Wireless Network Virtualization as an enabler for Spectrum Sharing

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***Abstract*—Spectrum Sharing and Wireless Network Virtualization have been explored as methods to achieve spectrum efficiency, increase network capacity and, overall, to address the existing spectrum scarcity problems. This work aims at exploring the link between these two topics, by specifically placing virtualization as a technology that can render spectrum sharing schemes feasible.**

No complete analysis can be made without taking into account three important axes: technology, policy and economics. In this light, in order to explore how virtualization enables spectrum sharing, flexibility is studied as a common attribute, due to the characteristics it presents regarding the three preceding axes.

By determining how spectrum sharing, wireless virtualization and flexibility tie together, ground can be laid toward exploring further opportunities that would enhance spectrum usage, making it possible for this resource to foster these days' ever-increasing demand.

I. Introduction

The lack of flexibility for spectrum use derived from rigid regulatory schemes resulted in high spectrum inefficiencies and in the scarcity of spectrum that we experience nowadays. The remarkable amount of past and present research efforts support the importance of this problem and have given as result significant and innovative advances towards solving the spectrum shortage issues and their consequences.

Spectrum sharing is not a new topic. The Federal Communications Commission (FCC) has made its efforts towards granting users with more flexibility on the use of spectrum, which rendered sharing of this resource feasible more than ten years ago [1]–[4]. Throughout these years, technologies have emerged, which have turned sharing into a realizable approach. In fact, with the advent of new technological mechanisms, new sharing arrangements arise, which have actually become more or less appealing depending on the underlying policy and economic requirements.

In this light, the focus of this work is on how wireless network virtualization, a relatively new technology, becomes an enabler for spectrum sharing. The analysis presented contemplates technical, economic and some policy perspectives, as these represent fundamental axes in the innovation of Telecommunications. The actual link between sharing and virtualization could be approached from myriad standpoints; nevertheless, in this work, this link has been addressed from a flexibility perspective. This attribute has been chosen because it represents a key characteristic for sharing to take place, which can be obtained through technologies such as virtualization. Additionally, flexibility permits us to explore the implications of the three aforementioned axes in the adoption of sharing schemes.

This work is structured as follows: section II presents an overview and taxonomy of spectrum sharing. Definitions, aspects and perspectives relevant to Wireless Network Virtualization are included in section III. Flexibility, in section IV, represents the meeting point between the two concepts, as this section aims at merging the flexibility needs of spectrum sharing with the flexibility that can be obtained from wireless virtualization. Additionally, policy perspectives, economic implications and the concerns regarding the incentives for establishing sharing schemes are covered in this section. The concluding remarks and future challenges are presented in section V.

II. Spectrum Sharing

The traditional, rigid, model of spectrum licensing focused on preventing harmful interference but it resulted in high spectral inefficiencies [5]. It is in this way that increasing the opportunities for spectrum sharing can be key toward alleviating spectrum scarcity. Nevertheless, before delving into specifics of spectrum sharing, it is important to recall that there are rights associated with spectrum, which drive different configurations for the use of this resource.

A. Rights-based Spectrum Usage Models

In order to establish a sharing scheme, first of all, it is essential to clarify which are the underlying rights associated with spectrum. As DeVany states in [6], "different configurations of rights and duties will differently affect an individual's cost-reward calculus, providing him with varying incentives for different resource uses." In light of this, three spectrum usage models can be presented (1) "Command-and-control" model, (2) "Exclusive-use" model and (3) "Commons" or "Open Access" model [2], [7], [8].

Command-and-control model: It was the traditional process of managing spectrum in the United States. By 2002, it was utilized for most spectrum within the FCC's jurisdiction and it comprised specific regulatory requirements, such as service restrictions, power limits, build-out requirements, among others, for the use of a given frequency band [2], [7].

Exclusive-use model: In this licensing model, the licensee has exclusive and transferable rights to the use of a specific spectrum band within a defined geographic area. The licensee is granted flexible use rights, which permit the primary users to utilize their spectrum for applications that have not been specified in the original license [9]; however, there are still technical requirements to ensure user's protection from interference. It should be noted that this model does not imply the creation of "full" property rights in spectrum.

Commons or Open Access model: In this model, an unlimited number of unlicensed (licensed-by-rule) users are allowed to share a given frequency. The usage rights are primarily governed by technical standards or etiquettes; however, users are not entitled to protection from interference [2], [7]. In this case, spectrum can be regarded as a "public" resource that should be equally and fairly accessible to all users without excessive regulation [8].

As it can be observed, the command and control model imposes far more regulatory constraints than the two other cases, thus limiting the flexibility of use of the spectrum resource. One of the main recommendations of the Spectrum Policy Task Force (SPTF) in its November 2002 report [2] was that the FCC should balance the three spectrum rights models in order to establish new regulation and thus include more flexible spectrum use opportunities for the users. Additional recommendations from the SPTF included that it might prove beneficial to adapt particular properties from more than one model to different frequency bands in order to exploit the benefits inherent to these changes. It was envisioned that if these models were consistently applied to the spectrum as a whole, there would be high potential to significantly reduce the artificial scarcity of spectrum that currently exists due to access barriers, in addition to reducing the cost of obtaining exclusive spectrum rights in the market as well as alleviating the congestion existent in the spectrum used on a commons basis [2], [7]. To elaborate on the above, there are two important factors that need to be considered in order to determine which model to choose: spectrum scarcity and transaction costs. The first refers to the degree in which spectrum demand exceeds the current supply due to the competing demands for use, while the second stems from the time and resources that a given user needs to spend in order to obtain spectrum access rights from one or many parties. It is thus that, in general lines, the following recommendations have been given for the application of each of the models [2], [7]:

- Command-and-control regulation should be minimized, being reserved only for those uses that yield clear, non-market public interest benefits and that require explicit regulatory guidelines in order to avoid market failure.
- The exclusive use model should be applied to the majority of spectrum, especially in those bands where scarcity is high and the transaction costs for establishing a market-based mechanism for the negotiation of spectrum access rights are relatively low.
- The commons model should be applied to those bands where scarcity is low and the transaction costs associated with negotiation and market mechanisms are high.

As it can be expected, the application of these spectrum usage models, or parts thereof, in specific spectrum bands calls for a rearrangement or emergence of new rights, which, as Demsetz states (in the context of property rights), "takes place in response to the desires of the interacting persons for adjustment to new benefit-cost possibilities." [10]. Along these lines, it is evident that with new rights, there is also the possibility for new spectrum usage models, namely, spectrum sharing scenarios.

B. Taxonomy of Spectrum Sharing

Spectrum sharing can be classified in myriad ways, depending on the considered criteria, fact that is largely reflected in the literature. In this work, I would like to present a taxonomy of spectrum sharing based on spectrum rights and taking into account the interaction of spectrum users and who sets the rules for sharing.

We shall remember that, as previously presented, sharing has its underlying basis on the rights that different users have, and are thus willing to share with others. In light of this, three types of spectrum sharing based on rights can be presented: (1) Property Rights Model, (2) Sharing among equals and (3) Primary-Secondary Sharing.
According to the interaction of the spectrum users, spectrum-sharing environments can be based on cooperation or coexistence [5]:

- Cooperation: Devices must communicate and cooperate with each other, even if they belong to different systems and administrative control, in order to avoid interference. A common protocol needs to be supported by all devices (and all systems) operating in the band.

