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Wireless Network Virtualization: Opportunities for Spectrum Sharing in the 3.5GHz Band

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Abstract

In this paper, we evaluate the opportunities that Wireless Network Virtualization (WNV) can bring for spectrum sharing by focusing on the regulatory framework that has been deployed by the Federal Communications Commission (FCC) for the 3.5GHz band. Pairing this regulatory approach with WNV permits us to present a sharing proposal where emphasis is made on increasing resource availability and providing flexible methods for negotiating for resource access. We include an economics framework that aims at presenting an additional perspective on the attainable outcomes of our sharing proposal. We find that by pairing regulatory flexibility with an enabling technology, within an appropriate economics context, we can increase resource access opportunities and enhance current sharing arrangements.

Keywords: Wireless Network Virtualization, Spectrum Sharing

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1. Introduction

The complexity of managing electromagnetic spectrum is not purely technical. There are crucial economic and regulatory implications that determine whether an alternative for making more efficient use of this resource would be beneficial or detrimental. Therefore, we perform an analysis that goes beyond the existing technical barriers and extends along three axes: regulation, technology and economics.

In this work, we focus on the 3.5GHz band and its regulation as well as the innovative technology of Wireless Network Virtualization (WNV) to explore the opportunities and challenges in introducing sharing opportunities. Our study focuses on one particular approach of WNV that is built on resource pooling. Thus, we will study the characteristics of resource pools, the interaction between user types (Incumbents, Priority Access and General Authorized Access users) and how economic considerations drive the definition of networks and the resulting types of competition. We expect that this comprehensive analysis will permit us to solidify the basis for further deployment of an appropriate virtualization environment for spectrum sharing.

This paper is organized as follows: the regulatory framework for the 3.5GHz band is presented in section 2; section 3 includes a description of WNV and the particular approach that will be considered in this work; section 4 includes a technical analysis, which presents the two models that could be adapted to the opportunities offered by regulation in the 3.5GHz band; section 5 analyzes three important aspects associated with Economics, which target at framing our model within this context, and finally, sections 7 and 8 present our conclusions and future work, respectively.

2. 3.5GHz Band: CurrentStatus

To date, the 3.5 GHz band in the U.S. has been allocated to federal services (e.g.,DoD radar systems), Fixed Satellite Service (FSS) and, for a finite period, to grandfathered terrestrial wireless operations in the 3650 - 3700 MHz band[1]. The Federal Communications Commission (FCC) and the National Telecommunications and Information Agency (NTIA) have made a significant effort toward opening this band for shared operations between federal and commercial users. The FCC has referred to this band as an “innovation band,” given that the main objective is to enable new spectrum access models that allow the use of modern technologies, thus enabling a move away from legacy spectrum management categories: Federal vs. Non-Federal; Licensed vs. Unlicensed and Carrier vs. Private [1]. The basis of this new spectrum sharing scheme is a three-tiered model for spectrum access, with each tier holding a different level of priority: Incumbent Access, Priority Access

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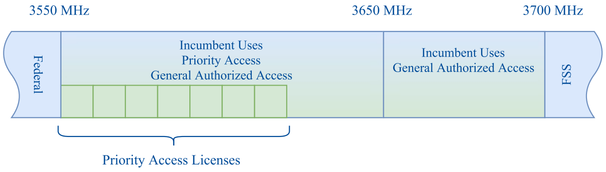

Figure 1. Tentative bandplan under the 3.5 GHz sharing framework.

and General Authorized Access (GAA). Some important characteristics of these tiers include [2]:

- Incumbent users comprise federal services and some legacy satellite and wireless operations. These users have superior spectrum rights over Priority Access and GAA users at all times and in all areas.

- The Priority Access tier consists of seven channels of 10 MHz each, which can be assigned to Priority Access Licensees. These licensees will have more predictable spectrum access than GAA users. Nevertheless, Priority Access Licenses (PALs)[1] will be granted as long as the demand is greater than the supply in the area of interest. If that is not the case, the entire band will be allocated for GAA use.

- General Authorized Access (GAA) will be granted by rule. In this way, GAA users could potentially access the entire 150 MHz band in areas where PALs have not been issued (or are not in use) and up to 80 MHz where PALs are in use. It is important to note; however, that GAA users will not be protected from interference from other Citizens Broadband Radio Service (CBRS) users.

Through these approaches, it is expected that this three-tiered approach will enable the adaption of spectrum use to market and user demands. Figure 1 illustrates the tentative bandplan, proposed by the FCC, for the 3.5 GHz band.

Sharing in the 3.5GHz band will be enabled by a Spectrum Access System (SAS). According to [2], "[t]he SAS serves as an advanced, highly automated frequency coordinator across the band. It protects higher tier users from those beneath and optimizes frequency use to allow maximum capacity and coexistence for both GAA and Priority Access users". In other words, the SAS is an entity that will be in charge of authorizing spectrum access to CBRS users in any frequency and location. Additionally, the SAS is in charge of providing Priority

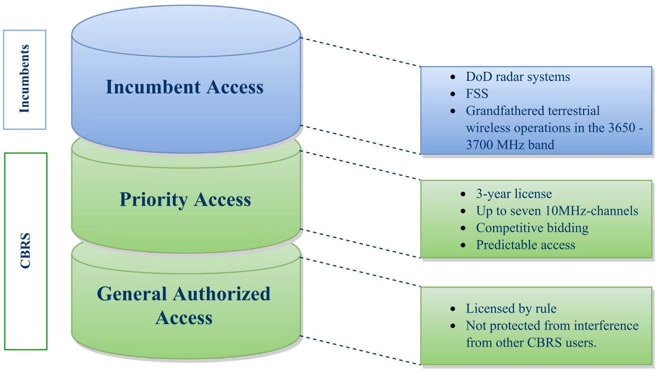

Figure 2. Three-tier sharing framework

Access Licensees and GAA users with alternative spectrum when they have been displaced by users with higher priorities[3]. In general terms, the SAS should fulfill the *automated frequency assignment* task that will enhance the band management flexibility pursued with this sharing scheme. With the flexible access model developed for this band, the FCC aims at creating a versatile band which will permit to adapt to market as well as technological opportunities[2]. Figure 2 summarizes some important details regarding this three-tiered sharing framework.

