market-based mechanisms started from defining spectrum property rights that can be further packaged into tradable units for secondary spectrum markets, where sharing is implemented. The commons approach is entirely built on spectrum sharing, where multiple different type of wireless systems and several deployments of the same systems use the same band. Fairness for sharing is obtained via obliging wireless devices to operate under technical conditions that implement spectrum sharing (e.g., duty cycles and limited transmission powers).

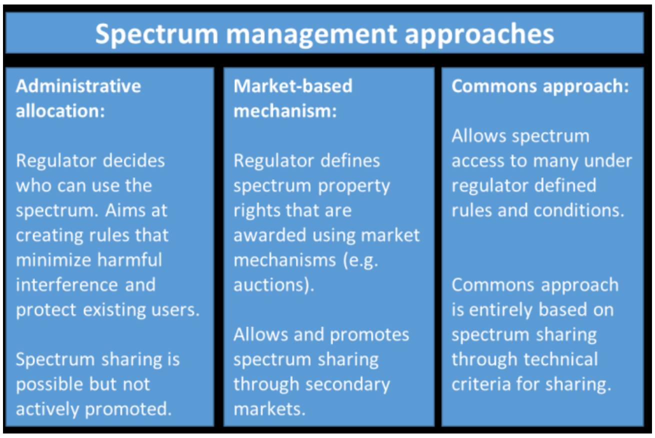

Fig. 1. A summary of spectrum management approaches.

Two licensing-based sharing models have recently emerged, the Licensed Shared Access (LSA) [26] from Europe and the Citizens Broadband Radio Service (CBRS) from the US [27]. The two-tiered LSA introduces additional licensed users on a shared basis while protecting the incumbents in the band. It allows regulators to decide the spectrum assignment methods for granting the LSA licenses. It builds on scale and harmonization in traditional exclusive licensing-based regulation and standardization and leverages the existing asset and capability base of MNOs. The European Telecommunications Standards Institute Reconfigurable Radio Systems Technical Committee (ETSI RRS) initiated a feasibility study “Temporary spectrum access for local high-quality wireless networks” [28] in 2017 to study LSA evolution towards 5G spectrum, localization of spectrum for novel 5G use cases, and enabling of horizontal sharing and sub-licensing for efficient use of spectrum assets.

CBRS extends the dynamics of two-tiered sharing approach through adding an opportunistic third License by the Rule General Authorized Access (GAA) layer, fine-grained census tract based localized spectrum allocation and sensing approach. In the second tier of Priority Access Licenses (PAL), the access rights are assigned through market-based mechanisms. Furthermore, the more dynamic CBRS concept was found likely to promote competition and foster innovation in the form of new enabling technologies, novel ecosystem roles, and Internet era platform-based business model designs. In 2016, the FCC finalized rules for CBRS [27] and introduced the light-touch leasing process to make the spectrum use rights held by PAL licensees available in secondary markets. Under the light-touch leasing rules, PAL 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 for 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 increased flexibility to serve specific or targeted markets. Furthermore, the FCC will let market forces determine the role of a Spectrum Access System (SAS), and as such, stand-alone exchanges or SAS-managed spectrum exchanges are permitted.

III. 5G Networks in Shared Spectrum Bands

The traditional mobile communication business value chain has changed in the recent years, as MNOs market dominance has been shaken by Internet giants offering Over the top (OTT) services that have reduced MNOs' role to bit pipes [29]-[30]. The upcoming 5G technology is expected to further change the mobile communication market structures, by addressing different vertical sectors' specific local service demands [1]-[2]. This market development challenges the traditional MNO dominance and gradually opens the market for new stakeholders.

From technical viewpoint, the 5G networks are targeted to be deployed in a wide range of frequency bands with distinct characteristics. The first 5G network deployments in Europe are primarily planned for 3.6 GHz (3400-3800 MHz) and 26 GHz (24.25-27.5 GHz) bands [1]-[3]. Additionally, MNOs can deploy 5G networks in their existing licensed spectrum bands below 3 GHz, such as the 700 MHz band. What is specific in the upcoming 5G bands is that the use of higher carrier frequencies changes the deployment models from wide coverage areas to local service areas. At the same time, this development makes spectrum sharing more feasible, because the potential interferences are also limited to local areas. This calls for new spectrum assignment models for defining and awarding the access rights to deploy 5G networks that can serve different verticals' specific needs.

