Matching Markets for Spectrum Sharing

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Abstract—**Next generation networks are designed to improve connectivity and capacity, adding to the current range of available services and expanding their reachability. For these systems to work, they need to be compatible with legacy technologies in addition to making use of (limited) available spectrum resources. This is one of the reasons why spectrum sharing has been at the forefront of the list of enablers for such systems. From federal-commercial sharing to finding opportunities in millimeter-wave spectrum, we have witnessed the formulation of multiple approaches to making spectrum sharing happen.**

Existing work on spectrum sharing is wide ranging and includes technical as well as market-based approaches. The study of spectrum markets is of particular interest, as it merges a market approach with the technical limitations inherent to electromagnetic spectrum. In this manner, spectrum markets settings have called for different definitions of spectrum-related resources as a means to increase market thickness and thus improve the opportunities for market success. In a similar vein, we find proposals of network models which aim at adapting technical definitions of spectrum resources, such as those that are the product of virtualization. In this work, we adopt a market perspective for spectrum sharing within the context of more comprehensive network definitions such as those envisioned for next generation networks. To this end, we explore matching market concepts and middleman theory in order to shed light on factors that may impact the performance and, ultimately, the success of spectrum markets.

I. INTRODUCTION

Many solutions have been developed to promote efficiency in the utilization of spectrum resources. Technical approaches deal with the complexity of defining spectrum due to its multidimensionality [1] and variability. At the same time, market approaches for the assignment of spectrum, mainly pointing to the utilization of auctions, grow in complexity as we attempt to provide a spectrum marketplace where buyers can place expressive bids.

In past work, we have focused on the study of what renders secondary spectrum markets viable [2], [3]. Particularly, in [3], we point out that homogeneous commodities are key for adding thickness to the market, and hence improving the conditions that lead to viable market scenarios. In that work, homogeneous commodities are defined by taking into account virtualization and LTE-A characteristics.

As a means to further spectrum markets research, we find it important to explore them within a network context that may resemble that of next-generation networks. To this end, we build upon the network definition presented in [4] and, utilizing Agent-based Modeling, we study the possible behavior of agents and the factors leading to the development of viable spectrum markets.

The objective of this work is to study a network where virtualized spectrum resources can be traded. In this way, we detach ourselves from a standalone market analysis, and look at the broader context in which markets may operate. This calls for exploring economics factors that drive agents' participation in the market, how the existing demand can be managed and how this may point to the final profit obtained from market transactions. In this paper, we explore the general definition of such a network and we describe the interactions that take place among the market participants in order to define the market demand. We utilize matching markets concepts and middleman theory in order to delve into demand-generating interactions. We consider this step to be crucial towards dealing with market congestion and providing better spectrum access opportunities.

This paper is organized as follows: section II provides a detailed description of the model that we have developed for this study; section III presents the factors taken into account for our experiment design; section IV presents the results obtained through agent-based model simulations; section V elaborates on the implications of our model and results, and in section VI we present our concluding remarks and future work.

II. MODEL DESCRIPTION

One of the main objectives of this work is to analyze markets as entities that operate within a communications network, instead of looking at them as standalone institutions. For this purpose, we work with a model definition that accounts for multiple market participants, and which provides us with enough flexibility to adapt to network scenarios of interest.

A. General Model Overview

The particular network model we build upon is that introduced by Doyle et al. in [4]. This framework envisions heterogeneous physical networks that collaborate through virtualization to provide a consistent service to end users. Such an approach suggests three main participating entities: Resource Providers, Virtual Network Builders and Service Providers.

- Resource providers (RPs) are current resource owners who may be interested in making their resources available for resale in the market.

- Service providers (SPs) are new market entrants, or existing providers, who require additional resources to fulfill the demand of their own end users.
- Virtual Network Builders (VNBs) act as a brokers or middlemen. As such, they are in charge of aggregating resources from the pool and assigning them to the SPs who are requesting them.

Figure 1 illustrates the workings of this model. As shown, this model considers two important parts: (1) defining and generating the market demand, and (2) fulfilling that demand, using pooled resources. In this work, we address the first part of this model. We envision this process as a *partnership forming* stage between SPs and VNBs, akin to customer – broker (i.e., middleman) relationships that we form in real life. Indeed, inspired by real-life examples, we delve into what drives these relationships and extrapolate these characteristics to a spectrum market scenario.

The characteristics of VNBs as middlemen are detailed in subsection II-B and the specifics of the model we have developed are presented in subsection II-C

B. Virtual Network Builders as Middlemen

One of the tasks assigned to VNBs in our model is that of analyzing the resources available in the common resource pool. Heterogeneous pooled resources may cause this task to be significantly complex, as VNBs need to aggregate resources in a manner that satisfies the requirements of their SP customers.

As complex as the resource aggregation task may be, it is not the only aspect associated with the functions of middlemen in our model. In [5], the author provides a thorough analysis of the different tasks that middlemen fulfill and divides them into six categories. In what follows, we explore the categories that apply to the workings of the VNBs in our network model.

- **Bridge:** Reduces the "physical, social, or temporal distance" between buyers and sellers. In this way, this type of middleman is able to find opportunities between two disconnected sets of participants.
- **Insulator**: Limits the information flow between buyers and sellers, or in this particular case between RPs and SPs.
- **Certifier:** Provides value for both, buyers and sellers, by screening available options, scouting for the requirements of buyers and endorsing its findings through their own reputation. In this manner, the middleman reduces the asymmetry of information between buyers and sellers.
- **Enforcer:** Makes sure that the buyers and sellers (i.e., RPs and SPs) are not failing to provide the service or utilize the resources as convened.
- **Risk bearer:** Reduces uncertainty for both negotiating parties. In fact, "[b]y building diversified portfolios, [these middlemen] are better able to weather volatility than their trading partners"[5].