- Coexistence: There is no explicit signaling among devices in the band. For instance, devices might sense the presence of others for interference avoidance purposes.

Regarding who sets the rules for spectrum sharing, given that we are dealing with users holding different degrees of spectrum rights, the sharing-rules can be set by the regulator, as it has traditionally happened, or they can be set by a licensee entitled to sufficient spectrum rights as to share this resource with other users. Furthermore,

- The regulator has the ability to influence all spectrum, instead of only a, perhaps small, frequency band.
- The licensee may charge a fee for granting access and managing the spectrum. Such a fee could be a one-time payment or a usage-based charge. Situations may arise in which the licensee is a manufacturer who will allow access to his spectrum only to its own devices, thus ensuring a certain level of technical homogeneity.

The main difference between the regulator and the licensee lies on their objectives for setting the spectrum-sharing rules. The goal of the regulator is to find solutions that will best suit the public interest, while a license-holder will, most likely, be interested in maximizing its own profits [5].

Characteristics and examples of each of these scenarios are presented in what follows.

Property Rights Model: Property rights can be defined as "the ability to buy; hold; use; sell; dispose of, in whole or in part; or otherwise determine the status of an identifiable, separable and discrete object, right or privilege." [11]. According to Coase and Hazlett, the creation and enforcement of property rights would be necessary and sufficient factors for economic development [12]. As a matter of fact, this mechanism can lead the way to crystallizing the idea proposed by Ronald Coase some fifty years ago [13], by which he established that through a clear definition of property rights, scarce resources can be assigned via pricing mechanisms without the need of government (or regulator) intervention. Indeed, "Coase's theorem" states that when property rights are well defined and transferable, in the absence of transaction costs, every government allocation of property rights will be equally efficient This is the result of all parties privately bargaining to correct any externalities [14], [15]. In this way, the property rights model contemplates a market-driven approach, in which spectrum resources are assigned via market forces to users who value it the most.

According to DeVany, in order to create a property rights system, which will lead the way for the operation of a market system, it is necessary to consider three key elements (1) a valuable and unambiguous definition of rights that are compatible with the physical characteristics of spectrum (2) an enforcement mechanism for these rights; and (3) provide the means for the initial distribution of the spectrum-use rights to the public [6]. Additionally, an important emphasis on the flexibility of property rights is made. For instance, in [16], it is stated that property rights should be flexible enough and they should be even given in perpetuity. This would make it possible for spectrum to be traded, aggregated and disaggregated. In terms of the distribution of rights to the public, this model envisions that the pricing-mechanism could be employed for the allocation and assignment of the entire spectrum. Proposals along these lines include the transition approach presented in [17], which considers necessary a "large-scale, two-sided 'band restructuring' auction of spectrum" (also known as "big-bang" auction), which includes spectrum voluntarily offered by licensees and unassigned spectrum. However, the authors also consider necessary not only to accurately define property rights, but also to provide the incumbents with the appropriate incentives to participate in this auction. This represents quite an idealistic approach given the challenges inherent to its realization. Probably we will see a small-scale example of this model once the incentive auction that the FCC has envisioned for the Broadcast Television Spectrum [18] takes place.[1]

An additional option comprises the adoption of secondary markets for spectrum. Secondary markets are those markets in which the seller of a good is not who sold the good for the first time. It should be noted that 'secondary' refers to the trading subsequent to the initial allocation of rights by the regulator, it does not have the same connotation as 'secondary use', given that the users who obtain spectrum in a secondary market may be granted primary, or exclusive rights to the use of spectrum [19]. Through a well-functioning secondary market, as demand and supply shift, spectrum is expected to shift to more efficient uses, perhaps by parties outside of the initial spectrum allocation [20]. In order to support the benefits derived from secondary markets for spectrum, Professor Cramton's statement can be quoted: "secondary markets are essential for the efficient and intensive use of spectrum. Secondary markets identify gains from trade that are unrealized by the primary market which in this case is the FCC spectrum auctions." [21].

[1] According to the latest update posted on October 2014, the FCC anticipates that applications for the auction will be received in the Fall 2015 and that the auction will start in early 2016. Information available online: http://www.fcc.gov/blog/incentive-auction-progress-report. Last accessed on January 9, 2015.

Secondary markets arrangements have already been analyzed and approved by the FCC [3]. Current regulation allows two different configurations, in terms of transferred rights: Spectrum Manager and *De facto* transfer lease. In the first case, the initial licensee negotiates access to the spectrum with a given user (now lessee), but retains the *de jure*[2] and *de facto*[3] rights over the spectrum i.e., it retains the legal rights over the spectrum license and remains accountable to the FCC with regards to the spectrum usage and interference caused to other users. In the *de facto* transfer lease, the licensee grants the lessee with *de facto* rights over the spectrum. In this manner, the lessee will be held liable for the usage of the spectrum and thus accountable to the FCC. However, the initial licensee will still hold the *de jure* rights over the spectrum.

Given that the entire spectrum is envisioned to be allocated and assigned via market forces, there is not an explicit notion of coexistence or cooperation. Users will be able to establish the spectrum usage and sharing they find more profitable according to their property rights and they will be able to negotiate in order to achieve optimality. Regarding who sets the rules, since this model is based on property rights, spectrum users or property rights' holders will be in charge of determining the sharing conditions with little or no intervention from the regulator.

Sharing among equals: In this environment, all devices have equal rights. There is more flexibility in terms of the behavior among peers; however, the key factor in this type of environment is whether all devices have the incentive to limit the interference they cause to those they share the spectrum with. In fact, different users under this arrangement need to coordinate with each other in the shared bands.
Sharing among equals may refer to sharing among equal primary devices, sharing among equal secondary devices or even sharing among equal regional infrastructures [5], [19].

Coexistence: No device is given a clear priority. Most of these arrangements are the result of taking advantage of the deployment of unlicensed bands. It is important to note that devices in this type of scenario should not have stringent quality of service requirements. Additionally, as previously mentioned, it is not only necessary to have technical capabilities for interference avoidance; devices should also have the incentives to avoid a greedy behavior, which may actually lead to a tragedy of the commons [22]. In such a situation, the (mis)behavior of devices leads to an overconsumption of the shared resource resulting in low-quality performance for all devices in the band.

Spectrum commons is a clear example of this type of sharing. It can be set up by the regulator, such as the case of unlicensed bands where devices coexist e.g., WiFi and cordless phones. Commons can also be established by a primary user as is the case of private commons. In such a configuration, the primary user specifies a set of technical parameters for operation in the band he has previously been granted a license for, and authorizes users of devices operating under those parameters to access it. The general restrictions and technical requirements that accompany the original license also apply for the users of the private commons, and thus may shape the requirements established by the primary user. Regulation dictates that devices operating in this environment should utilize peer-to-peer technologies [4].

Cooperation: All devices should actively communicate and cooperate without regard to their owner or proprietary system. In this type of scenarios, we may find devices negotiating with each other in order to avoid collision. There are important benefits derived from cooperation. For instance, cooperative gain could be exploited, which refers to the gain that can be obtained from network architectures in terms of communications efficiency on a system basis. This gain is the result of cooperative strategies that various terminals and elements carry out in a networked system [23]. Additionally, a cooperative approach could represent cost-effective solutions to provide coverage to large regions where other options (e.g., Wi-Fi based micro cellular systems) are not economically feasible [5].

