Simulation Framework for Impact Assessment of Next Generation Spectrum Authorization Regimes

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Abstract—**New wireless technologies with enhanced multi-band capabilities will have a strong impact on spectrum management. While radio access technologies become more flexible in terms of usable spectrum, authorization regimes need to be rethought. Regulators thus will be expected to set the stage for more flexible spectrum usage scenarios in combination with a heterogeneous set of applications and services. In contrast to the current command and control approach, spectrum management would encompass the definition of abstract access and usage rules applicable to a variety of applications. Consequently, impact assessment of regulatory measures in regimes with increased flexibility and heterogeneity requires detailed ex-ante modelling with a strong focus on dynamic components. In this paper, it is argued that neither technical bottom-up nor economical top-down modeling on its own serves the goal to capture the dynamics of a flexible environment to a sufficient degree. To fill the gap, a combined simulation framework is proposed to model authorization procedures in a nationwide spectrum management ecosystem based on multiple local scenarios.**

Keywords—Dynamic Spectrum Management, Spectrum Economics, Techno-Economic Simulation, 5G Spectrum

I. INTRODUCTION

A more flexible use of radio spectrum promises to enhance the capacity of wireless networks. For more than a decade, the debate on technologies, regulations and standards has produced substantial theoretical knowledge in that area, e.g. [1], [2], [3]. However, the potential benefits have not lead to any widespread operational system up to now. On the one hand, this is because the evolution towards more flexible spectrum access comes up with certain – and not seldom substantial – technological, economic, legal and regulatory challenges [4]. On the other hand, resource sharing is to a strong extend a strategic issue, especially in public mobile communications, where operators require guaranteed spectrum access to preserve their profits [5]. The latter explains why frequency trading is rarely considered as an option for European mobile operators, although the regulatory framework already permits spectrum transactions in many countries. However, current research in new wireless technologies, such as 5G/IMT2020 addresses more and more an integration of different services and business models delivered via the same network infrastructure. For example, new communication standards will facilitate “network slicing”, a technology which aims at slicing a single physical network into multiple isolated logical networks, which can be configured according to specific technical or commercial needs of the implemented services [6]. Within this paradigm, network infrastructure, but also radio spectrum is considered an essential asset [7], enabling a variety of services with individual quality requirements – a view, which also motivates thinking of new forms of spectrum authorization in the EU [8]. In [9], the concept of “network slicing as a service” (NSaaS) is outlined, which promises to further ease service orchestration (and creation) in 5G networks. Combined with augmented multiband capability of wireless devices, the usage of frequency bands will thus become increasingly interchangeable which offers a serious potential for more flexible spectrum usage. Consequently, future wireless technologies call for the development and implementation of suitable authorization mechanisms, encompassing increased flexibility, but also their integration into legacy spectrum access regimes.

As more dynamic approaches are often associated with a higher degree of automation – which implies a loss of immediate control for both regulators and spectrum users – they bear the fundamental risk of an unpredictable spectrum configuration (in terms of availability and interference protection) to operators. In particular, sound network and investment planning requires the amount of effectively available spectrum resources to be known in advance and therefore flexible and automated systems are not yet considered for usages requiring reliable spectrum access. Hence, the predictability of available resources constitutes a critical feature of future spectrum management systems, and thus any candidate system must provide evidence that requirements of the applications can be met throughout the entire operational phase of the system. In contrast to current assignment procedures, such as auctions or individual license requests, an evaluation of widely automated systems would refer to scenarios, where spectrum transactions are performed continuously and over the entire operational time and in potentially large numbers. This motivates the development of dynamic simulations of the affected spectrum management ecosystems, including spectrum demand and assignment simulations, for ex ante evaluations.