Additionally, in the particular case of resource access, middlemen can minimize the *intellectual* barriers posed by the knowledge required in order to successfully obtain resources from an auction. This includes appropriately expressing resource needs, and remaining updated on how to remain competitive in an auction.

C. Defining and Generating Market Demand via Matching

As previously mentioned, the first stage of our model consists of developing a mechanism that defines and generates the market demand. To this end, we need to consider a portion of the existing, geographical demand and convert it into the demand that will be satisfied using pooled resources. To this end, we consider a partnership-forming process between VNBs and SPs. In what follows, we delve into the details behind this matching process [1].

Let $\mathcal{S} = \{s_1, s_2, ...s_n\}$ be the set of n participating SPs and $\mathcal{B} = \{b_1, b_2, ...b_m\}$ the set of m participating VNBs. Each of the agents in $\mathcal{S}$ and $\mathcal{B}$ are assigned a risk profile, which guides the values they assign to their own parameters and the preferences they express with regards to the members of the other set. For this purpose, we assign to all $s \in \mathcal{S}$ and all $b \in \mathcal{B}$, a risk value defined as $rv = U(0, 2)$. In this way, the variable rv takes a uniformly distributed integer in the range [0,2]. Consequently, the risk profile of s_i and b_j is assigned as follows:

$$riskProfile(rv) = \begin{cases} \text{averse} & \text{if } rv = 0 \\ \text{neutral} & \text{if } rv = 1 \\ \text{taker} & \text{if } rv = 2 \end{cases} \tag{1}$$

1) Configure real and advertised SPs' and VNBs' fees: Each SP and VNB have real values of their willingness to pay for a service and the minimum fee required to operate, respectively. Nevertheless, these real values do not necessarily match the fees and values they advertise in the market. In this subsection, we present how these parameters have been defined in our model.

a) Service Providers: Each SP has a *real* and an *advertised* value regarding their willingness to pay for the service of a VNB. The real valuation of an SP can be translated into a measure of how interested is an SP in transacting with a VNB. To capture this, we assign a level of valuation for each SP in the system, which is a uniformly distributed integer in the range [0,2].

$$vl_i = U(0, 2) \quad \forall i \in S$$

In this way, the valuation level of s_i is finally assigned as follows:

$$valuationLevel(vl_i) = \begin{cases} \text{low} & \text{if } vl_i = 0 \\ \text{medium} & \text{if } vl_i = 1 \\ \text{high} & \text{if } vl_i = 2 \end{cases} \tag{2}$$

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[1] To maintain the tractability of the model, we utilize a uniform distribution for assigning parameter levels (e.g., risk, valuation, shading) and values (e.g, price assigned, demand levels) associated with the SPs' and VNBs' activities.

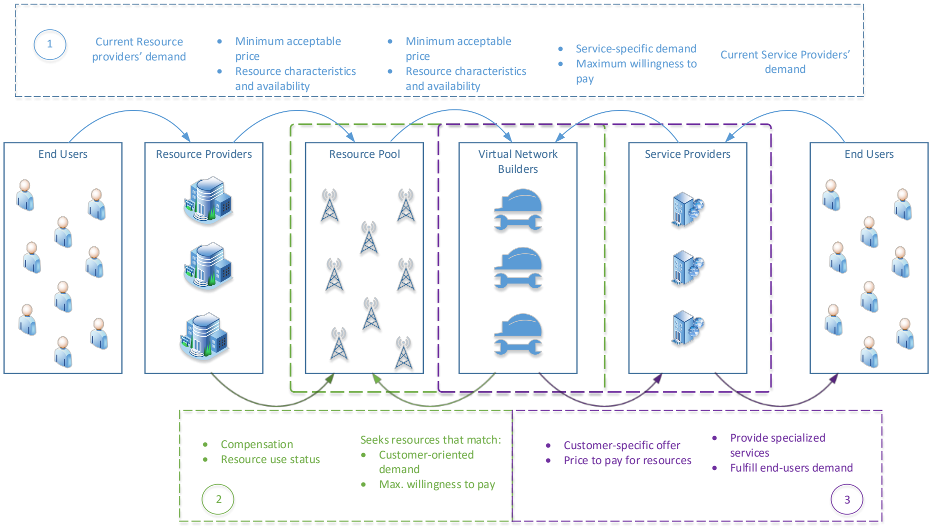

Fig. 1. General Network Interactions

We assume that there is a minimum price (reserve price) advertised in the system for the revenue expected by a VNB and also a maximum, known, price that any VNB can charge. In this way, we work with a range of prices that will be chosen by s_i according to its valuation level vl_i. These fee thresholds are included in Table I.

Valuation Level (vl_i)	**Real Fee Range**
0	$p_i = U(p_{min}, p_{med})$
1	$p_i = U(p_{med}, p_h)$
2	$p_i = U(p_h, p_{max})$

TABLE I
VNB FEE RANGE ACCORDING TO SPS’ VALUATION LEVEL

The limits utilized for the different fee levels are the following:

$$p_{min} = 25 \tag{3}$$

$$p_{max} = 100 \tag{4}$$

$$p_{med} = \frac{p_{max} + 2 \times p_{min}}{3} \tag{5}$$

$$p_h = \frac{2 \times p_{max} + p_{min}}{3} \tag{6}$$

The fee *advertised* by each SP, on the other hand, depends on its risk profile. As such, these prices include a level of *shading*, which is consistent with the risk a given SP is willing to take. Table II shows the three levels of price shading that have been defined.