3. Wireless Network Virtualization: The Technology of Choice

From the regulatory approach presented in the previous section, we infer that flexibility for innovation is a key policy objective. For innovation to be successful we should not only contemplate regulatory flexibility; in fact, we also require technology to allow for adding such flexibility to the network. Along these lines, we find that there is a significant link between Wireless Network Virtualization (WNV) and adding technical flexibility to networks and systems.

Through virtualization, different components of the network are partitioned, combined, sliced and abstracted to create virtual instances of the network. Further, each type of partition, combination or abstraction will yield distinct types of virtual networks giving us the impression that we are working with a *new* network, different from the original[4]. As a result, multiple virtual networks operate on one single network , each serving specific purposes and utilizing distinct technologies. Furthermore, co-existing virtual networks may be different from each other [5, 6], or as stated in [7], Mobile Network Virtualization "promises multiple personality network elements in terms of virtual ownership by multiple operators. That means multiple networks running virtually (i.e., logically) and concurrently within one physical network equipment or hardware". Notably, this would call for

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[1] PALs are defined as an authorization to use a 10 MHz channel in a single census tract for three years. These licenses will be assigned in up to 70 MHz of the 3550 - 3650 MHz portion of the band[2].

an important degree of isolation embedded in the virtualized systems, which will permit a sound co-existence of virtual entities.

With the adequate application of virtualization technologies, we would be able to devise improved alternatives for the use, sharing and assignment of existing resources[8]. This could provide a degree of flexibility that would aid in maximizing the spectrum access and management options on the operator side. Several alternatives for the application and deployment of WNV have been explored. However, given the characteristics of the new sharing framework for the 3.5GHz band, we consider virtualization from the perspective of *resource pooling*. This approach requires multiple entities/providers to share their resources in a pool and then make them accessible to additional users/providers. To elaborate on the resource pooling concept, the authors in [9, 10] have compared it to the Cloud (in a computer science context), given that, in principle, it gives us the illusion of an infinite amount of resources, which are available on demand without the need to incur in high upfront commitments and actually permitting users to pay for them on a short-term basis or as needed. Focusing on the idea of *access on demand*, we could expect that the users who have access to the pool will be allowed to choose the resources that are most suitable for a particular service, but which may belong to different incumbents or access tiers.

Centering our attention on spectrum, the objective of pooling this resource is to "enhance spectral efficiency by overlaying a new mobile radio system on an existing one without requiring any changes to the actual licensed system"[11]. Thus, the deployment of spectrum pools would imply a different resource allocation system, where the existing and new hardware can be operated transparently, or in other words, as if there were no other system concurrently present in the same frequency range[11]. In this manner, we can merge the key concepts behind WNV and the creation of resource pools and present them as important alternatives for providing enhanced spectrum access and sharing opportunities [10–13].

4. Sharing Proposal

In this section, we provide an overview of a sharing proposal which applies virtualization and resource pooling concepts in order to enhance the sharing process in the 3.5GHz and other available frequency bands. We present this proposal through a description of the possible network participants, the network configuration and the applicable interactions for resource transfer or negotiation.

4.1. Network participants

The sharing model we envision relies on three main types of participants: resource providers (RPs), service providers (SPs) and an intermediate entity known as Virtual Network Builder (VNB). In what follows, we present an overview of the roles and duties of each participant.

Resource Providers. The RPs are current incumbents who are willing to make their resources (or slices thereof) available in the pool. Examples of RPs include:

- Incumbents who, after serving the traffic requirements of their own customers, have unused resources and are willing to share them in the pool, in exchange of a payment.
- Entities who are dedicated to the provision of resources and do not have any additional customers besides those who have access to the pool.

Service Providers. These entities seek access to the pool as a means to obtain the necessary resources to fulfill the demand of their customers. Note that the SPs are not limited to new market entrants. In fact, these can be existing providers who, provisionally, require additional resources to meet the traffic generated by their customers.

Furthermore, we can think of SPs as entities who are in charge of providing specialized services such as access to video streaming, social media, file storage/transfer, among others. In this way, the demand of each SP will depend on the requirements or their particular service.

Virtual Network Builder. The VNB is an intermediate entity (i.e., middleman) in charge of facilitating the transfer of resources from the pool to the SPs. For this purpose, the VNB aggregates the pooled resources according to the SPs' requirements (e.g., price, service-specific demand, etc.) and the price set by the RPs. We expect the VNB to be a profit seeking entity (i.e., it will charge a fee for its resource aggregation duties).

4.2. Network Description

In order to determine the type and characteristics of the resources available in the pool and the applicable interactions for resource access and sharing, we contemplate two possible scenarios: a local and a global approach.