There are also business developments in the vertical sectors towards the deployment of their own local 5G networks tailored for specific service delivery without being tied to the existing MNOs. In fact, regulators in several countries in Europe are considering or have already introduced local spectrum licensing to allow the establishment of local mobile communication networks in parts of the 3.6 GHz band, see e.g. [31]. There, the models for assigning the access rights can be closer to administrative allocation than market-based mechanisms.

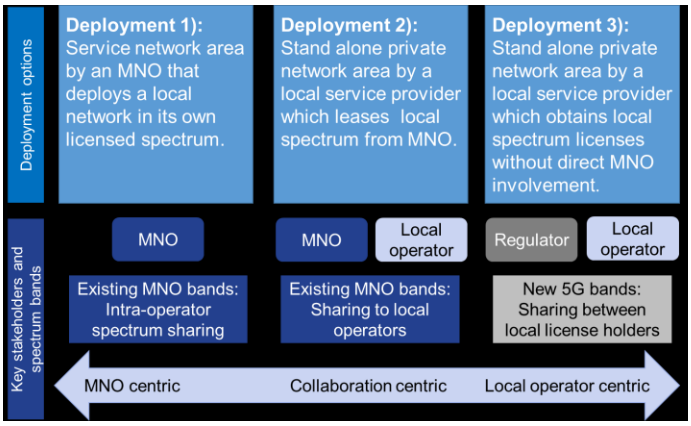

Fig. 2. Deployment models and spectrum options for local high-quality 5G networks.

Along with the regulatory approaches towards assigning local spectrum licenses, the development of 5G networks has recently expanded from the traditional MNO centric deployment models to alternative local network operator models. Local 5G operators are foreseen to emerge as new entrants to the mobile market that offer local high-quality services in high-demand spatially confined locations, such as factories, sports arenas and campuses [2], [28], [32]-[35]. The emergence of local high-quality 5G wireless networks is highly dependent on local spectrum availability and increasingly building on spectrum sharing [28], [32]. Due to their geographically restricted area, the starting point of local high-quality networks operation is the use of shared spectrum bands. This deployment model also helps in the protection of potential incumbents in the band.

Different deployment models and spectrum options for local high-quality 5G networks, summarized in Figure 2, lead to different deployment models [28] [32]. For example, MNOs can deploy local networks in their existing licensed frequency bands in Deployment option 1). Alternatively, different stakeholders can deploy stand-alone private 5G networks in spectrum bands subleased from MNOs with Deployment 2). The third deployment option is without any direct MNO involvement, so that local high-quality wireless networks are deployed through locally issued spectrum licenses by different local operators. All these deployment models are based on different spectrum access models and the associated spectrum valuation is obviously different.

IV. Spectrum Valuation Approaches

The value of spectrum and the development of approaches to spectrum valuation have attained a considerable amount of attention in literature from technical, business and societal perspectives. An overview of research literature around spectrum valuation is presented next, followed by the identification of the key elements of spectrum valuation that are needed in the context of future local 5G networks operating in shared spectrum bands. This literature review focused on scientific publications and was conducted through searching spectrum value related publications and the bibliographies of the publications. Additionally, there is a vast body of studies on spectrum value sponsored by different stakeholders focusing on specific stakeholder views, which are omitted here.

A. Analysis of Existing Spectrum Valuation Approaches

An extensive review of research literature on the value of spectrum was first conducted to develop a thorough understanding of the existing approaches taken by scholars from different perspectives. Table I summarizes the main approaches in the research literature. Then, a series of expert workshops was arranged to review the different approaches to find commonalities and develop classifications. Each of the workshops included 5-10 participants representing the different stakeholders of the mobile communication business ecosystem. The different spectrum valuation approaches were classified according to three main categories following the logic of [5] including engineering value, economic value and strategic value, which are shown in bold font in Table I. The valuation approaches belonging to these main categories are presented under them.