Risk Level	**Price Shading**
Taker	$d_r = d_A = U(0.10, 0.15)$
Neutral	$d_r = d_N = U(0.05, 0.10)$
Averse	$d_r = d_P = U(0, 0.05)$

TABLE II
PERCENTAGE OF PRICE SHADING ACCORDING TO EACH SP’S RISK LEVEL

We assume that a risk averse SP is interested in maximizing its chances of matching; hence, its shading level is low.

Taking into account the price shading levels, d_r, in Table II, the advertised prices are defined according to (7). This definition applies to all $i \in \mathcal{S}$.

$$advPrice_i = (1 - d_r) \times p_i \tag{7}$$

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To translate all the valuation and fees information into preference sets, we have mapped the fees advertised by SPs to specific *price levels*. These levels are defined according to the ranges included in Table III.

Price Level	**Price Advertised**
0	$p_{med} > advPrice_i \geq p_{min}$
1	$p_h > advPrice_i \geq p_{med}$
2	$p_{max} > advPrice_i \geq p_h$

TABLE III
PRICE LEVELS ASSIGNED ACCORDING TO RANGE OF PRICES ADVERTISED BY s_i

b) Virtual Network Builders: Similarly to SPs, each VNB also defines *real* and *advertised* fees. In this case, fees refer to the minimum payment that a VNB requires to fulfill its services.

The real fee a VNB can charge is limited by its quality or reputation. To bootstrap the market, the quality level of b_j, ql_j, is randomly assigned following (8)[2].

$$ql_j = U(0, 2) \tag{8}$$

In this way, the final quality, q_j, of b_j stems from its own quality level, as expressed by (9). In consequence, we expect a higher quality VNB to charge higher fees for its services.

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[2] We expect to incorporate a reputation building mechanism based on the performance history of b_j in future versions of this work.

Quality Level	Real fee of b_j
0	$f_j = U(f_{min}, f_{med})$
1	$f_j = U(f_{med}, f_h)$
2	$f_j = U(f_h, f_{max})$

TABLE IV
REAL FEE OF A VNB ACCORDING TO ITS QUALITY (OR REPUTATION) LEVEL

The actual fee assigned by each VNB falls within the range specified in Table IV for each quality level.

$$q_j(ql_j) = \begin{cases} \text{low} & \text{if } ql_j = 0 \\ \text{medium} & \text{if } ql_j = 1 \\ \text{high} & \text{if } ql_j = 2 \end{cases} \tag{9}$$

The limits utilized for the fee ranges included in Table IV are defined as follows:

$$f_{min} = 25 \tag{10}$$

$$f_{max} = 100 \tag{11}$$

$$f_{med} = \frac{f_{max} + 2 \times f_{min}}{3} \tag{12}$$

$$f_h = \frac{2 \times f_{max} + f_{min}}{3} \tag{13}$$

VNBs' *advertised* fees result from different levels of fee shading, which are consistent with the risk level of each VNB. In this way, the advertised fees include a percentage increase on a VNB's real fee. The range for this percentage increase is presented in Table V.

Risk Level	% of Fee Increase
Taker	$i_r = i_A = U(0.10, 0.15)$
Neutral	$i_r = i_N = U(0.05, 0.10)$
Averse	$i_r = i_P = U(0, 0.05)$

TABLE V
PERCENTAGE OF FEE INCREASE ACCORDING TO EACH VNB'S RISK PROFILE

As shown in Table V, we assume that risk averse VNBs' shading level is low, as substantial price increases may reduce their matching opportunities. The final fee advertised by b_j, $advFee_j$, is given by (14). Each VNB is then assigned a *fee level* depending on the range in which its advertised fee falls. The fee levels and their corresponding ranges are included in Table VI.

$$advFee_j = (1 + i_r) \times f_j \tag{14}$$

Fee Level	Fee Advertised
0	$f_{med} > advFee_j \geq f_{min}$
1	$f_h > advFee_j \geq f_{med}$
2	$f_{max} > advFee_j \geq f_h$

TABLE VI
VNBS' FEE LEVEL ACCORDING TO THE RANGE OF THE ADVERTISED FEES

2) Service Providers' Demand or Geographical Demand: Considering there are o end users in the network, each one of them is randomly set as a customer of one of the existing SPs. For this purpose, each end user is assigned a uniformly distributed random integer between 1 and the number of SPs. This number corresponds to the ID of the SP that will be serving this particular end user. In consequence, the traffic that each SP needs to serve will be the aggregate of the demand of its p end users. This is defined by (15), where t_{ij} is the traffic of end user u_{ip}, and u_{ij} is the j-th user of s_i.

$$T_i = \sum_{j=1}^{p} t_{ij} \tag{15}$$

The actual traffic of each end user is defined as an exponentially distributed random number with mean tm. In current tests of the model, we use the value $tm = 4.0$Mbps

The geographical demand accounts for all the traffic that SPs are not able to cover with the resources they currently own. Indeed, it results from comparing an SPs' coverable traffic to its traffic to serve. The coverable traffic of s_i, Tc_i, is defined in (16), where rsc_i is the amount of resources already available to s_i and C is the capacity per resource.

$$Tc_i = rsc_i \times C \tag{16}$$

If the coverable traffic, Tc_i, is greater than the traffic to serve, the demand of s_i is zero. Otherwise, the geographical *resource* demand of s_i is given by (17) and the geographical *throughput* demand of s_i is given by (18).