Local Approach. This represents an initial, simple setting for sharing, where the resource pool is comprised of resources belonging *only* to the 3.5 GHz band. As such, from the regulatory approach presented in [2] and as shown in Figure 1, the following assets would be available for pooling:

- 3550 - 3650 MHz band: 0 - 70 MHz for PALs and 30 - 100 MHz for GAA
- 3650 - 3700 MHz band: 50 MHz for GAA

Given this resource limitation, in this scenario we do not contemplate an explicit participation of or interaction with the RPs. In fact, for the design of this approach we focus on managing the responsibilities of the SAS. At a minimum, the SAS is in charge of the automated allocation of resources (i.e., spectrum access management). Nevertheless, in a virtualized environment, we consider the possibility of the SAS outsourcing part of its spectrum pool management duties to the VNB. In this light, the VNB should negotiate with the SAS for access to the 3.5GHz band, while taking into account the particular demand of each of its SP customers. Thus, the SAS would treat the VNBs as large spectrum users or operators. As such, VNBs would auction for PALs from the SAS and compete with other Priority Access and GAA users under the same rules. In a broad sense, this is consistent with the notion of *polycentric governance* described in [14]. This structure is portrayed in Figure 3.

Given that the VNB should account for the resources to serve the aggregate requirements of its customers, the demand from the VNB should be significantly larger than that of individual entities. When posting bids for PALs, the VNB operations could lead to two important consequences: 1) the VNB can compete with other large stakeholders (e.g., Verizon, AT&T) in terms of the amount that the latter are able to pay for obtaining a license; 2) it is likely that the 'demand greater than supply' constraint for PAL assignment will be met given the aggregate demand carried by the VNB. In this light, this *local* approach provides opportunities for enhancing the sharing arrangements.

As shown in figure 3, there is a certain hierarchy among the different entities that belong to this type of network. Indeed, we could associate specific tasks and behaviors to each layer: the SAS would be considered as the regional spectrum access coordinator. It would be in charge of the automated process of assigning licenses to the entities in the layer below and, in turn, it would remain accountable to the regulator (i.e., the FCC) and incumbents in the layer above. The next layer consists of the VNBs or large Network Operators who negotiate spectrum access directly with the SAS. These are entities that require larger spectrum assignments than smaller SPs. The final layer of the hierarchy will be composed of individual SPs who require spectrum from VNBs or from large Network Operators (as in the case of Mobile Virtual Network Operators (MVNOs)).

As previously mentioned, this approach increases the sharing opportunities in the 3.5GHz band; however, it does not fully exploit the capabilities of virtualization. For the virtualization process to be evident we may consider pooling resources that belong to multiple providers who are willing to make them available to a larger number of SPs. This scenario is explored in the following section through our global approach.

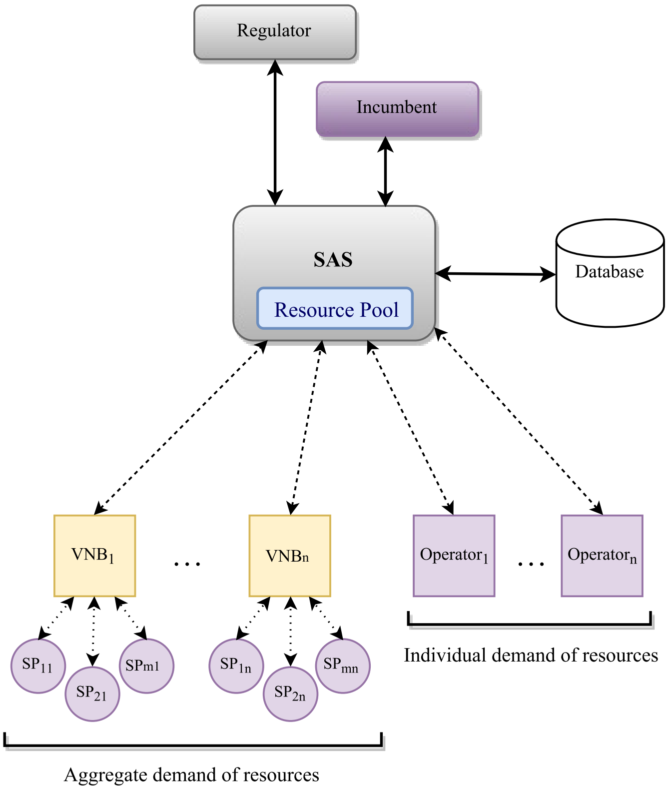

Figure 3. Virtual Network Builders as part of the sharing scheme in the 3.5 GHz band

4.3. Global Approach

This is a more complex arrangement that targets at adding flexibility to the network and increasing the access opportunities for the service providers. In this scheme, we envision the resources of the 3.5GHz band as *one* of the multiple inputs to the resource pool. Indeed, we expect the pool to be also formed by licensed and unlicensed bands shared by resource providers. In this way, this heterogeneous pool would represent increased alternatives for the VNB to aggregate resources and thus satisfy the service requirements of a larger range of SPs. This model follows the proposal presented in [12]; hence an additional objective is to facilitate the creation of service-driven networks.

The changes in the architecture under the global approach are shown in Figure 4. Note that the VNBs still need to negotiate with the SAS for access to the 3.5GHz band.