Studies on engineering value ([5]-[7], [14], [36]-[39]) clearly highlight cost-centric views and are concerned with the saving in the total cost of ownership from the availability of additional spectrum. Economic value ([8], [12], [14], [16], [37]-[38], [40]-[41]) has attracted most attention by scholars and provides a comprehensive approach that considers expected future profits from the use of services offered through spectrum. Economic value considering business profits and not only cost savings goes beyond the engineering value. The strategic value ([5], [36]) takes a different standpoint, by considering the market position ensured by spectrum assignment.

TABLE I. SPECTRUM VALUATION APPROACHES

Main concept	Desciption	Ref.
Engineering value	Savings in the total cost of ownership obtained from using additional spectrum band compared to the cost of the alternative of expanding the existing network to obtain the same capacity.	[5] [6] [7]
Deprival method (opportunity cost):	Difference in the value of business with and without the spectrum.	[14] [36]
Opportunity cost	The cost of the most economically rationale alternative.	[37]
Marginal value	Difference between the cost of network densification and the cost of additional spectrum available.	[36]
Production function method	Value of spectrum is determined by the value of the physical infrastructure that 1 MHz of spectrum can substitute at the margin.	[38]
Present value of spectrum	Difference in present values of the total cost of ownership with and without the new spectrum.	[39]
Economic value	Present value of the discounted future profits earned by way of using the spectrum.	[5], [8] [40]
Sea level component of economic value	Value driven by the rising and falling general profitability of spectrum for particular use. Affects the profitability of all bands of similarly.	[8]
Band specific component of economic value	Driven by the physical characteristics of the spectrum (carrier frequency, bandwidth, pairings), development of the band's ecosystem (both technology and users and services; economies of scale), and encumbrances to use (incumbents, service restrictions, license conditions).	[8]
Private use value	Benefits that individuals derive from their use of spectrum.	[40]
Private external use value	Benefits enjoyed by individuals who do not use a service arising from the use of that service by others.	[40]
Social value	Value that citizens benefit from the contribution of spectrum usage towards social goods.	[40]
Benchmarking method	Market prices of spectrum derived from information of similar bands in other countries.	[14] [37] [38]
Discounted cash flow analysis	Net present value (NPV) of spectrum from future expected profits.	[14]
Real options approach	Considers the delay of using the spectrum until capacity demand is large (NPV + options value).	[14]
Incremental value of additional unlicensed spectrum	Congestion alleviation plus incremental option value.	[12]
Value of spectrum in use	Sum of the overall benefits created by spectrum usage services minus the sum of the (non-spectrum) costs of providing those services.	[41] [16]
Current value of unlicensed spectrum	The sum of the value of spectrum in all uses in those bands.	[12]
Strategic value	Reflects the expected market position of an operator resulting from spectrum assignment decisions.	[5] [36]

The existing spectrum valuation approaches summarized in Table I reveal that quite different concepts are used by different scholars for spectrum valuation, while describing the same phenomenon. Moreover, although most of the approaches consider economic value, prior research has made use of such key concepts as price, cost and value almost interchangeably, which cannot be recommended. Price can be understood as an amount to be paid to get something, such as an access to spectrum. Cost denotes the expenses incurred in the production of something, such as defining spectrum or building a network. Value implies the utility of worth of something for someone – typically in use, such as the utility of spectrum for an operator. As said, the engineering value approaches are much cost-oriented, the economic value approaches utility of worth based and to some extent price-oriented, and the strategic value approach pulls the two last together. However, none of the approaches addresses, for example, the book value, tax value or liquidation value of spectrum.

B. Key Elements for Spectrum Valuation

Next, we proceed with the analysis of spectrum valuation approaches to identify the key elements that are needed in defining and assessing spectrum value for specific radio services. Using the approaches presented Table I as a baseline, a series of expert workshops dwelled deeper into the different spectrum valuation approaches, to discover key elements that are needed for spectrum valuation in the context of the new generation of mobile communication networks. Figure 3 summarizes the identified key elements of spectrum valuation.