$$d_i = \frac{\lceil T_i - Tc_i \rceil}{C} \tag{17}$$

$$d_i = \lceil T_i - Tc_i \rceil \tag{18}$$

To adapt this values to the final preference vector, we have also classified the SPs' geographical demand into three levels. These levels are defined by expressions (19 – 22). Note that the maximum total demand or d_{max} refers to the case where an SP serves all the end users in the area, i.e., o end users, and each end user has a traffic demand equal to the average t_m. Table VII further illustrates how the demand of s_i is classified into multiple levels.

$$d_{min} = 0 \tag{19}$$

$$d_{max} = o \times t_m \tag{20}$$

$$d_{med} = \frac{d_{max} + 2 \times d_{min}}{3} \tag{21}$$

$$d_h = \frac{2 \times d_{max} + d_{min}}{3} \tag{22}$$

3) Choices and Preferences of VNBs and SPs: This model considers a set of choices and preferences for s_i and b_j, for all $i \in S$ and $j \in B$, respectively. In what follows, I refer to how the values for these parameters have been assigned and how they account toward defining the final preference vectors of SPs and VNBs.

Demand Level	Demand Range
0	$0 \leq d_i < d_{med}$
1	$d_{med} \leq d_i < d_h$
2	$d_h \leq d_i < d_{max}$

TABLE VII
SPS' DEMAND LEVELS ACCORDING TO THE RANGE OF THEIR DEMAND VALUE

a) Choices of SPs: Choice parameters are associated with the activities of SPs and their operational requirements. Indeed, choices reflect the values that SPs choose to advertise based on their risk profile and valuation levels. In this way, SPs express their choices in terms of:

- **Price:** defined according to the advertised price levels presented in Table III.
- **Demand:** defined according to the demand levels included in Table VII.

These parameters take integer values between 0 and 2, which stand for low, medium and high levels, respectively. In order to manage these parameters, we have represented the value level associated with each parameter as a 1×3 vector where the kth element can take a value of 0 or 1, depending on whether the value corresponds to a low, medium or high level (23). These vectors are pv_i and dv_i for price value and demand value, respectively.

$$\text{level vector} = [L, M, H] \tag{23}$$

$$\text{low level} = level0 = [1, 0, 0] \tag{24}$$

$$\text{medium level} = level1 = [0, 1, 0] \tag{25}$$

$$\text{high level} = level2 = [0, 0, 1] \tag{26}$$

b) Choices of VNBs: In a similar manner to the case of the SPs, the following parameters have been considered as relevant for the matching process between VNBs and SPs:

- **Quality:** As previously presented, the quality level or reputation is randomly assigned to each VNB in the initialization process.
- **Fees:** The fee level of each VNB is defined according to Table VI.

These parameters take integer values between 0 and 2, which stand for low, medium and high thresholds. These levels are also expressed as vectors, qv_j and fv_j for quality and fees, respectively (23).

c) Preferences of SPs: SPs express their preferences regarding the choices advertised by the VNBs. In this way, for our matching model, we consider the following VNB parameters:

- VNB reputation or quality
- VNB advertised fee

These preferences are expressed as vectors, which represent the preference for a low, medium or high value for each of the aforementioned parameters. Further, these preferences are linked to the risk profile of each SP, which justifies the preference level. In this manner, each preference vector, qp_i or pp_i, is a 1×3 vector, where the kth element is a binary value. The kth element is equal to 1 if s_i prefers that value level for a particular parameter. This is further illustrated in Table VIII.

Risk level of s_i	**Reputation/Quality Preference of s_i**	**Price Preference of s_i**
Averse	$qp_i = [0, 0, 1]$	$pp_i = [0, 0, 1]$
Neutral	$qp_i = [0, 1, 1]$	$pp_i = [0, 1, 1]$
Taker	$qp_i = [1, 1, 1]$	$pp_i = [1, 1, 1]$

TABLE VIII
SP PREFERENCE VECTORS ACCORDING TO RISK LEVEL

d) Preferences of VNBs: A VNB expresses its preferences regarding the choice parameters advertised by SPs:

- SPs' advertised fee
- SPs' demand level

In the same manner as the SPs' case, the value of these parameters is assigned according to the risk level of each VNB. The vector corresponding to each preference is presented in Table IX.

Risk level of b_j	**Price Preference of b_j**	**Demand Preference of b_j**
Averse	$pp_j = [1, 0, 0]$	$dp_j = [1, 0, 0]$
Neutral	$pp_j = [1, 1, 0]$	$dp_j = [1, 1, 0]$
Taker	$pp_j = [1, 1, 1]$	$dp_j = [1, 1, 1]$

TABLE IX
VNBS' PREFERENCE VECTORS ACCORDING TO THEIR RISK LEVEL

4) Comparing Preferences and Values: In order to create the matching preference vectors of each SP and VNB, we create a matrix for each of their preference parameters. In the case of the SPs, the ijth matrix element is the result of multiplying the preference vector of s_i times the transpose of the corresponding choice vector of b_j, as shown in expressions (27) and (28), which refer to SPs' quality and price matrices, respectively.

$$Q_s(i, j) = qp_i \times qv_j^T \tag{27}$$

$$R_s(i, j) = pp_i \times pv_j^T \tag{28}$$

For the VNBs, the ijth element of their preference matrices take into account the preferences of each VNB and the values assigned to the choice parameters advertised by SPs. Expressions (29) and (30) correspond to the VNBs' demand and price matrices, respectively.

$$D_b(i, j) = dv_i \times dp_j^T \tag{29}$$

$$R_b(i, j) = pv_i \times pp_j^T \tag{30}$$

5) SPs' and VNBs' utility: After defining the preference vectors, we find it appropriate to calculate the utility stemming from a matching between s_i and b_j. The idea behind defining this utility is for the SPs (VNBs) to find a subset of VNBs (SPs) that would be part of their final preference set. For this purpose, we propose to define weights that each SP and

VNB can assign to the different parameters that are being considered, according to how relevant these are for SPs' and VNBs' operations.