The virtualization process in this scenario would be complete when we envision the pool as a set of spectrum

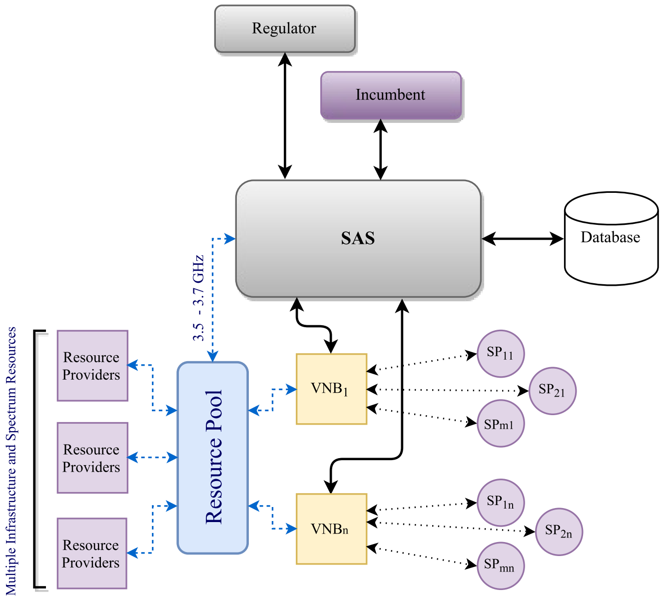

Figure 4. Generalized approach for sharing and virtualization.

and infrastructure resources which can be seamlessly accessed by the RPs and SPs. For this purpose, through WNV, RPs could be utilizing the same infrastructure as the one they are making available in the pool, just on different virtual slices/partitions. If virtualization is properly deployed, we could fully exploit the pooled resources given that we would have the illusion of higher *virtual* availability while preserving the fixed *physical* resources.

The VNB would be in charge of aggregating resources upon SPs' demand, which will in turn depend on the specific service that each SP intends to provide. Given the heterogeneity of the pooled resources, for aggregation purposes, the VNB can combine multiple frequencies, thus being able to create a *bundle* with specific capacity/rate characteristics. For instance, the pool could be formed by spectrum on the 3.5GHz band, LTE frequencies, 2.4GHz unlicensed spectrum. Given an SP with an specialized service that consists of the provision of video streaming to its end users, the duty of the VNB is to determine how many 3.5GHz, LTE and 2.4 GHz resource units should be combined (and in what proportions) in order to meet the SP's requirements. Note that for the creation of this multi-frequency bundle, we require the definition resource units in terms of parameters that would be common to all. For instance, we might define resources in terms of time-frequency units that specify their availability and service characteristics.

Note that at the basis we would still have physical resources, which are partitioned and assembled in different ways. Hence, we expect the SPs to be compatible and capable of using the resources offered by the VNB. One method to determine the suitability of resources is to evaluate their level of fungibility with the preferred resources of each SP [15].

Throughout the description of these approaches we have referred to *interactions* taking place between SPs and VNBs and VNBs and the resource pool. In what follows, we describe these interactions and the applicable methods.

4.4. Participants' Interactions

From the network model presented in 4.2, we infer that the main objective of the interactions among participants is to negotiate for resource access. Along these lines, we deem appropriate to consider a market mechanism in order to define these interactions and the final allocation of resources.

As previously stated, we find two instances where participants are likely to negotiate for resources: 1) Between SPs and VNBs and 2) Between VNBs and the Resource pool or Resource Providers.[2]

Figure 5 shows an overview of the expected interactions in each of the aforementioned settings.

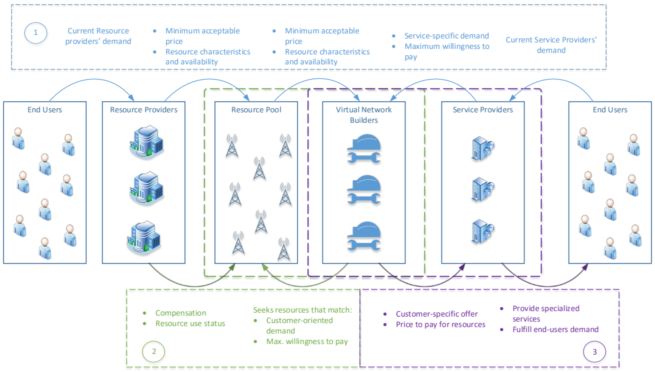

Figure 5. Interactions among network participants for obtaining resource access

As presented in [16], matching problems refer to those that involve "matching of the members of one group of agents with one or more members of a second, disjoint group of agents, all of whom have preferences over the possible resulting matches". The goal in this type of problems is to find a stable outcome, where there are no two agents that would prefer to be matched to each other rather than keeping their current matches. Given the characteristics of the network entities and the relationships/interactions we expect them to establish, we find it suitable to analyze them through the lenses of matching markets.

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[2] The interactions with the resource pool can be seen as indirect interactions with the Resource Providers as the latter are the owners or licensees of the available resources.

SP – VNB Interactions. We consider it appropriate to define this type of interactions as the formation of partnerships between SPs and VNBs. Along these lines, the specialized demand of each SP and the VNB requirements can be translated into sets of preferences. These preferences should serve to rank the members of the other set of possible partners and thus attempt to establish partnerships with the highest ranked ones. From the SPs perspective, the preferences may be defined in terms of the expected resources to obtain from a given VNB, the VNBs' reputation, their maximum willingness to pay and whether they are risk averse or prone. From the perspective of VNBs, their preferences may stem from the minimum payment they expect to receive, the expected partnership duration, the reputation of the SPs and their possibility to obtain an SP's required resources.

We contemplate the utilization of matching markets for carrying out the partnership formation process between these two entities. We find that the deferred acceptance algorithm proposed in [16] and extended to more complex settings in [17] can be adapted to the situation we study. In this way, each member of the SP set will propose a partnership to its preferred VNB. In turn, each VNB will evaluate its partnership proposals and temporarily accept the one that ranks highest in its own preference set. The SPs that have been rejected propose a partnership to the next VNB in their preference set. As expected, each VNB will choose their most preferred SP from its proposals. This process repeats until all SPs have been matched to a VNB, or until those without a match have been rejected by every VNB in their preference set. Note that some SPs may prefer to remain unmatched rather than forming a partnership that is unprofitable.