The analysis concluded that the economic value of spectrum is the main approach to build upon, while taking some elements from studies on engineering value and strategic value into account. The analysis also highlighted the stakeholder perspective as a key factor in understanding and assessing the value of spectrum. Authors in [6] have pointed out that the value of spectrum is not the same for all stakeholders, for example for MNOs and local operators. Authors in [5] present strategic value as a reflector of the expected position and competitive advantage of an operator from the assigned spectrum, which is completely defined from the operator stakeholder's view and is different for smaller and larger players. There is indeed a need to introduce the *stakeholder role's perspective* into spectrum valuation. This will also bring the spectrum supply and demand sides into spectrum valuation.

The *services offered in a spectrum band* highly influence the value of the band [8]. There can be significant differences in the value of the different services as the influence comes both through the expected future revenues and the deployment costs. The expected future profits and all items influencing the profits are particularly challenging to assess beforehand when making spectrum assignment decisions. The economy of the country in question affects also this element, because profits of even the same services are different in different countries.

The *spectrum allocation and assignment method* defining the conditions, parameters and restrictions for the use of spectrum influence the spectrum value greatly. Under administrative allocation, the initial assignment is critical. Under market-based mechanism the value of spectrum is re-evaluated in the secondary spectrum markets. Under the commons approach, the benefits of the wireless services come through all the different services deployed by different stakeholders.

Authors in [8] and [38] have noted in their studies on economic value that spectrum has higher value in more densely populated high-income regions. Thus, it is important to understand the *location-specific characteristics* that make spectrum value dependent on the location, as different areas have different profitability driven by both revenues and costs. Traditionally, population density has been a metric to consider in spectrum valuation, but such new use cases as machine-to-machine communications are not well characterized with population density. Location dependent spectrum value is however also related to the value of a property or land, which is also highly location specific.

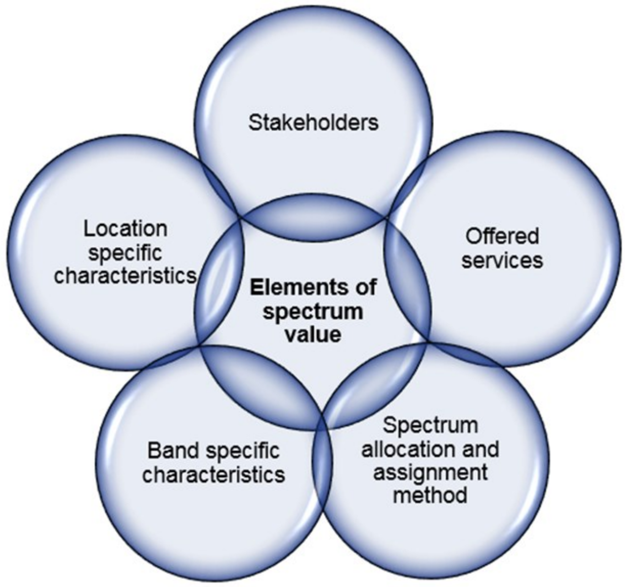

Fig. 3. Key elements of spectrum value.

Finally, *band-specific characteristics* have a high influence on the spectrum value. They include the physical propagation characteristics of spectrum, development of the band's ecosystem including scale and harmonization determining equipment availability, and encumbrances to use including incumbents and license conditions [8]. The introduction of new spectrum bands brings additional uncertainty into the valuation of that spectrum.

V. Spectrum Valuation for Local 5G Networks

Next, we consider spectrum valuation for local 5G networks operating in shared spectrum bands based on a series of expert workshops arranged with participants representing different stakeholders of the mobile communication ecosystem. There is very little prior work on spectrum valuation for 5G (see [14] and [40]), and more importantly, no common agreement on what valuation approaches to use. In the following, we will introduce views to consider for the different stakeholders for spectrum valuation for 5G.

A. Stakeholders Perspectives

The mobile communication business ecosystem consists of a wide range of stakeholders such as infrastructure and devices vendors, infrastructure constructors, facility owners mobile network operators, content providers, and end users [34]. Different stakeholders in the mobile communication business ecosystem value spectrum in rather different ways. Traditionally, the major stakeholder in spectrum valuation for prior generations of mobile communication networks (i.e., 3G and 4G) has been the MNO to which the national regulatory authority has assigned spectrum access rights. The emergence of local 5G networks call for the introduction of local 5G operators who may value the spectrum differently from the dominant MNOs. In Table II spectrum valuation is presented from the viewpoints of three central stakeholder roles: the regulator, the MNO and the entrant local 5G micro operator.