Weights are defined as uniformly distributed random numbers within a specific range, following expressions (31) and (32). This definition has been arbitrarily chosen to avoid increased complexity stemming from different weight distributions.

$$W_h = U(0.6, 1) \tag{31}$$

$$W_l = U(0.1, 0.5) \tag{32}$$

Given that each SP and VNB takes into account two parameters for forming their preference vectors, we have a final set of four different combinations of weights and parameters, as shown in Table X. The actual fashion in which an SP and a VNB choose the weight to assign is defined in section III, where we present our experiment design.

Quality / Demand	Price(VNB) / Price(SP)
H	H
H	L
L	H
L	L

TABLE X
WEIGHTS ASSIGNED TO SPS' AND VNBS' PREFERENCE PARAMETERS

The individual utility of each SP and VNB, i.e., the utility of a matching between s_i and b_j, is given by (33) and (34), where w_q and w_p are the weights assigned by s_i to the quality and price factors, and w_d and w_p are the weights assigned by b_j to the demand and price factors. These expressions show that the individual utility of SPs and VNBs stems from the sum of the weighted comparison between choices and preferences.

$$U_s(i,j) = w_q \times Q_s(i,j) + w_p \times R_s(i,j) \tag{33}$$

$$U_b(i,j) = w_d \times D_b(i,j) + w_p \times R_b(i,j) \tag{34}$$

We are also interested in exploring the joint utility associated with possible matches. To this end, we create a matrix A, where the ijth element corresponds to the sum of the individual utilities of s_i and b_j, as defined in (35).

$$A(i,j) = U_s(i,j) + U_b(i,j) \tag{35}$$

To define the final preference vector of each SP and VNB, we focus on the joint utility definition given by (35). This approach permits us to consider a wider range of possibilities for matching, in addition to allowing us to analyze the mutual benefit stemming from a partnership instead of individual gains.

Given our utility calculation method and the value that weights can take, the maximum joint utility of a match is 4 and the minimum is 0.4[3]. We assume that a SP–VNB pair having the minimum utility value should not be included in each other's preference vector. In this way, we consider that there should be a minimum utility threshold (between 0.4 and 4) that represents an acceptable partnership. We define this threshold as the middle point between the minimum and maximum possible values. In this particular case, the joint utility threshold is 1.8.[4]

The subset of feasible partnerships defines the final preference vector of s_i and b_j that will be utilized in the matching algorithm. As pointed out by Roth in [6] regarding the marriage problem posed by Gale and Shapley, "[p]references can be represented as rank order lists of the form $P(m_i) = w_3, w_2, ...m_i$, denoting that man m_i's first choice is w_3, his second choice $w_2[w_3 >_{m_i} w_2]$ and so on, until at some point he prefers to remain unmatched (i.e., matched to himself)". The same applies to the problem at hand. In this case, the final preference vector of s_i and b_j will contain a subset of members of the opposite set with whom it is possible to form a partnership, as expressed by (36) and (37). These subsets, or preference vectors, are sorted in descending order of joint utility value.

$$P(s_i) = b_k, b_l, b_m, ..., s_i \tag{36}$$

$$P(b_j) = s_o, s_p, s_q, ..., b_j \tag{37}$$

D. Algorithm for Matching SPs and VNBs

The matching between SPs and VNBs is implemented utilizing the *deferred acceptance algorithm*[5] for the many-to-one matching case. This means that a VNB can form a partnership with n SPs, where n = VNBs' quota or partnership size; while an SP can only form a partnership with one VNB. The value of n has been set to m, i.e., the total number of SPs in the network[6]. This algorithm has been implemented following its definition presented in [7], [8], [9].

As presented in [6], the outcome of this matching game is a matching $\mu : \mathcal{S} \cup \mathcal{B} \rightarrow \mathcal{S} \cup \mathcal{B}$ such that $b = \mu(s)$ if and only if $\mu(b) = s$. For all s and b, either $\mu(s)$ is in $\mathcal{B}$ or $\mu(s) = s$; and, either $\mu(b)$ is in $\mathcal{S}$ or $\mu(b) = b$. This means that the outcome matches SPs with VNBs, or to themselves, and if s is matched to b, then b is matched to s. It is important to note that we consider the case in which the SPs *propose* a partnership first, which leads to an S-optimal matching, μ_S [6].

Once the matching process is over and we obtain the final matching μ, each VNB learns about its customers and each SP learns the ID of the VNB with whom it will be working. These partnerships further lead to the definition of *market* demand as a subset of the initial, *geographical* demand.

1) Market Demand: The market demand consists of the throughput needed by the matched SPs to fulfill the traffic demand of its end users.

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[3] These minimum and maximum values correspond to pairs of SPs and VNBs that are compatible in at least one factor. We ignore cases in which utility is 0, as this implies that SPs and VNBs are not compatible at all.

[4] We assume this value to maintain the problem tractability. However further thresholds that increase/limit the number of possible partnerships can also be analyzed.

[5] For a full description of this algorithm, please refer to [6].