When the rules are set by the regulator, we can find cooperation within unlicensed bands in wireless local area networks as well as cooperative mesh networks where the regulator sets the etiquette. When the licensee sets the rules, he might set the corresponding etiquette for the deployment of cooperative mesh networks.

Depending on the underlying agreement, we could find examples of cooperation in the deployment of virtual networks. In this particular case the rules may be set by the regulator or by the licensee.

Primary-Secondary Sharing: It is important to first provide a definition of primary and secondary users. A primary rights holder, or primary user, is the entity that holds spectrum access rights that are protected from interference. Normally, this user is the one who obtained the license from the regulator in the first place, and it can also be referred as licensee. Secondary users are those entities that can access a spectrum band, but they need to avoid causing harmful interference to the primary users of that band. There can be various secondary users

[2] "By right; based on laws or actions of the state." Definition obtained from http://www.merriam-webster.com/dictionary/de%20jure

[3] "Exercising power as if legally constituted; resulting from economic or social factors rather than from laws or actions of the state." Definition obtained from http://www.merriam-webster.com/dictionary/de+facto?show=0&t=1421624333

contending for access to a band [19].

Coexistence: Secondary users do not require permission from the primary user in order to access the band. The regulator may determine specific bands that need to be shared by existing primary users and dictate the sharing etiquette. Examples of these cases include Federal-Commercial sharing, where the primary users are Federal users such as DoD radars and meteorological satellites, and the secondary users may be different entities who can utilize the spectrum not in use by the primary, outside of predefined exclusion zones and as long as they do not cause interference to the primary user. A second example is spectrum sharing in TV Whitespaces, where the primary users are TV Broadcasters and the secondary users are unlicensed devices who can operate as long as they have geolocation capabilities (except for the case of mobile devices operating in client mode), and evidently, they do not cause harmful interference to the primary user.
When it is the primary user who sets the rules, secondary users can access the spectrum through spectrum overlay or underlay mechanisms. In this manner, secondary users can access the spectrum without requiring permission from the primary at every instance.

It is important to note that Cognitive Radios is a useful technology for the deployment of coexistence environments [5].

Cooperation: Secondary users can access a spectrum band only when the primary user grants them permission to do so. In this scenario, the secondary user may (or may not) pay a fee for spectrum access. Due to the explicit coordination with the primary user, this model is useful for guaranteed QoS and infrequent spectrum use.

The regulator can mandate cooperation between primary and secondary users in order to achieve more efficient utilization of a specific band. Authorized Shared Access (ASA) and Licensed Shared Access (LSA) constitute an example of this type of scenario. ASA/LSA will allow a secondary user to have exclusive-use of the spectrum when the primary user is not using it. This type of arrangement is suitable for spectrum that is currently used by non-mobile incumbents, that presents low and/or localized utilization and which is hard to re purpose within a reasonable time frame. Under ASA/LSA the primary user can determine what, when and where to share the spectrum and it also gives the secondary users higher QoS guarantees. In fact, in order to achieve an efficient agreement, the licensee, the secondary user and the regulator participate in the negotiation [24]–[26].
Real-time secondary markets are an example of a primary-secondary sharing environment based on cooperation where the primary user will set the rules. In such an arrangement, any licensee may consider making his spectrum available to other uses, regardless of the use he actually gives to the spectrum [27]. In this manner, secondary users are able to individually negotiate spectrum access rights, i.e., lease spectrum, for short periods of time (in the order of hours, minutes or even fractions of seconds) from the primary user in exchange of a fee. The relationship of primary-secondary is maintained, given that the rights are transferred only for the duration of the spectrum lease, which in this case can be significantly short.

Figure 1 summarizes the taxonomy of spectrum sharing presented in this section.

C. *Enabling Spectrum Sharing*

Various spectrum sharing arrangements were presented in the previous subsection; however, we shall remember that the underlying resource, spectrum, is not unidimensional nor it is perfectly fungible. In truth, different authors have pointed out several levels and dimensions in which spectrum can vary [6], [28] and studies have also been performed on the impact of spectrum's fungibility limitations [29], [30]. These factors evidently have restricted the opportunities for spectrum sharing.

Taking into account the preceding shortcomings, throughout the years, different technologies and mechanisms have been devised for enabling spectrum sharing. For example, we can point out multiple-access techniques, spread spectrum mechanisms, super-cell and mini/micro cell deployments, cellular reuse, spectrum reuse through directional antennas, the development of software-defined and cognitive radios, among others. Nevertheless, the sharing experience could be definitely enhanced if we were to use an "enabler" that could permit to bypass (at least) some of these shortcomings. Overcoming these substantial physical barriers inherent to the nature of electromagnetic spectrum could definitely increase the opportunities for alleviating spectrum scarcity. In the next section, I would like to explore the features of wireless network virtualization that could convert this technology in an enhanced spectrum sharing enabler.

III. Wireless Network Virtualization

Wireless network virtualization is a topic that is currently under exhaustive study. It is quite difficult to present a unique definition of wireless network virtualization as it has been shaped and adapted to different research works and contexts. Nevertheless, I consider it important to first lay out some general concepts and characteristics in order to determine the scope of Wireless Network Virtualization that is being applied to this work.