The problem of matching markets for spectrum sharing is explored in [18]. In this work, we consider a "many-to-one" matching process between VNBs and SPs, which means that an SP can form a partnership with only one VNB, while a VNB can form a partnership with as many SPs as present in the market. Additionally, we focus on providing an overview of the multiple factors that would play a role in this matching process. Hence, the results show the influence of the VNBs' reputation in the resulting number of partnerships. In turn, under the set of preferences studied, we evaluate the percentage of the overall geographic demand that is covered through the resulting partnerships. This process sheds light on how a matching model could alleviate some of the complexity stemming from spectrum sharing arrangements.

Figure 6 depicts a general overview of the partnership formation process between SPs and VNBs.

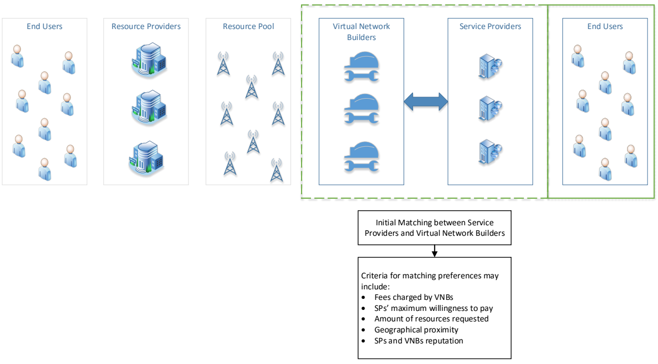

Figure 6. Matching process between VNBs and SPs

VNB – Resource Pool Interactions. Once the set of VNB – SP partnerships have been defined, each VNB needs to obtain an appropriate bundle of resources from the pool. These resources correspond to the aggregate demand of all the partners of a given VNB. In order to reflect the influence of pricing mechanisms and to ensure that spectrum resources are assigned to those users who value them most, we consider a simple auction mechanism to carry out the VNB – RP interactions. This approach does not drive us far apart from the matching concept. As presented by Roth in [19], auctions are matching markets where preferences are defined in terms of prices, and the latter determine who obtains the resources[3].

The specific process we propose for this set of interactions is portrayed in figure 7. This approach follows the model presented in [21].

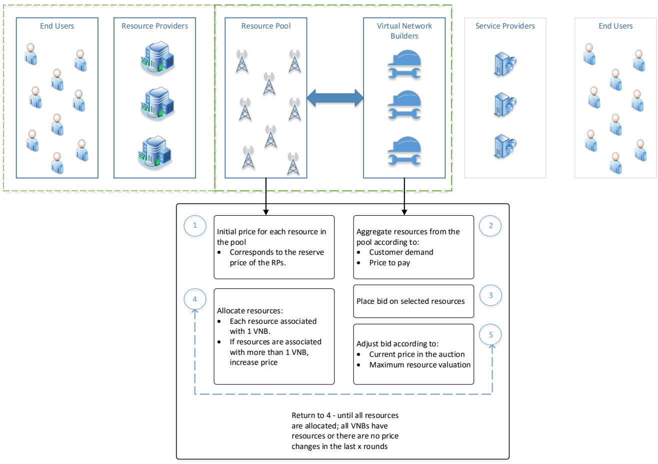

Figure 7. VNBs' interactions with the pool to aggregate resources and gain access.

Feedback Mechanism. For this approach to function properly, we consider it important to include a feedback

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[3] A more detailed description of these interactions within a more general spectrum sharing context can be found in [20]

mechanism which permits every participant to adjust their preferences and advertised parameters. These updates allow the market participants to become more competitive in the market and minimize their losses. In the particular case of VNBs, past performance is crucial for developing a meaningful reputation mechanism, which would also have an impact on the VNBs that an SP may prefer.

Interaction with the SAS. The interactions previously describe account for the market between RPs, VNBs and SPs. Nevertheless, it is important to remember that if a VNB assigns resources belonging to the 3.5 GHz – 3.7 GHz band, it should still register these assignments with the SAS database. In this way, we would have only a few entities (i.e., the VNBs) reporting the usage of a larger number of SPs, which may minimize the number of transactions required to fulfill this registration process.

5. An EconomicsFramework

The definition of participants' interactions is framed within markets concepts which account for part of the economics framework definition of our proposal. In this section, we extend this framework and present additional concepts which permit to provide an appropriate context for our sharing scheme.

5.1. The Innovative Architecture from an Economics Perspective

Innovation has driven significant changes, not only in the technological field, but also on the markets developed to sustain and spread that innovation. In order to place our virtualization ideas within the appropriate context, we point out some significant similarities between our study and the work developed by Hagel and Seeley-Brown in [22].

From the various proposals presented in [22], we find an important similarity between our virtualized approaches and the concept of reverse markets. In such markets, customers can seek the greatest possible value from a broad set of providers which are available at an appropriate time and place. Reverse markets have further led to the design of *process networks*, which are in charge of mobilizing "highly specialized companies across more than one level of an extended business process"[22]. Process networks adopt a *pull* model "where resources are flexibly provided in response to a specific market demand"[22]. When the network needs cannot be easily determined in advance, operators and providers could create platforms permitting them to mobilize their resources readily. This model further suggests a different means to deal with uncertainty given that it can "help people come together and innovate by drawing on a growing array of specialized and distributed resources" [23]. In this light, the ultimate benefit from process networks and pull systems, in terms of uncertainty, would be the possibility of not seeing it as a threat, but as an opportunity to innovate[23].

In this context, we could also associate the characteristics of the VNB with that of a *process orchestrator*, which is an entity in charge of organizing and managing process networks. Some of its duties include determining the eligibility of an entity to participate in the process network; defining the role of each participant in particular process implementation and ensuring that each participant performs as expected and is rewarded accordingly [22]. The orchestrators should focus on expanding the range of participants and creating strong relationships among them. In this way, more specialized skills are accessible, and at the same time, the collaborating parties can build their capabilities faster[23].