[6] This value was assigned as a means to establish uniformity among the VNBs in the network and to avoid imposing particular market structures; however, it can be adjusted to fit scenarios of interest

Let's refer to the set of SPs matched with b_j as $MS_j = \{ms_{1j}, ms_{2j}, ..., ms_{nj}\}$. In turn, we can refer to these SPs as VNB b_j's customers. Each VNB should gather information about the resource demand of each of its customers and the maximum price they are willing to pay for these resources[7]. Demand includes the quantity (in Mbps) and the type of resources required. In this model, we assume that SPs can be divided in two types, regarding the services they offer to their customers. As such, they may require resources of type 1, utilized to provide video streaming services, or resources of type 2, required for low throughput, bursty traffic such as Internet of Things applications. It follows that each VNB b_j creates a demand inventory for each resource type and its goal is to obtain the same type of resources from the common pool.

III. EXPERIMENT DESIGN

We developed an experiment in order to determine whether varying the weights assigned by SPs and VNBs to particular parameters, influences the final matching outcome. For this purpose, we created four groups corresponding to the possible weight level combinations (see Table X). Each SP and VNB is randomly assigned to one experimental group, and thus assigns the corresponding weights to its utility calculations. Figure 2 illustrates this experiment design.

This experiment permits us to present an additional set of results and hence determine how different groups of SPs and VNBs perform in the matching process.

IV. SIMULATION RESULTS

The model and experiments described above have been developed using MATLAB. We relied on Python, and its statistical and mathematical packages, for processing and presentation of the simulation results.

In order to capture a broad overview of the matching process, we study different scenarios, which take into account multiple SP and VNB market configurations. In the case of SPs, we explore settings with 4, 5, 6, 10, 20 and 50 participants. For the VNB market, we consider monopoly, duopoly and oligopoly (i.e., 3 and 4 VNBs) configurations.

The simulations account for a daily market; hence our results correspond to aggregate measures from 30 daily interactions × 12 months × 10 repetitions (to account for model replicability). In each simulation run, we have included a training period, in order to avoid the influence of the transient period in the final results.

A. Percentage of Matched SPs and VNBs

Figure 3 shows the percentage of SPs that are matched to a VNB in the market. These results also represent the percentage of *geographical* demand that is converted into *market* demand, via the matching process. We observe that as the number of VNBs increases, a higher percentage of SPs is matched or, a higher percentage of the geographical demand becomes market demand.

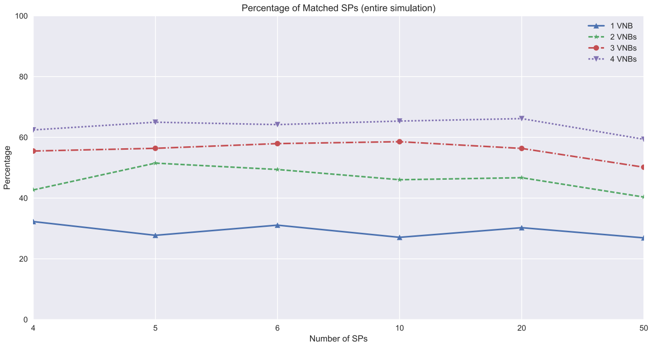

Fig. 3. Percentage of Matched SPs according to the number of VNBs in the market

From the VNBs' perspective, we explore the number of partners that the middlemen have, in average, according to their reputation (or quality). Figures 4, 5, 6, and 7 show these results for scenarios with 1, 2, 3 and 4 VNBs, respectively. These figures show that VNBs with higher reputation partner with a larger number of SPs.

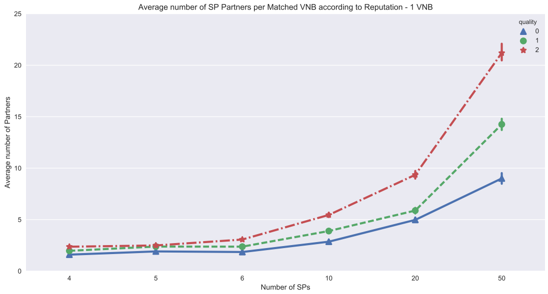

Fig. 4. Average number of partners per VNB. Scenario with 1 VNB

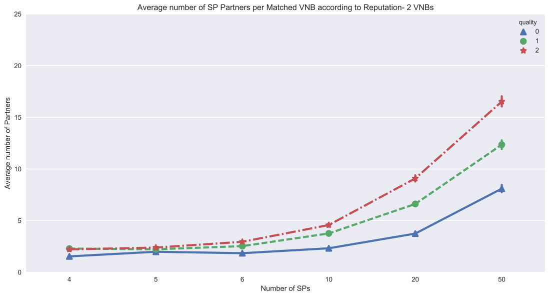

Fig. 5. Average number of partners per VNB. Scenario with 2 VNBs

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[7] Note that there is a difference between the VNB fee and the resource price. The first is intended to cover the cost incurred by each VNB in obtaining the resources from the pool, while the latter corresponds to the valuation that each SP has for the spectrum-related resources.