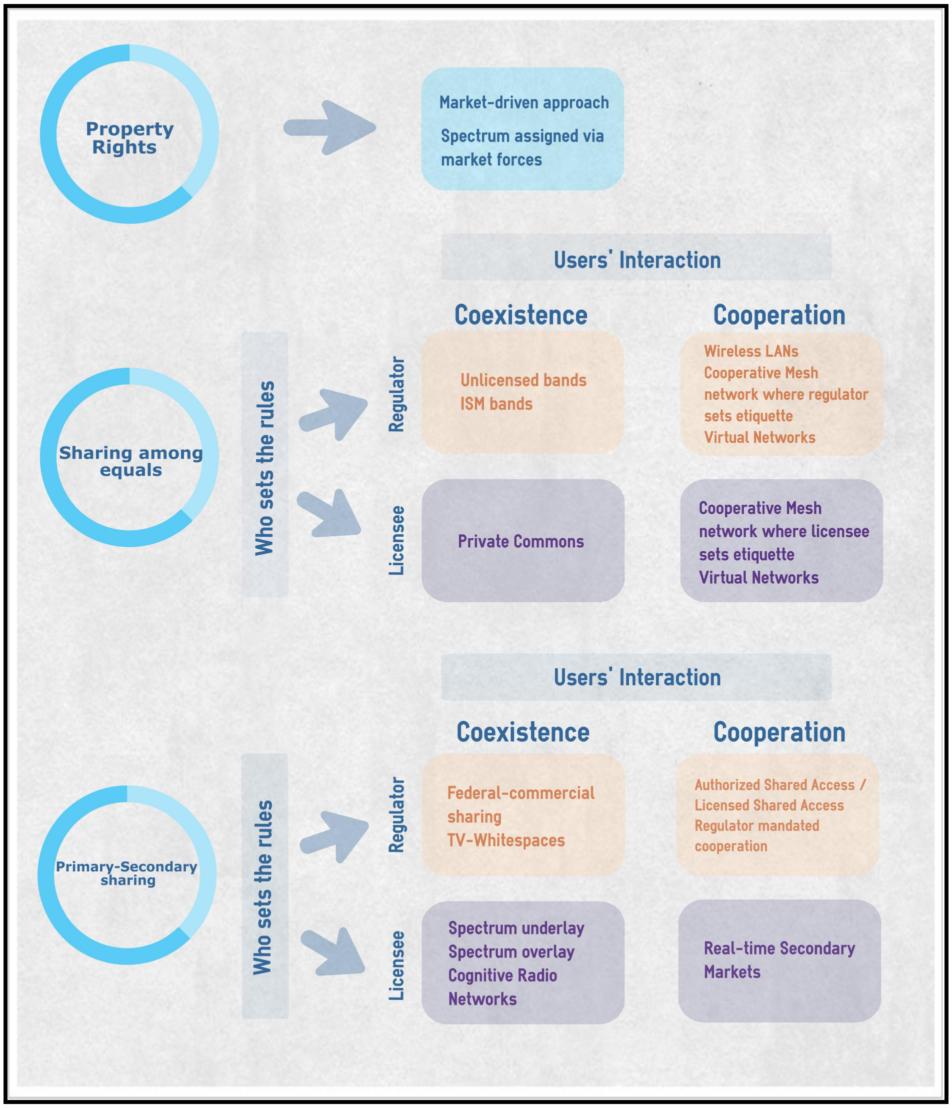

Fig. 1. Spectrum Sharing Taxonomy

A. *General Definitions*

In a broad sense, virtualization refers to the creation of a virtual version of something instead of the actual "thing" itself [31]. Nevertheless, it is important to point out the definition of virtualization from a Computer Science perspective, given that we owe the initial notions of virtualization to this field. An interesting and comprehensive concept in that context is presented in [32], which states that "Network virtualization is any form of partitioning or combining a set of network resources, and presenting (abstracting) it to users such that each user, through its set of partitioned or combined resources has a unique, separate view of the network. Resources can be fundamental (nodes, links) or derived (topologies), and can be virtualized recursively. Node and link virtualization involve resource partition/combination/abstraction; and topology virtualization involves new address spaces." From these concepts, we can expect that, through virtualization, the diverse components of the network are partitioned, combined, sliced and abstracted in order to create virtual instances of the network. When these components are wireless network assets, then we can talk about wireless network virtualization. Through this approach, we can further expect that different types of partitions, combinations and abstractions will yield distinct types of virtual networks; furthermore, the abstraction of each part of the network will represent a particular perspective, resulting in the notion of dealing with a *new* network, different from the original [32]. Note that, each virtual network created should have the ability to operate without (necessarily) being aware of the underlying virtualization process. We shall not forget; however, that there must be a certain degree of isolation between the virtualized instances of the network and their users that could permit individual virtual networks to contain operator-specific protocols and architectures. These protocols can actually differ entirely from one co-existing virtual network to another [33], [34].

Wireless network virtualization is expected to provide significant means to overcome the spectrum scarcity that we have been experiencing. In fact, this mechanism is aimed at providing opportunities for spectrum access to a greater number of users, through the creation of increased alternatives regarding the use, sharing and assignment of the existing resources [35]. An additional, important benefit derived from virtualization is the flexibility it adds to the network. It gives operators the capabilities they require in order to make changes to the network (e.g., expand it or shrink it) according to their needs while significantly reducing costs that would be otherwise prohibitive [34].

B. Aspects and Perspectives of Wireless Virtualization

Delving deeper into virtualization, according to [33], there are three important aspects of wireless virtualization: (1) depth and scope of virtualization, (2) virtualization of different wireless technologies and (3) virtualization of client-side or infrastructure-side technologies.

Regarding the scope, virtualization can be applied network-wide or in a localized manner. The first type of virtualization refers to high-level perspectives which focus on the management of the wireless network, developing design guidelines and abstraction interfaces that integrate the existing wireless resources into a virtualized network infrastructure. The localized scope implies low-level perspectives that normally explore the virtualization of resources pertaining to individual nodes in the network.

When talking about virtualization depth, reference is made to the extent of penetration of the slicing[4] and partitioning mechanisms on the wireless resources. In fact, with deeper virtualization, the entire protocol stack can be eventually virtualized. The depth is particularly tied to the granularity of the virtualized resources and it will also dictate where the virtualization managing entity and resource allocator (e.g., hypervisor) will be located within the virtualization architecture.

Wireless network virtualization can be applied to a wide variety of access technologies; for instance, we could point out (1) very short range wireless devices (e.g., Bluetooth, Zigbee, Personal Area Networks and sensor networks), (2) Short range devices (e.g., IEEE 802.11 based WLANs) and (3) medium and long range devices (e.g., WiMAX, LTE and other WMAN technologies) [33].

The infrastructure-side as well as the client-side of the network can be considered for virtualization, and a step further constitutes the integration of virtualization on both sides of the network. The choice of the type of virtualization depends on the scope and on the type of applications that the virtualized network will serve for. For instance, from the infrastructure perspective, the resources for the downlink and/or uplink communications can be virtualized. From the client-side perspective, virtualization can be employed to satisfy lossless handover, advanced mobility management and to optimize the uplink allocation, among other objectives. Nevertheless, there are some network configurations such as mesh networks, machine-to-machine configurations and ad-hoc networks where the distinction between infrastructure-side and client-side is not clear. In some of these cases, one wireless node may perform functionalities of a basestation and a client.

Exploring further where virtualization can be applied, three different perspectives of wireless virtualization can be pointed out [33]: (1) flow-based; (2) protocol-based and (3) spectrum-based virtualization These perspectives are relevant to the type of resources being virtualized and the depth of slicing.

Flow-based wireless virtualization mainly focuses on providing mechanisms for the isolation, scheduling, service differentiation and management for uplink and downlink traffic flows that belong to different slices. Virtualization of the MAC scheduler can also be considered through this method, resulting in enhanced QoS guarantees for each slice. If only this type of virtualization is implemented, all the virtual slices will share the same protocol stack. Examples of research works performed along this lines include OpenFlow [36] (flow-based SDN-enabling technology), OpenRoads (or OpenFlow Wireless) and vBTS[5] [37].

Protocol-based wireless virtualization focuses on "the isolation, customization and management of multiple wireless protocol instances on the same radio hardware" [33]. Varying degrees of protocol-based virtualization are feasible, namely partial and full implementation. In the partial implementation, multiple instances of the same protocol stack can share the radio resources while

[4]"Slicing of resources refers to the process of assigning a particular resource to be part of a network slice." Slicing does not necessarily imply resource virtualization and sharing (i.e., an entire base station could be assigned to a slice without actual virtualization of the base station). For a resource (or a slice) to be virtualized, it is required that multiple users or slices share the same physical resource [33].

[5]Virtual Base Transceiver system for WiMAX. This framework focuses on the implementation of virtualization of base stations' radio resources in order to achieve isolation between multiple virtual networks. The authors have presented results from their virtual basestation prototype which demonstrate enhanced mobile network performance, isolation across slices belonging to different flow types and capabilities for the customization of flow scheduling.

utilizing dissimilar configurations. In the full implementation, different protocol stacks can operate on the same radio front-end through the decoupling of the wireless protocols from the physical hardware. One option to achieve this is through Software-Defined Radio (SDR) technologies.