To summarize, the local and global models we present in this work adapt to the pull system studied in[22], given that it explores the possibility of generating supply from the aggregation of (specialized) resources belonging to different entities. Additionally, it aims at managing local resource assignment by means of a general orchestrator, which in our models corresponds to the Virtual Network Builder. Since we are dealing with a framework in which different entities (SPs) are providing a service with the aggregation of resources belonging to other operators (RPs), we envision a service-based type of competition. In this way, it is important to shed some light on the nuances, opportunities and challenges of switching from a traditional facility-based competition to service-based competition.

5.2. Facility-based vs. Service-based competition

When we analyze facility (or infrastructure)-based competition and contrast it with service-based competition, we are not facing a "black or white" type of situation. Instead, we find a wide range of possibilities and arrangements between these two poles. This has important implications in terms of the complexity of the strategies adopted by incumbents and entrants and the regulatory schemes that are optimal.

At the core of these competition decisions, we have a set of trade-offs that incumbents and entrants should take into account. Indeed, each user will decide to enter in either arrangement depending on the level of profitability that it represents. For instance, incumbents should evaluate the benefit from investing in their own infrastructure and sharing it with new entrants versus the possible threat of competing with new market entrants who possess their own market infrastructure. New entrants, on the other hand, should determine how limited their competitiveness will be in the market if they are subject to the lease arrangements provided by the incumbents, and at the same time, they should contrast those limitations with the investment required for deploying their own infrastructure (i.e., opportunity cost of technology adoption)[24, 25].

Referring to a traditional view of networks, we find that it widely favors facility-based competition and sees service-based competition as the stepping stone for the rise of the first. Nevertheless, if we adopt the process networks perspective presented in subsection 5.1, we could envision models and systems that successfully operate under service-based competition. Furthermore, when adapting our virtualization considerations, a wider array of resource usage models can be considered, which not only represents additional service opportunities for the new entrants, but also decreases the threat that these users can pose to the incumbents, e.g., threat caused by new entrants providing the same service as the incumbent. Moreover, the aggregation and assignment activities of the VNB could make the negotiation process easier for entrants and incumbents, thus reducing the associated costs. In this way, we would obtain positive conditions for a successful switch toward service-based competition.

5.3. Value Chains vs. Value Networks

According to [12], "[t]he value chain includes all the activities that exist as a direct result of usage of the cellular network. The purpose of creating the chain is to understand where the costs are incurred and the revenue is generated". Generally, a value chain is associated with a particular network operator or incumbent, and it will help to determine the activities that will be more profitable. Due to the significant changes in spectrum sharing arrangements, technology use and service availability, we can expect that the traditional value chain will shift to new perspectives in which, not only an incumbent's view on how to derive value from its resources and make profits is considered; instead, we might be interested in a new approach which encompasses the interactions of multiple users for generating valued services.

We have already evidenced examples that portray significant changes in the structure of value chains, such as the appearance of MVNOs, the evolution of Wi-Fi which has turned its hotspots into important complements of regular mobile networks, and also the creation of over-the-top services. From these examples, one can notice that different parts of the value chain that generate revenue, can be actually controlled by entities different from those that have deployed and control the parts associated with the highest costs [12]. In this way, as value chains continue to evolve, it is possible to observe how various value chains become intertwined for the creation of more complex networks where different entities are simultaneously involved in more than one value chain. We can refer to these as *value networks*.

A value network presents multiple entry and exit points, which increase the complexity of operations for all the members involved[26]. Additionally, it is expected that this network will be formed by "different actors drawn form a range of industries that collectively provide goods and services to the end users"[26]. For this purpose, these industries should show a higher level of specialization in particular activities, instead of managing the overall production of services. Furthermore, the companies involved are expected to dynamically evolve and perhaps specialize and gain expertise in additional areas. Hence, for the final service provision, relationships among multiple, specialized companies should be established[26].

This new notion of specialization and interaction among entities, calls for the modification of the boundaries of a company, which is evidently accompanied by a corresponding trade-off: value of specialization versus the transaction costs associated with external suppliers [26]. In this light, for setting their boundaries, firms should consider a balance between facing low transaction costs from internal production of services, hence lower agency costs, and the economies of scale derived from obtaining resources from external entities[26].

Ultimately, the interaction of multiple users proposed by the value network approach permits us to study a firm's relationship with other network members and thus understand where value lies in the network and how it is created by multiple parties; how the activities of a firm will affect the network and how other members are likely to respond [27].

From the concepts presented in this section, we can find the relationship between value networks and process networks, which are illustrated in Figure 8. Both mechanisms envision the aggregation of specialized entities to provide valued services, targeting at the deployment of service-driven networks and the accompanying type of competition.

6. Putting things together

Analyzing the network presented in figure 4, as a whole, we can point out important details that map to the concepts presented throughout this paper.

The entities in this network may have different degrees of specialization in multiple areas. In turn, these entities share their resources with others, thus promoting the development and provision of additional, perhaps more specialized services. This creates intertwined value chains as there is greater value extracted from a set of resources initially owned and used by a reduced group of incumbents or RPs.