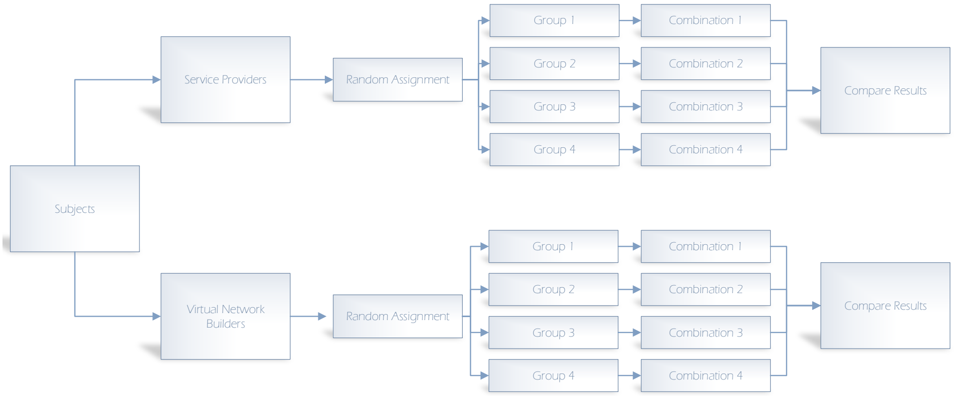

Fig. 2. Scheme of the experiment designed for testing the impact of the weight of different SP and VNB matching parameters

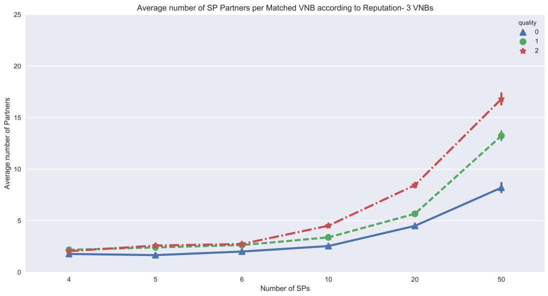

Fig. 6. Average number of partners per VNB. Scenario with 3 VNBs

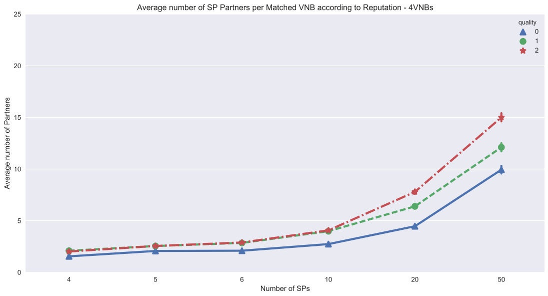

Fig. 7. Average number of partners per VNB. Scenario with 4 VNBs

B. *Fees that SPs(VNBs) are willing to pay(receive)*

As presented in subsection II-C1, SPs and VNBs define different fees to pay and receive, according to their risk level. In figure 8, we show the distribution of the real, maximum fees that each SP is willing to pay for the services of a VNB i.e., the distribution of SPs' real valuation of VNB services. In figure 9, we show the fee that each SP advertises for the same services. As it can be observed, the distribution of 75% of advertised the values is lower than that of the real fees. This is the result of the shading percentage (i.e., fee decrease) that each SP applies, depending on its own risk profile[8].

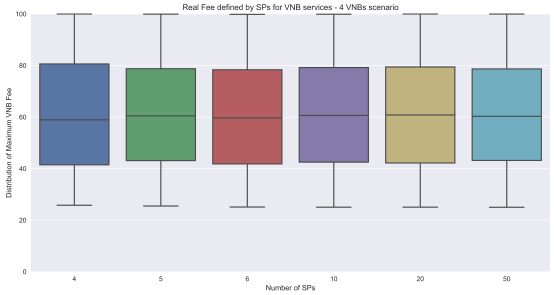

Fig. 8. Distribution of real, maximum fees that SPs are willing to pay for VNB services

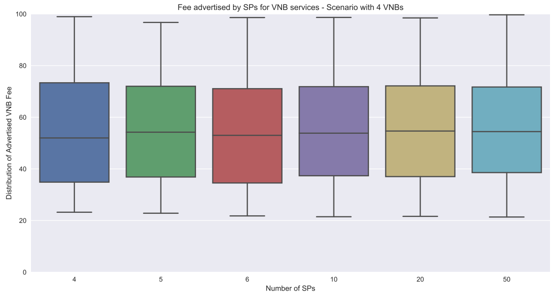

Fig. 9. Distribution of advertised fees that SPs are willing to pay for VNB services

In the case of VNBs, we differentiate their real and advertised fees according to their reputation. In this manner, figures 10 and 11 show that VNBs with higher reputation levels advertise (or expect) higher fees from their SP partners. Similarly to the SP case, VNBs' advertised fees also include

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[8] The results presented in figures 8 and 9 correspond to a scenario with 4 VNBs. The distribution obtained for other VNB market configuration does not present significant variations.

a level of price shading (i.e., price increase) consistent with their risk profile[9].

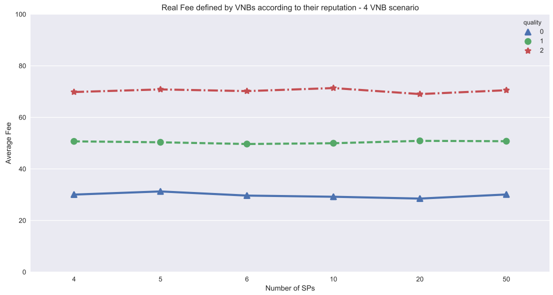

Fig. 10. Distribution of real, maximum fees that VNBs expect to receive from their SP partners

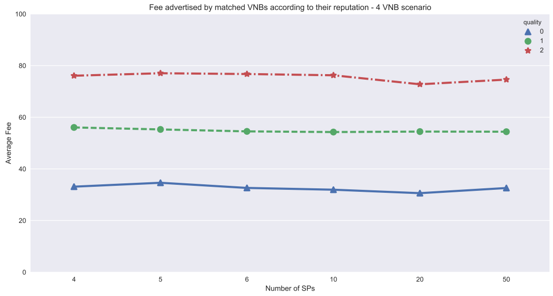

Fig. 11. Distribution of advertised fees that VNBs expect to receive from their SP partners

C. Overall group performance

The experiment defined in section III, aims at exploring whether the weights assigned to different matching parameters influence the outcome. In other words, we are interested in finding out, which experimental group outperforms the rest in the matching process. For this purpose, we have compared the percentage of matched SPs, and the number of SP partners per VNB resulting from each experimental group. Along these lines, figure 12 shows a swarm plot pointing to the experimental group with a higher percentage of matched SPs, for the different SP and VNB market configurations. Similarly, figure 13, points to the experimental groups with a larger number of SP partners per VNB for every tested scenario.