TABLE II. SPECTRUM VALUATION FOR LOCAL 5G NETWORKS FROM STAKEHOLDERS' PERSPECTIVES

Element of spectrum value	Stakeholders		
	Regulator	MNO	Local 5G micro operator
Offered services	Division based on services is getting less relevant as a diverse set of services can be delivered through 5G mobile communication networks.	Mobile broadband and various tailored services.	Diverse set of services to different customer segments including closed private networks or neutral hosting for MNOs.
Spectrum allocation and assignment method	Need to find a balance between different allocation methods that promote innovation and competition while ensure investments.	Spectrum property rights with long license durations are preferred.	Different methods that allow local access to spectrum are feasible.
Location specific characteristics	Population density traditionally used, but new metrics are needed to characterize the demand for spectrum.	Current wide area coverage is expanded by local deployments in high-demand areas.	Operations are fully confined to local areas in various vertical use cases.
Band specific characteristics	Incumbent spectrum usage limits the availability of bands. Very wide bandwidths available in higher 5G bands. Propagation characteristic limit network coverage to local area.	MNOs have existing spectrum licenses in other bands and can aggregate new 5G bands, which makes their dependency on the specific new 5G band lower.	Local operations are highly dependent on local spectrum availability and band specific characteristics and unlicensed access is the only other option.

In terms of services, the range of services that can be offered in bands allocated to the mobile service will drastically expand from the traditional voice, text and mobile data. Various vertical sectors' needs will increasingly be served through 5G networks and the future profits will be highly use case dependent. From the MNO's perspective, a majority of the services offered in mobile communication spectrum continue to be mobile broadband, although there will be new services tailored to verticals. From the local operator's perspective, a diverse set of service offerings can emerge, ranging from serving MNOs' customers as a neutral host to operating private networks for specific verticals with different revenue potential. The expected future profits of these emerging service offerings are difficult to assess beforehand.

Spectrum allocation and assignment decisions are done by the national regulators, whose view is to give the spectrum to those, who can ensure the highest economic value that not only considers direct profits of the companies, but also societal impacts. MNOs have highlighted the need for investment certainty in 5G through spectrum decisions that allow exclusivity with long enough license durations. On the other hand, local 5G operators might be interested to try different methods to get local spectrum access rights, such as the deployment options 2) and 3) in Figure 2.

In spectrum allocation and assignment, the fee structure once the spectrum price has been determined either via auction or administratively, must be resolved. The question is how the fee is to be paid. There are three types of payment mechanism to consider: a lump sum (a total price is paid at the start of the license period); an annual fee (the price is spread across the license period); and a hybrid approach (up-front and annual fees are combined). With high upfront payments there is a possibility that local operators would need to struggle to raise funds or they could be faced with a large financing cost, hence deterring them from implementing such solutions. On the other hand, annual fees may be less attractive for regulators, who will be faced with higher risks of losses, if some operators should become insolvent. This might also not satisfy the regulator, who has been asked to raise funds for the national treasury through spectrum awards. On the other hand, there is a clear policy objective to promote industry development and innovation.

Location specific characteristics in 5G will have a distinct role compared to prior generations, as the population density previously used for assessing the spectrum demand, network dimensions and service profits no longer necessarily applies to many upcoming 5G vertical use cases. The role of communications between machines can instead be the dominant factor, which calls for new models to understand both the revenue potential and the spectrum demand, and ultimately the spectrum value.

Finally, the band specific characteristics of upcoming 5G bands, namely the 3.6 GHz and 26 GHz in the coming years in Europe and potentially other higher carrier frequency bands later, are quite different from what they are currently in cellular mobile communication networks that serve wide areas. The new 5G bands will be limited in network coverage and walls of buildings will also limit the network coverage. For MNOs, these new 5G bands are additional bands in their spectrum portfolios that have a range of bands with good coverage properties, which allows them to plan their service delivery accordingly. For local 5G operators, service offerings are highly influenced by the band specific characteristics, as they are critically dependent on those bands. Without access to other licensed bands, they can only use the commons approach.