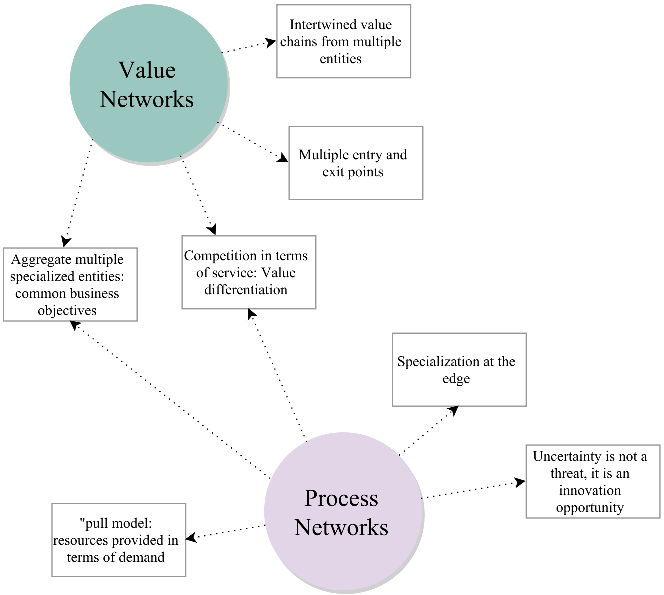

Figure 8. Similarities between Process and Value Networks.

Additionally, this translates in a wider array of services provided throughout the network, which defines it as a service-based competition environment.

From the perspective of the RPs, there are increased opportunities for analyzing whether participation in the pool results in a profitable arrangement. This presents them with options to continue to participate, increase their participation or exit the network. The SPs at the other end of the network will generate a dynamic demand, dependent on the type of service that lies at the core of their business model. This represents less restrictions in terms of resource access and thus definition of the service to provide.

In a traditional system-based competition model, each SP would need to negotiate with every RP from which it requires resources. This is not a practical solution in terms of transaction costs, and possible restrictions in the establishment of leasing agreements with RPs. In the network we study, both RPs and SPs will negotiate resource access with a single entity: the VNB. In fact, the VNB will aggregate the required type and amount of resources based on the demand of the SPs, which is expected to be service-specific and dynamic. At the same time, the VNB should be in charge of providing the appropriate compensation to the RPs and/or negotiating with the SAS depending on the type of resources accessed.

Note that the flexible management of the resources belonging to the pool responds to the utilization of an enabling technology such as wireless network virtualization. In this way, the co-existence of multiple RPs and SPs would be ensured. It is evident that there is a greater degree of flexibility stemming from this network when compared with traditional system-based or facility-based competition arrangements. In the case of the latter, we can expect higher transaction costs associated with negotiations, given that specific leasing agreements should be developed among particular RPs and SPs, on a one-to-one basis. In the virtualized case, the negotiation is done through the VNB, which reduces the resulting overhead and allows for the seamless negotiation with multiple entities at a time. However, when designing the negotiation mechanisms between the VNBs and the SPs, we should take into account a framework that reduces agency costs, thus deterring strategic behaviors which could affect the overall welfare in the system.

7. Conclusions

We propose the incorporation of virtualization to the regulatory framework defined by the FCC for the 3.5GHz band and thus formulate a sharing proposal which encompasses the flexibility opportunities offered by them. The analysis we present does not reflect regulatory and technical considerations only, it also explores economic factors that play a key role for the deployment of successful sharing models.

The studied fields pose important challenges and opportunities for the sharing model we devise. In this way, we have been able to find some benefits that could stem from embedding virtualization as the technical enabler for sharing approaches. Indeed, virtualization would permit to add technical flexibility to the network, which is required to accomplish the regulatory flexibility that the current regulation seeks. By means of this technology, resources with distinct physical characteristics and ownership can be pooled and made available, in a seamless manner, to a larger number of providers.

We have pointed out how the addition of a new entity, the Virtual Network Builder, could allow for the distribution of the functionality that has been assigned entirely to the SAS. Furthermore, the VNB could act as a facilitator of the negotiations between RPs and SPs. In this way, it is likely that smaller entrants will have higher opportunities to access spectrum. This results from having a VNB in charge of aggregating the demand from multiple users and negotiating for spectrum access. In this way, the VNBs could be better competitors in the market than smaller entities alone, and their possibilities to obtain resources may be significantly enhanced.

In the economics context, we found significant similarities between the characteristics and objectives of process networks and those of value networks. When adapting these concepts to our model, we expect virtualization to allow for a seamless aggregation of resources from multiple entities thus permitting to exploit the specialization of network entities at their edge. This would provide an avenue for achieving common or service-differentiated business objectives, which could lead to appealing service-based competition opportunities taking place in current telecommunications market scenarios. Overall, our analyzed framework suggests that in an environment where multiple users with varied levels and areas of specialization come together to innovate, we could actually derive opportunities instead of threats from the uncertainty of sharing.

8. Future Work

In our efforts to extend our work, we consider it important to delve into details regarding how rights are adapted to these novel sharing schemes and, how social concepts and constructs influence the deployment of accurate models. Following the study presented in [28], we expect bundles of rights to be redefined in virtualized scenarios, which will in turn have a significant impact on the model design, outcomes and evaluation.

From a social perspective, our analysis of process and value networks has shed light on the interaction of multiple entities in order to achieve common and service-differentiated business objectives. In turn, these entities will be sharing assets, which could be mapped to the *common-pool resource* definition. [4] Keeping this in mind, and as explored by Ostrom in [29], we could expect *collective-action problems* to arise under our virtualization scenarios. As pointed out by Ostrom, a possible solution is the adoption of polycentric governance approaches, which implies the development of systems of governmental and non-governmental organizations working at multiple scales. The authors in [14] have already explored the inclusion of CPR concepts and polycentric governance to the design of the SAS and how this would help define facilitating conditions for the development of successful systems. In this way, we consider that analyzing CPR and Polycentric governance notions would provide us with a richer view on how to design our virtualization system.