Spectrum and radio frequency front-end virtualization are the deepest types of slicing that are currently being studied. This perspective of virtualization implies the abstraction and dynamic allocation of spectrum bands to each user via spectrum reshaping and radio slicing techniques. In this perspective, the RF front-end is entirely decoupled from the protocols, making it possible for various virtual wireless nodes to use a single front-end or vice versa This approach can be implemented via Cognitive Radio and Dynamic Spectrum Access techniques

The aforementioned perspectives are not mutually exclusive. In fact, they can be combined to yield deeper levels of virtualization and reach larger scopes, which could possibly lead to the deployment of fully virtualized wireless infrastructures. In turn, this represents further flexibility, isolation and granularity of control over the wireless infrastructure [33]. Figure 2 presents a summary of the preceding aspects and perspectives of Wireless Network Virtualization.

In light of what has been presented, we can expect the applications of wireless network virtualization to be vast and certainly depend on particular interests associated with solving specific problems and overcoming precise challenges. For instance, we can find virtualization mechanisms that focus on the virtualization of infrastructure, others that focus on the virtualization of the air-interface and others that focus on virtualizing intermediate resources that facilitate a given goal.

Additionally, there are different characteristics of the resources that virtualization exploits in order to achieve the preceding aspects and perspectives. Nevertheless, the flexibility to opt for dividing different flows, protocols and spectrum resources is primordial for the existence of wireless virtualization, and in fact, such a characteristic is shared with spectrum sharing. It is for this reason that in order to establish how wireless network virtualization enables spectrum sharing, I would like to focus on this particular attribute: flexibility.

In the following section, the notion of flexibility that applies to this context is explained, and examples will be presented from regulatory, technical and economic perspectives.

IV. Flexibility

Flexibility is one important factor towards the realization of spectrum sharing.[6] In fact, we can infer how flexibility is strongly tied to spectrum sharing from section II, but we can also determine the strong correlation that it holds with wireless spectrum virtualization from section III. Flexibility could be explored more deeply in the particular contexts of spectrum sharing and wireless virtualization; nevertheless, the main objective of this section is to shed some light on how we can leverage the flexibility granted by wireless network virtualization towards a more efficient realization of spectrum sharing scenarios. Within this analysis, it is key to explore some policy issues associated with flexibility, as well as the economic implications of it.

A. Policy Perspective

From a regulatory perspective, in order to achieve flexibility, licenses should be technology-neutral. This would grant a license-holder not only the flexibility to employ the technology that he sees fit, but also to provide services he considers commercially viable [8]. In this way, flexibility enables spectrum users to make fundamental choices about how they will use the spectrum (including whether to use it or to transfer their usage rights to others) taking into account market factors such as consumer demand, availability of technology and competition [2]. Additionally, flexibility allows agile licensees to put spectrum to its most valuable use with the most effective technology, without being delayed by regulatory processes (i.e., regulator's authorization) [38]. Furthermore, a flexible regulation can facilitate the fluidity and dynamics of spectrum markets [39]. In the most general terms, flexibility would allow users to make use of spectrum in the way they wish.
It is important to note; however, that with flexible regulation, the need to develop enforcement[7] measures that adapt to this flexibility arises. This renders the rights to use the spectrum more practical [10] and may be a source of certainty and incentives for the licensees.

In summary, regulatory flexibility implies that users are not subject or tied to cumbersome regulatory requirements in order to access and use the spectrum. However, they require an enforcement framework that provides a given measure of assurance and certainty to enter the sharing process. This can be considered as the first step towards enabling spectrum sharing. Nevertheless, there is the need of "technical" flexibility that could

[6]No claim is made that flexibility is the most or the only important factor for achieving successful spectrum sharing scenarios. This factor has been chosen due to its intrinsic relation with wireless network virtualization and how it ties to regulatory and economic aspects, which are relevant to the development of this work.

[7]Enforcement will not be deeply explored as it is out of the scope of this paper.

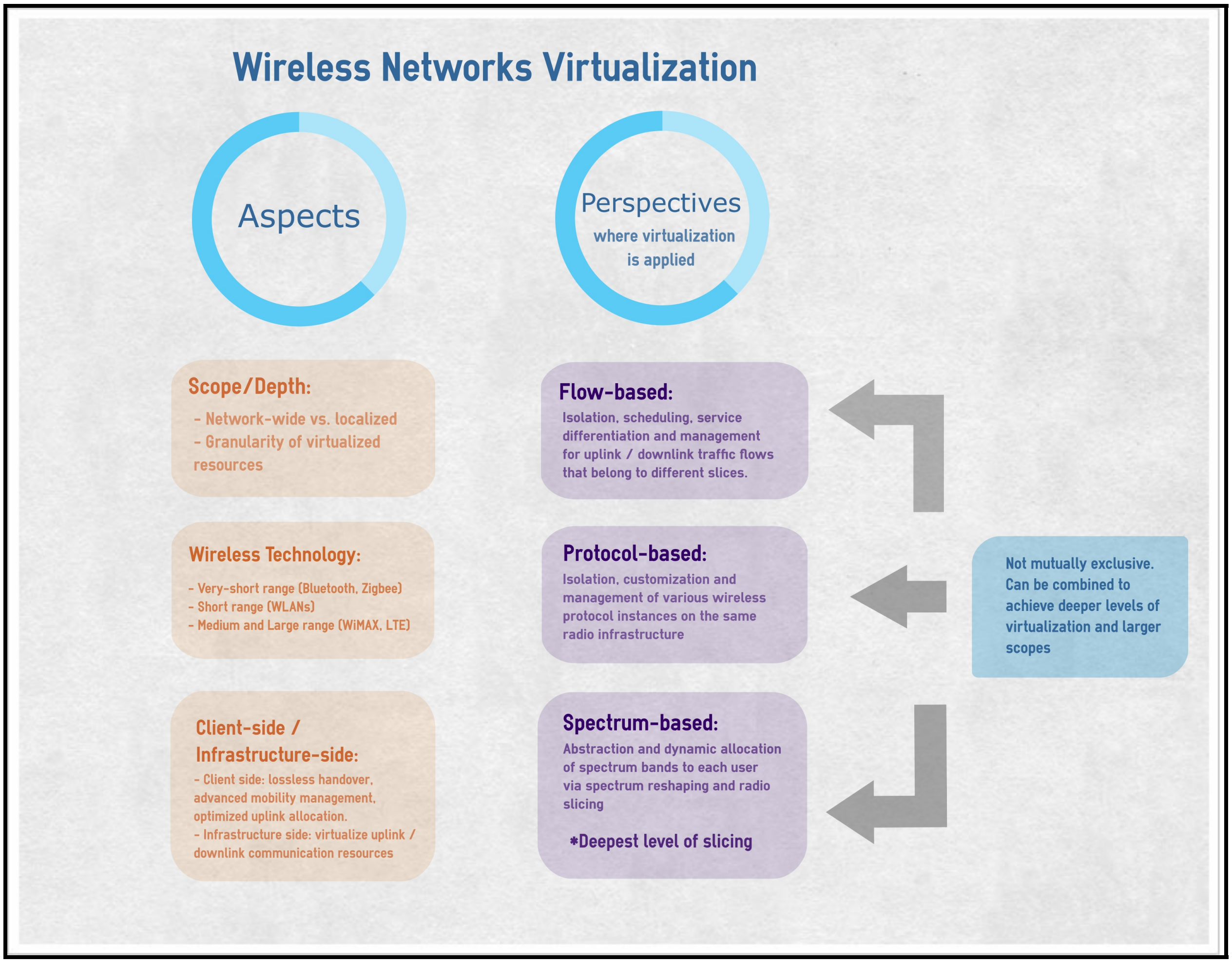

Fig. 2. Wireless Network Virtualization Aspects and Perspectives

render the regulatory flexibility feasible and even more advantageous.