VI. DISCUSSION

5G brings local high-quality wireless networks to various vertical domains, if there is spectrum available locally at an affordable cost level to those who need it when they need it. This is the pre-requisite for the industrial transformation and new innovative businesses across multiple sectors envisaged through 5G. Ensuring spectrum availability for location specific networks should be a key priority for regulators, and it requires adjustments to the presently dominant spectrum allocation and assignment methods. Mechanisms to increase the availability of spectrum inherently rely on spectrum sharing, where existing spectrum property rights can be repackaged and traded to others and completely new local spectrum property rights can be defined and assigned flexibly. This should be made possible with upcoming 5G spectrum decisions by the regulators and it would have benefits for the different stakeholders. MNOs would gain profits by leasing parts of their existing bands in locations, where some local operator would like to act. For MNOs, 5G networks in the upcoming 5G bands will therefore bring opportunities to expand their existing networks, while for local 5G operators, these networks form the core of their business and should be promoted by regulators. Regulators will face both of these concerns on their behalf.

The traditional stakeholder roles are expected to evolve as indoor base stations are likely to be integrated more and more to the building design. Therefore, the lifetime and ownership of a building is becoming more and more important for spectrum allocation and assignment as well. It is more likely that the investment on base stations is naturally connected to other building investments. It is also more likely that the owner of building, spectrum and base stations should be the same entity although another party might operate the base stations and services. Until now, unlicensed spectrum has been a sufficient enabler and successful solution for best effort service but the delivery of more ambitious services require guarantees to building owner, which in turn requires defining spectrum property rights. In practice, the building owner could then sell/lease the spectrum to another part, e.g. MNO or micro operator, if necessary.

This research started from the need to understand the value of spectrum in the context of future local 5G networks and has resulted in the first findings, which by no means tell the whole story. From a theoretical viewpoint, more research is needed to develop both a consistent terminology and a mapping of different spectrum valuation approaches into a comprehensive framework for 5G spectrum valuation. Operational models for spectrum valuation including the different stakeholders' views, and continuing from such conceptual analyses as presented in this paper, is an important topic for a further study.

From the empirical viewpoint, work is needed to be conducted for the analysis of spectrum value in different 5G spectrum bands from the regulator's, MNOs' and local operators' perspectives. At the moment, this is challenging due to the limited amount of data from 5G spectrum assignment decisions and high uncertainty of market data, but even a preliminary analysis could give insights on the potential value of spectrum options for different vertical domains served by local 5G networks. Moreover, because regulators in many countries are considering local licensing in the 3.6 GHz band, empirical data will become available in the near future. It would be important to make local 5G spectrum valuation cases visible and share the emerging experiences. If currently only three or four MNOs serve whole nations, in the future thousands of 5G local operators may provide services in certain areas and shared spectrum bands. Valuation of spectrum will be critical for their business.

VII. Conclusions

Operations in higher carrier frequencies planned for 5G will allow the emergence of local high-quality 5G networks that have the potential of promoting innovation and competition in the market and advance society in totally new ways. There is increasing interest for local 5G networks deployed by different stakeholders to complement MNOs' networks especially for vertical specific service delivery. This paper has highlighted the importance of understanding the different approaches for spectrum valuation in the context of the upcoming 5G networks, whose deployment will be location specific to complement the previous generations that address wide-area coverage.

We have analyzed the existing spectrum valuation approaches and expanded spectrum valuation to cover local 5G networks in shared spectrum bands. In doing that, we have identified the key elements of spectrum valuation and considered the spectrum value from the views of different stakeholder. It is critical to consider the changing stakeholder roles and the potential of new local operator models in the upcoming 5G spectrum decisions through assessing the value of spectrum. Although the future market potential of local 5G network deployment models is difficult to predict beforehand and makes spectrum valuation demanding, it is necessary to address it both conceptually and empirically.

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