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[4] According to [29], "[c]ommon-pool resources are systems that generate finite quantities of resource units so that one person's use does subtract from the quantity of resource units available to others. Most common-pool resources are sufficiently large that multiple actors can simultaneously use the resource system and efforts to exclude potential beneficiaries are costly".

References

[1] Leibovitz, J. (2015), Breaking down barriers to innovation in the 3.5 ghz band. URL https://www.fcc.gov/blog/breaking-down-barriers-innovation-35-ghz-band.

[2] Commission, T.F.C. (2015), Report and order and second further notice of proposed rulemaking. in the matter of the commission's rules with regard to commercial operations in the 3550 - 3650 mhz band. URL https://apps.fcc.gov/edocs_public/attachmatch/FCC-15-47A1.pdf.

[3] Marshall, P., Spectrum access system: Managing three tiers of users in the 3550 - 3700 mhz band. URL http://wireless.fcc.gov/workshops/sas_01-14-2014/panel-1/Marshall-Google.pdf.

[4] Wang, A., Iyer, M., Dutta, R., Rouskas, G.N. and Baldine, I. (2013) Network virtualization: Technologies, perspectives, and frontiers. *Lightwave Technology, Journal of* **31**(4): 523–537.

[5] Wen, H., Tiwary, P.K. and Le-Ngoc, T. (2013) *Wireless Virtualization* (Springer).

[6] Zaki, Y., Zhao, L., Goerg, C. and Timm-Giel, A. (2011) Lte mobile network virtualization. *Mobile Networks and Applications* **16**(4): 424–432.

[7] Panchal, Jignesh S., R.Y. and Buddhikot, M.M. (2013) Mobile network resource sharing options: Performance comparisons. *Wireless Communications, IEEE Transactions on* **12**(9): 4470–4482.

[8] Gomez, M.M., Cui, L. and Weiss, M.B.H. (2014) Trading wireless capacity through spectrum virtualization using lte-a. *TPRC Conference Paper* .

[9] Forde, T.K., Macaluso, I. and Doyle, L.E. (2011) Exclusive sharing and virtualization of the cellular network. *New Frontiers in Dynamic Spectrum Access Networks (DySPAN), 2011 IEEE Symposium on.* .

[10] Forde, T. and Doyle, L.E. (2013) Cellular clouds. *Telecommunications Policy* **37**(2-3): 194–207.

[11] Weiss, T.A. and Jondral., F.K. (2004) Spectrum pooling: an innovative strategy for the enhancement of spectrum efficiency. *IEEE Communications Magazine* **42**(3): S8–14.

[12] Doyle, L., Kibilda, J., Forde, T.K. and DaSilva, L. (2014) Spectrum without bounds, networks without borders. *Proceedings of the IEEE* **102**(3): 351–365.

[13] Hua, S., Liu, P. and Panwar, S.S. (2012) The urge to merge: When cellular service providers pool capacity. *IEEE International Conference on Communications* .

[14] Weiss, M.B., Lehr, W., Acker, A. and Gomez, M.M. ((forthcoming)) Socio-technical considerations for spectrum acess system (sas) design. In *Dynamic Spectrum Access Networks (DYSPAN), IEEE International Symposium on.*

[15] Gomez, M.M. and Weiss, M.B. (2013) How do limitations in spectrum fungibility impact spectrum trading? *Telecommunications Policy Research Conference* .

[16] Gale, D. and Shapley, L.S. (1962) College admissions and the stability of marriage. *The American Mathematical Monthly* **69**(1): 9–15.

[17] Sotomayor, M. (1992) The multiple partners game. In Majumdar, M. [ed.] *Equilibrium and Dynamics* (Springer), 322–354.

[18] Gomez, M.M., Weiss, M.B., McHenry, G. and Doyle, L. (2017) Matching markets for spectrum sharing. *TPRC Conference Paper* URL https://ssrn.com/abstract=2944197.

[19] Roth, A.E. (2015) *Who Gets What and Why* (Houghton Mifflin Harcourt Publishing Company).

[20] Gomez, M.M. (2017) *Secondary Spectrum Markets: from 'Naked' Spectrum to Virtualized Commodities*. Ph.D. thesis, University of Pittsburgh.

[21] Roth, A.E. and Sotomayor, M.A.O. (1992) *Two-sided matching: A study in game-theoretic modeling and analysis*, 18 (Cambridge University Press).

[22] Hagel, J. and Brown, J.S. (2005) *The Only Sustainable Edge: Why business strategy depends on productive friction and dynamic specialization* (Harvard Business Press).

[23] Brown, J.S. and Hagel, J. (2005) The next frontier of innovation. *McKinsey Quarterly* (3): 82–91.

[24] Baranes, E. and Marc, B. (2005) An economist's guide to local loop unbundling. *Communications & Strategies* (57): 13.

[25] Bourreau, M. and Doğan, P. (2004) Service-based vs. facility-based competition in local access networks. *Information Economics and Policy* **16**(2): 287–306.

[26] Li, F. and Whalley, J. (2002) Deconstruction of the telecommunications industry: from value chains to value networks. *Telecommunications Policy* **26**(9): 451–472.

[27] Peppard, J. and Rylander, A. (2006) From value chain to value network:: Insights for mobile operators. *European Management Journal* **24**(2): 128–141.

[28] Cui, L., Gomez, M.M. and Weiss, M.B. (2014) Dimensions of cooperative spectrum sharing: Rights and enforcement. *New Frontiers in Dynamic Spectrum Access Networks (DySPAN)* .

[29] Ostrom, E. (2008) Polycentric systems as one approach for solving collective-action problems. *Indiana University, Bloomington: School of Public & Environmental Affairs Research Paper* (2008-11): 02.