B. Technology Perspective

From a technical perspective, flexibility can be explored through the lens of wireless network virtualization. Network virtualization, in general, provides a convenient means of sharing resources across a wide set of users while allowing integration with other virtualized substrates [37]. In fact, a fully-virtualized and open infrastructure will not only allow to share the infrastructure resources, but it will also make it possible for different virtual instances (e.g., MVNOs) to deploy different protocol stacks over the same radio resources. Furthermore, with the advent of more sophisticated underlying technologies (e.g., LTE-Advanced), flexibility can be enhanced by taking basic radio resource blocks as the fundamental units of virtualization. These virtualized units can be further allocated via multiple access, multiplexing and spectrum slicing techniques [33].

One of the foundations of wireless virtualization is the decoupling of Service Providers' functions from those of Infrastructure Providers. This further allows the decoupling of resources from services [40] and makes virtualization processes take place in a given layer independently from the other layers. For example, the virtualization of resource blocks would take place independently from the higher-layer architecture. It should be further added that the flexibility (in addition to isolation and granularity of control) over the wireless infrastructure is enhanced as the depth of virtualization is increased [33].

The characteristics above are extracted from particular research works, which have focused on exploiting the flexibility factor (explicitly or implicitly) in order to make the spectrum resource available to a larger number of users (i.e., to provide spectrum sharing opportunities). For instance, an important research effort is the creation of "resource pools" through the virtualization of different network instances [41]–[44].

Some authors make an analogy of this pool of resources to the cloud (as we normally refer in a computer science context). The actual success of the notion of clouds is derived from having the illusion of infinite resources, which are available on demand, the elimination of high up-front commitments (thus costs) and also the ability to pay for the resources on a short-term basis, or as needed. In fact, the latter implies that users who need spectrum can obtain it from different service providers (i.e., the service providers that best support their requirements) [31], [44].

In the particular context of spectrum, pooling is envisioned to decrease scarcity. As contributions of spectrum to the pool increase, lower is the probability that a given user (with access to the pool) will experience spectrum shortage [45]. This increased spectral efficiency is achieved given that spectrum pooling permits to overlay a new radio system on an existing one without requiring any changes to the licensed system currently in place [42]. It should be pointed out that the benefits from spectrum pooling can be especially extracted in environments where we find a great number of infrastructure providers in the same geographical area (e.g., dense urban areas with highly overlapping cellular networks) [40].

The aforementioned advantages constitute an important basis for spectrum sharing; nevertheless, it is essential to explore how exactly spectrum pooling supports the deployment of spectrum sharing. To fulfill this task, I would like to point out two important approaches that particularly benefit from the creation of spectrum pools: (1) MVNOs and (2)Air-interface Virtualization.[8]

Wholesale networks are the closest example to a cloud that currently exist. Mobile Virtual Network Operators (MVNOs), in their simplest form, comprise the reselling of cellular services purchased on a wholesale basis from a Mobile Network Operator (MNO). An MVNO does not incur in significant capital expenditure on spectrum and infrastructure, and it is responsible for setting its own retail prices. MVNOs could be set on a voluntary basis, when MNOs resell their excess capacity after serving their customers, or on a regulatory basis as a means to increase competition and thus avoid monopolistic behavior from existing MNOs.

The incorporation of resource pools can lead the way to the provision of service-driven arrangements, which could have an impact on the way MVNOs work. In fact, MVNOs could opt to establish agreements with more than one network operator. For example, an MVNO may contract for low-latency services with one network and high-quality indoor services with another. Additionally, each service could have a different geographical scope (e.g., nationwide and coverage of dense urban environments, respectively) [43], [44].
The benefit that the MNOs could obtain from the resource pool is that they have increased options for reselling their excess spectrum besides MVNOs. In fact, they could offer their resources to other cellular entities and users taking the form of a band manager.

Taking one step further, the virtualization of the resources within the pool is envisioned. This could lead the way to the slicing of the resources pertaining to the pool, which could later be aggregated into new configurations thus offering more specialized services.

The evolution of new technologies such as LTE-Advanced represent increased opportunities for the application of wireless virtualization. For this reason, air-interface virtualization will be analyzed in the context of this technology. The goal of LTE air-interface virtualization is to adapt the existing resources to the traffic load variation of different virtual networks. For this purpose, the virtualization of the eNodeB[9] is proposed. In this case, an entity called "hypervisor" is added on top of the physical resources and it is in charge of allocating them to the virtual instances that are running atop. In this way, it is the hypervisor's duty to allocate the air-interface resources. In order to perform a proper allocation, it needs to collect relevant information from the individual virtual eNodeBs, such as channel conditions, QoS requirements and information regarding the service contract with each of the virtual operators. In fact, the scheduling of resources can be performed in terms of any of these factors, or additional ones such as bandwidth, data rates, interference, among others. The virtualization process happens when the hypervisor converts these attributes into an appropriate number of Physical Resource Blocks (PRBs) to assign to each operator, making sure that there is an appropriate level of fairness and that this allocation permits the users to fulfill their requirements. Indeed, the scheduling of the PRBs represents the splitting of the frequency band among the eNodeBs of each operator [34], [46], [47].

A factor that can complement this process is the possibility to perform carrier aggregation provided by LTE-Advanced [48], [49]. In this manner, there are further opportunities for spectrum to be assigned, and in fact, this could lead to the creation of virtual bandwidth units, which actually spread across multiple physical bandwidth units (i.e., PRBs) [33]. The aggregation of PRBs in such a way permits to translate this resource into new ones, such as bandwidth or wireless capacity, which can be further assigned to the different users, adding to the level of transparency and flexibility that can improve spectrum sharing.

[8]These are not the only existing mechanisms; however, important benefits relevant to spectrum sharing can be inferred from these approaches.

[9]The enhanced NodeB is the part of the LTE infrastructure that is in charge of sending/receiving data to/from the LTE users [34].

An interesting factor that can be inferred from these applications of virtualization is the fact that they leave room for the negotiation of resources. The utilization of a scheduler (or hypervisor) has been mentioned; nevertheless, market mechanisms (i.e., auctions) can also be devised as effective mechanisms for resource assignment [35], [50], [51]. When this approach is employed, we can expect that the auction will be performed on continuous goods, rather than discrete items. In other words, spectrum requesters will be able to specify their constraints and conditions and, more importantly utilize the spectrum for more specialized services/requirements they may have [31]. Additionally, the transparency that springs from virtualization, may facilitate the achievement of liquidity requirements desired for markets success [35].

Some specific models include the application of combinatorial auctions, which permit users to request resources that comply with a set of particular characteristics, thus obtaining a "package" that fulfills the user requirements, instead of one particular, discrete, item [31]. Other examples of spectrum markets have been modeled through Stackelberg auctions via Agent-based Computational Economics in order to assign the virtualized resources to the users in (nearly) real-time [35].

All of these examples show that through the application of virtualization, the flexibility that spectrum sharing requires is significantly enhanced, thus representing promising and encouraging opportunities for a more substantial deployment of spectrum sharing instances. However, we shall remember that even when barriers to spectrum sharing are removed, it is still important that spectrum users have the appropriate incentives for sharing. In particular, [45] points out that an important incentive for resource pooling is establishing "co-primary rights". Furthermore, Doyle et al. mention in [31] that a key point is that successful collaborative consumption or exclusive sharing schemes are not heavily biased towards any particular user. Additional to these rights-related factors, there are important underlying economic factors that will drive the realization of the mechanisms above, which are presented in the following subsection.