Fig. 12. Group distribution of matched SPs according to different SP market configurations

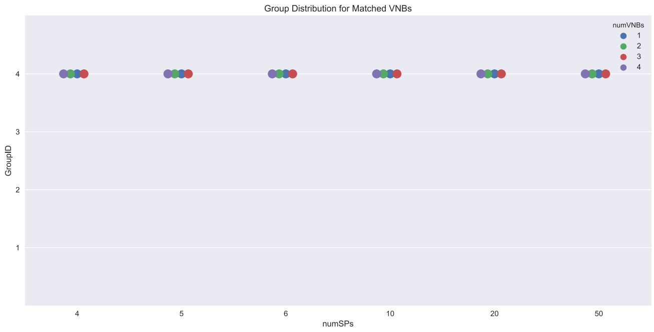

Fig. 13. Group distribution of matched VNBs according to different SP market configurations

As it can be observed, SPs and VNBs that belong to experimental group 4 obtain better overall matching results. This means that participants assigning higher weights to both parameters are, in average, matched more often (in the SPs case) and to more partners (from the VNBs' perspective). Note that this does not imply that members of other groups are not matched. This is just a representation of best overall performance in all the simulation scenarios that we tested. These results could also provide VNBs and SPs with information on how to increase their success opportunities in the matching process.

V. DISCUSSION

The objective of this work is to present an alternative for exploring parameters that influence the workings of spectrum markets. We find that the key for markets to operate well stems not only from defining appropriate transaction mechanisms (i.e., auctions), but instead, from providing market participants with more meaningful ways in which they can express their requirements and preferences. Adopting a matching markets approach, permits us to delve into these details and explore them through a partnership forming process, which is akin to our interaction with real-world middlemen. This approach permits SPs and VNBs to determine, a priori, what are their priorities and restrictions for entering the market.

Existing work on cloud markets [10], [11], [12], points to the complex process that resource buyers need to follow at

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[9] Figures 10 and 11

the time of defining their resource needs. By implementing an approach that relies on a middleman for easing the resource acquisition process for the SPs, we aim at bridging the gap between resource needs and availability. We can further leverage on additional characteristics of VNBs as middlemen, which can provide us with further advantages. For instance, looking at the entire model, VNBs can limit the flow of information between SPs and RPs. This would avoid having these entities learning (or inferring) each other's business models, resource needs and service details. Hence, in the partnership forming process, SPs have no information on the owners and type of resources available in the market. In the resource aggregation stage, VNBs do not communicate any details regarding their partners. They only need to express their demand characteristics and the price to pay for resources. As an additional benefit from VNBs, these entities can fulfill the demand of SPs that would not be competitive in the market, otherwise. Hence, our approach would be a method to level the playing field and lower the entry barriers that new, or small, participants may face.

Our analysis shows that configurations with a larger number of VNBs, provide greater opportunities for SPs to access market resources. This is portrayed in the percentage of matched SPs. Additionally, we show that our model accurately captures the difference in performance of VNBs with distinct reputation. These results follow our real-world intuition, given that in regular interactions, middlemen (or brokers) with higher reputation tend to attract a larger number of customers. In a similar manner, reputation has an effect on the fees that VNBs expect. These results are consistent with our model and show the accuracy of its implementation.

This represents the first stage in a larger, more complex, network model. Indeed, the following stage comprises the negotiations that VNBs need to carry out in the market to fulfill their customers' demand. Starting the process with our matching approach permits VNBs to handle a *known* demand, hence, making their market participation less uncertain. With time, VNBs can learn from previous market results and adjust their number of partners, or their demand preferences. It is important to note that this matching process can be paired with any existing resource assignment mechanism (e.g., optimization processes or auctions). This provides us with the necessary flexibility to explore the most adequate methods that apply to the resource definition and environment characteristics.

VI. CONCLUSIONS AND FUTURE WORK

The current stage of this work elaborates on the settings of a partnership-forming process between VNBs and SPs. Indeed, we provide a detailed overview of the factors that we have taken into account and the role that we envision for them in a matching process. Additionally, we consider different SP and VNB market configurations, which allow us to explore the matching possibilities stemming from these scenarios and, from a modeling perspective, these allow us to test our model scalability to more complex settings.

In subsequent publications, we plan on addressing the resource assignment problem via market mechanisms. This would permit us to delve into the adequacy of the pricing levels, the efficiency in resource assignment and the profit that each entity can obtain from this approach. Additionally, we are interested in pairing our entire network model with applicable governance mechanisms. We are particularly interested in exploring opportunities stemming from polycentric governance approaches, such as those presented in [13]. This combination of perspectives may allow us to shed light on previously unaddressed details behind the development of market mechanisms suitable for fostering next-generation networks and technologies.

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