C. *Economics Implications*

From an Economics perspective, implementing flexibility has its costs. Given that spectrum sharing can result from the combination of various usage models in different frequency bands (or the entire spectrum), the same factors mentioned in subsection II-A for the choice of spectrum usage models can be pointed out as drivers for the choice of spectrum sharing mechanisms. These factors are:

1) Spectrum scarcity

2) Transaction costs

Spectrum scarcity arises when the demand for spectrum is greater than the supply.

Regarding transaction costs, it is important to delve a little bit deeper into the definitions and where they originate from. In a general sense, the costs of conducing an activity, namely spectrum sharing, are called transaction costs. They may be generated by diverse reasons. For instance, transaction costs may be the result of laying out the ground for spectrum sharing activities (in terms of regulation and technology); they may be derived from the time/efforts spent on negotiating in order to achieve an agreement between the sharing parties, or they could be even generated by enforcement and administrative requirements [9], [52]. Note that transaction costs are proportional to the number of entities participating in the economic activity, in this case spectrum sharing [6].

Another important factor, source of additional costs is externalities. Many economic activities generate incidental benefits (external economies) or harm (external diseconomies) to third parties for whom this benefit/harm was not precisely intended. The total costs or benefits caused by this activity do not match the cost incurred or the benefit obtained by the entities performing the activity in the first place [6], [52], [53]. Someone acting on its individual self-interest, will not take into account these externalities, unless compensated to do so. In fact, the tragedy of the commons is an example of the dangers that arise when people fail to take into account the costs they impose on others [22], [52]. In this context, transaction costs are the costs that a given user needs to incur in order to compensate others for the unintentional consequences of their activities (i.e., negotiate with respect to externalities) and perhaps achieve an internalization of the external costs.

Tying these concepts back to flexibility, it can be asserted that, within a flexible spectrum rights scenario, the negotiations to change the initial regulatory arrangements of spectrum will take place if the possibility of being able to make these modifications makes it worthwhile to incur in the costs associated with them [13]. Certainly, when transaction costs are high, only the most beneficial types of negotiation are undertaken.

Within the spectrum sharing context, different types of spectrum sharing options would be more appealing depending on the level of scarcity and transaction costs. For instance, scenarios where scarcity is high and transaction costs associated to the market-based transfer of rights are low can incentivize the assignment of exclusive-use licenses that can later be transferred via market transactions to other users and uses (e.g., real-time secondary markets). On the other hand, scenarios where scarcity is low and the transaction costs derived from market mechanisms are high may favor the deployment of commons configurations.

In addition to the aforementioned factors, when assessing the feasibility of sharing mechanisms, it is also important to take into account the "value" of spectrum in the sharing environment and the efficiency in spectrum use derived from the sharing process.

First of all, it is important to note that, economically speaking, spectrum is not a store of value in itself; instead, it is an input for the production of valued services. In light of this, "the value of a given spectrum license is limited by the profits that can be made with its use, which are, in turn, limited by the profits from alternative ways to provide the same service". Profits are evidently derived from revenues less investment and operating costs incurred in deploying services with the spectrum band. It follows that to the extent that the profitability of spectrum-based services varies, the value of the spectrum making these services possible will vary as well [54].
In the particular context of spectrum sharing, there are certain profit-reducing factors such as: restricting how a single user would make use of a spectrum band under a shared scheme in contrast to an exclusive license and limiting the quality of the services offered. However, sharing can also be less costly, when compared to fully re purposing a band for other uses. It is in this manner that when considering spectrum-sharing frameworks, it is key to assess the foregone revenue of sharing in order to understand the costs and benefits of a shared band. For instance, a smaller scope of services will cause the reduction of revenues, proportionally to the decrease in service, as will any decrease in the quality of services offered.

Regarding efficiency, a desired spectrum sharing option is the one that represents a more efficient alternative for spectrum use. Taking into account that the total value of a band of spectrum is the sum of the values for each use of this band, a measure of efficiency and inefficiency can be identified. Along these lines, "if the reduction in value to each shared use is such that the sum of these uses is less than the total value from a single exclusive use, then sharing is inefficient." Conversely, "if the cumulative value from shared uses is greater than the highest value to a single user, then sharing is efficient" [54]. It should be added, that for increased efficiency, this cumulative value should be higher than the transaction costs.

To summarize what has been presented, it can be concluded that 1) spectrum sharing should only be implemented if the forgone value to the primary user from sharing is less than the added value to secondary user(s) and 2) spectrum sharing is efficient when the cumulative value to all users is higher than the potential value to a single user [54].

1) Incentives: The trade-offs that spectrum sharing involves are tightly linked to the "value" of spectrum, and consequently, they have an important impact on the incentive for opening spectrum-sharing opportunities.

According to [55], adding flexibility to spectrum rights has two opposing effects. In a first instance, added flexibility gives users the opportunity to optimize their services with fewer constraints, which in turn increases the value of the spectrum license. However, at a second instance, flexibility may allow entry of new users and thus increase competition, factor that will result in the reduction of value of those same licenses. In light of this, given a spectrum sharing arrangement, existing licensees will have little or no incentive to share their excess or unused spectrum if the new users will provide the same service that is currently provided by them. An option that would incentivize licensees to share or trade their spectrum would be if they were able to establish enough restrictions so as to protect their current services, not only in terms of physical requirements (e.g., interference, QoS) but also in terms of competition. In absence of this possibility (and when sharing is the chosen arrangement), licensees need to find different alternatives to remain competitive in the market such as the introduction of value-differentiated services and innovation. Existing MNOs will also find motivation for sharing if this represents substantial savings in operational expenditures and if they can experience capacity and coverage gains from an efficient pooling of resources [56].
From the new spectrum users perspective (e.g., new operators or market entrants), spectrum sharing represents important opportunities to access spectrum as it will, most likely, become less expensive.[10] From the end users perspective, service prices may be driven down due to competition in data communication services.

The particular case of licensees who do not pay for spectrum access (e.g., spectrum for Federal use) should be mentioned. Generally, these licensees do not have enough incentives to properly represent their actual spectrum needs and requirements [57]. In fact, until these users internalize the costs inherent to their spectrum use, they will not have the incentive to find more efficient uses of their spectrum or maximize the social value of this resource [54].

Uncertainty is another essential factor when we explore incentives. In fact, spectrum sharing potentially increases uncertainty about the profitability of a project. This uncertainty is mainly associated with the availability of spectrum and how harmful will the interference

[10] We are focusing on the spectrum aspect of sharing and virtualization, this is why the decrease in cost of access to this resource is mentioned. It is evident that sharing other network instances represents significant benefits in terms of lowering capital and operational expenditures, not to mention the avoidance of high sunk costs.

caused by the new spectrum users be [54]. Other key factors include the time that users can access the spectrum for. As a matter of fact, when the rights to use the spectrum are granted for a short period, efficient opportunities for sharing may be deterred [15]. The shorter the period available to recover the costs and investments incurred, the greater the aversion for users to enter in such a negotiation [15].

In this light, an important factor associated with the provision of incentives and reduction of uncertainty is the definition of appropriate enforcement mechanisms. Indeed, users are willing to incur in enforcement-related costs, which are proportional to the value of the resource they are "protecting" [58]. In this way, through an appropriate definition of enforcement mechanisms, the incentives of users for sharing may rise, as there are better defined notions of rights and accountability to support the sharing process.

It can be inferred that spectrum sharing, virtualization and the flexibility derived from them lay a dark shadow over networks centered around a single license holder. Instead, light is shed over networks formed by various entities (some of them virtual) sharing the underlying resources. It is in this way that in order to address properly all the changes generated by spectrum sharing and the resulting changes in the value of spectrum, different entities are prompted to better understand where the value is generated in the network and how it is created, which might be the responses from other network participants and how the activities of the entities themselves affect the network [59].

In Figure 3, some important remarks regarding the policy, technology and economics perspectives of flexibility are highlighted, in addition to the benefits that stem from them.

V. Conclusion and Future Challenges

The analysis made in this work suggests that there is a lot of room for wireless network virtualization to exploit flexibility and thus enable spectrum sharing. In fact, wireless virtualization does not only make spectrum sharing possible, but it is also enhanced by it. For instance, it is spectrum sharing that renders spectrum efficiency and some levels of increased capacity possible in virtualized environments.

In all these scenarios; however, an important consideration to make is that for innovation to be successful, it needs to take into account the entire system. By system I mean the wireless technology, spectrum policy and the economics behind them.

Regarding policy and economics, there is no complete independence of the economic and legal systems. Law can be designed in such a way that certain desirable transactions may be impossible to achieve. For example, regulation may impose costly and time-consuming procedures that can cause market failure or deter otherwise appealing sharing arrangements. These costly procedures can stem from laying out the initial regulatory requirements for spectrum sharing, or they can also be linked to deploying adequate enforcement mechanisms. It is in this way that a flexible definition of rights constitutes only the starting point for the rearrangement of these rights via more appealing mechanisms [13] (e.g., spectrum sharing and virtualization).

In terms of technology and policy, no significant advancement will be successful and have practical value if there is no policy approach rendering it feasible. In other words, new technologies can alleviate spectrum scarcity, if and only if, spectrum policy is reformed to match the technology. It would be thus essential to achieve a regulatory framework that could foster the technological advances that portray spectrum sharing as a promising solution for the evident constraints originated by the current and upcoming spectrum requirements.

From the virtualization standpoint, the choice of resources and functionalities that are partitioned and sliced may affect the flexibility of the whole implementation, thus posing restrictions for the subsequent spectrum sharing schemes. Additionally, it is important to note that particular wireless standards have specific requirements that represent challenges at the time of incorporating them to a given virtualization layer. This can impose further constraints when envisioning heterogeneous networks that deal with different wireless technologies, and, evidently, are expected to address diverse purposes. In other words, towards the efforts of working seamlessly with distinct technologies, particular characteristics of one or other technology may be lost or degraded [33]. On top of this constraints, it is key to remember that for a virtual network to be successful, it needs to provide the proper isolation among the virtual instances created. New technologies, such as LTE-A, offer significant opportunities which may lay the ground for overcoming some of the aforementioned constraints.

Finally, even if the increased spectrum demands represent an important driver for virtualization and spectrum sharing, users, operators and regulators need incentives in order to adopt changes. Incentives, and the lack thereof, for the adoption of spectrum sharing have been presented in this work; however, there will still not be a clear answer unless the value of the sharing outcome, as well as the value of what is sacrificed to obtain such result, are known with some certitude [14].

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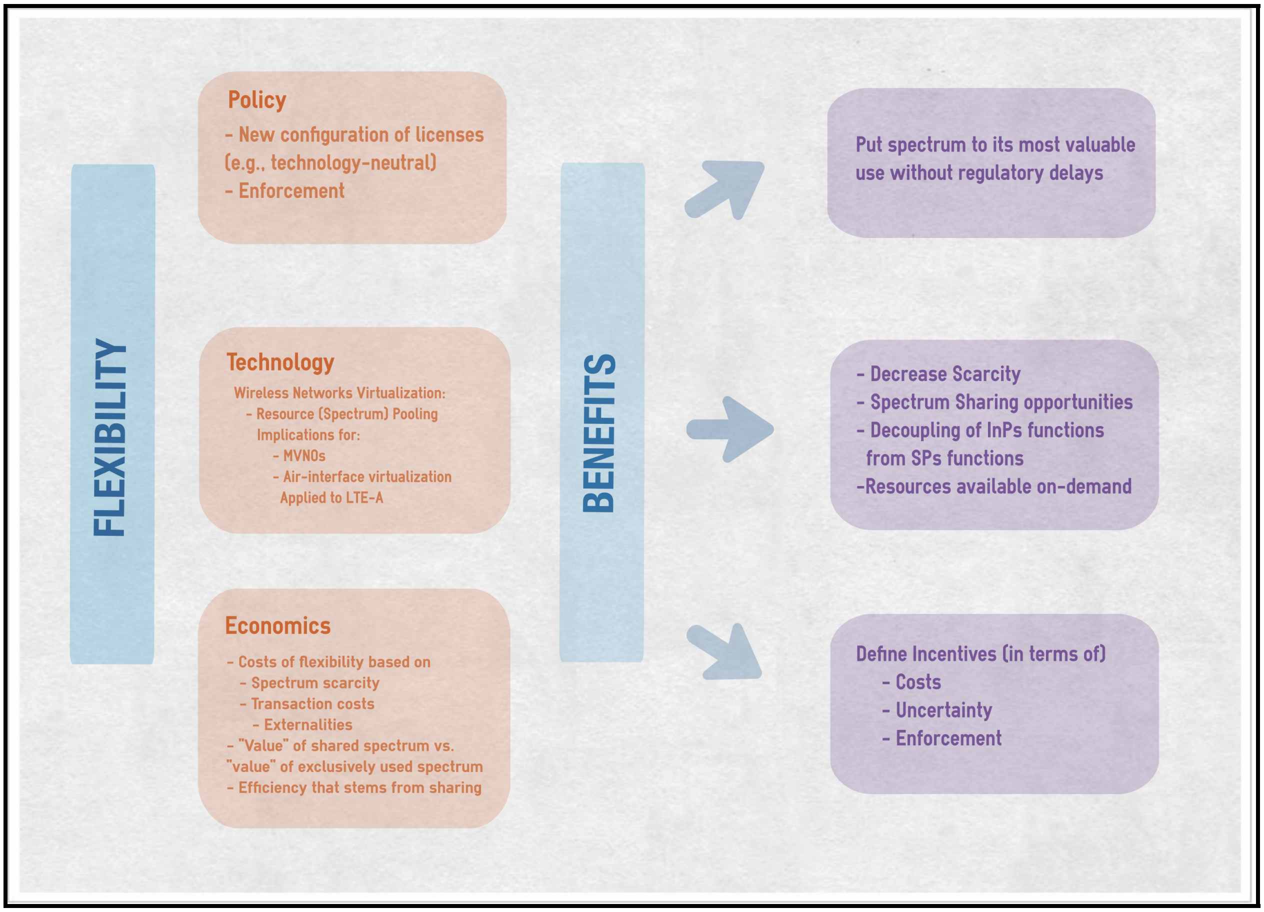

Fig. 3. Policy, Technology and Economics perspectives on Flexibility and the associated benefits.

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