A joint simulation of spectrum usage and assignment scenarios requires detailed modelling of the ecosystem leading to complex and computationally intensive models. Existing simulation tools often focus on only one of these two sides resulting, either in detailed network simulations e.g. for planning purposes, or economic simulations with often strongly simplified technical assumptions. For example, [10] and [11] have developed and simulated small spectrum usage scenarios

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focusing on a theoretical evaluation of algorithms for secondary spectrum trading, but the scenarios were not designed to simulate the effect on a real-world ecosystem. The latter has been covered by [12], who developed a simulator for testing allocation mechanisms under realistic demand patterns. However, the simulation was conducted specifically for mobile telephony scenarios. A more general spectrum usage simulation approach is proposed by López-Benítez and Casadevall in [13] and [14], who developed a simulation framework, which addresses spectrum usage based on the occupation of radio channels but not on subscriber behavior. Beyond that, a considerable number of network simulators exists, generally capable to model the full protocol stack of various types of wireless communication networks (e.g. ns-3, OMNet++, SimPy etc.) [15], but which are too complex to scale for regulatory purposes. For that reason, and due to the emerging significance of dynamic spectrum access regimes, we propose a new framework for the establishment of simulations. It is suited for the requirements of regulators, and specifically designed as a testbed to study the behavior of algorithms to be applied in heterogeneous assignment scenarios. It is required to capture the individual needs of spectrum users.

In this paper, we focus on a modelling framework for a spectrum management ecosystem enabling spectrum usage and assignment simulations in the context of dynamic spectrum access. In section II, basic forms of spectrum access are summarized. Section III outlines the overall framework approach, whereas in Section IV basic entities to be modeled in the regulatory, economic and network domain are presented. In section V, a notation for the description of spectrum transactions is introduced, and in section VI potential use cases for the application of the framework are developed. Section VII Summarizes the paper and provides an outlook on future work.

II. Spectrum Access Regimes

The current spectrum management paradigm considers numerous forms of spectrum access which can be interpreted as derivations from either of the two fundamental forms "general authorization" and "individual authorization". Additionally, the shared use of spectrum may be considered as a third elementary form, but effectively represents a combination of the aforementioned, and adds a hierarchical and a potentially dynamic component. A general taxonomy of spectrum access models can be found in [1], where 15 different models are distinguished. A more specific classification is given by [16], consisting of four model types to classify dynamic spectrum access according to the criteria "property rights vs. open access" and "horizontal vs. vertical sharing".

A. Categories of Dynamic Spectrum Access and Sharing

In the property rights regime, spectrum is assigned individually and usage rights can be traded or leased. The tenure of usage rights enables a higher degree of protection, even in dynamic usage scenarios. Horizontal sharing allows introducing various types of secondary markets and mechanisms, such as spot markets, real-time auctions, brokering, etc. This requires reliable spectrum monitoring systems and usage databases [16]. Benefits from horizontal sharing can be expected predominantly in heterogeneous scenarios, as it is more likely that similar users (e.g. mobile operators) have similar load patterns and spatial footprints [1]. Vertical sharing can be enabled by spectrum holders through granting access to their unused spectrum (white spaces) [16]. In open access regimes, usage rights are not directly considered, instead vertical sharing refers to a situation, where incumbent operators still exist, but no dedicated permission for spectrum access has to be requested from the latter. In horizontal scenarios, no incumbent user exists, and all users dynamically share spectrum on an equal footing [16].

B. Mechanisms for Dynamic Spectrum Access

The introduction of new spectrum access regimes ultimately requires new mechanisms capable to manage frequencies in a highly dynamic usage environment, where processes are handled by automated platforms acting on the basis of algorithms instead of human decisions. Mechanisms can be designed either with a focus on an optimal resource allocation (in terms of frequency band, channel access time, transmission power etc.), or with a focus on market transactions (trading/leasing) between (competing or non-competing) primary and secondary users or among secondary users [17]. They may, for example, be implemented in third party entities, representing the role of the regulator and are often called spectrum brokers [18], [19]. Notwithstanding the final design of future spectrum management systems, the paper illustrates the relevance of fundamentally new classes of spectrum assignment procedures. Three basic types (real-time auctions, brokering and direct trading) are presented and compared in [11], but this classification is still at a high-level. In fact, mechanism design for spectrum sharing includes a variety of solution approaches, such as game theory (comprising a large number of game types), price theory (auction theory and bargaining theory), or market theory (considering market equilibria and oligopoly markets) [17]. The translation of economic concepts to spectrum markets is aggravated by rapidly varying spectrum demand, imperfectly informed agents (spectrum users), and a complex resource allocation problem, resulting from the fact that radio spectrum is a multidimensional resource; in particular, mechanism design is faced with several obstacles [5]:

- Resolving the tradeoff between real-time adaption and optimality of the outcome (due to model complexity).
- Provision of reliable technical systems (platforms, protocols, monitoring systems) for implementation.
- Prevention of collusive behavior, untruthfulness, and irrationality. The latter refers to suboptimal decisions based on erroneous or incomplete information.
- Complexity of the market structure in (heterogeneous) real-world scenarios.

Capturing the variety of spectrum access models and potential use cases represents a major challenge for the simulation of a spectrum economy, the results of which are expected to qualify as a basis for regulatory decisions. Even if a decision is to be taken only for a particular band and a small number of applications, a universal modelling framework ensures consistent decision-making for future evaluations. Therefore, in the subsequent such a generic framework and notation of the spectrum award process is developed.

III. Modelling Framework

Our approach shall be applied in particular to study the dynamics related to flexible spectrum management and its effects on the spectrum management ecosystem. Therefore, the focus has to be laid on interactions between individual actors within the system.

A. Requirements Related to Regulatory Modelling

From an economic perspective, it is generally sufficient to evaluate whether and how spectrum resources can be efficiently distributed among users, and how efficiency can be maintained. For the development simulations this indicates that spectrum users can be considered as entities of a spectrum economy, which try to acquire and release spectrum in the course of predetermined assignment procedures (mechanisms), which themselves must be provided in the simulation environment. Such a setting allows studying specific questions under well-defined and controllable conditions. If, in addition to that, a simulation is required to qualify for predictions of the effects on real-world scenarios and to serve as a basis for upcoming regulatory decisions, then further criteria must be met. In 2008, the Electronic Communications Committee (ECC) within the European Conference of Postal and Telecommunications Administrations (CEPT) has issued guidelines for impact assessment, suggesting certain requirements for the development of spectrum usage simulations. The "determination of impact on stakeholders" requires to *"[...] identify the costs, benefits and impacts to determine the likely effects (for example economic, social, environmental) on all stakeholders, including consumers and relevant spectrum users of the concerned band"*, and suggests a quantification of these impacts [20]. Consequently, impact analyses should also include a quantitative estimate on the effects on concerned stakeholders, i.e. spectrum users and subscribers.

B. Two-Domain Simulation Approach

Although some simulations have considered detailed demand models, no approach is known that captures heterogeneous usage scenarios according to a common modelling framework which potentially could be applied also to legacy assignment scenarios to evaluate the interactions with existing approaches. This inspires the development of a general simulation framework consisting of two basic parts: An economic simulation (1), focusing on strategic interactions between spectrum users and managing spectrum access, and a spectrum usage simulation (2), addressing the simulation of the users' spectrum utilization, which serves as a basis for deriving valuations for certain frequency bands (see Fig. 1). The economic simulation represents the strategic domain, where decisions on spectrum acquisition and release are taken and executed with respect to economic aspects: Spectrum users can be considered as utility-maximizing entities which act on the basis of individual utility functions, depending predominantly on the underlying business models. Departing from the spectrum user types, regional footprints, technologies applied, and initial spectrum configuration, the network simulation is configured and conducted to calculate the effective spectrum usage and to derive estimates on how much additional spectrum would be needed (or could be disposed) to satisfy the subscribers' demand. This information is fed back to the economic simulation and used to determine the optimal amount of spectrum to acquire or release, respectively.

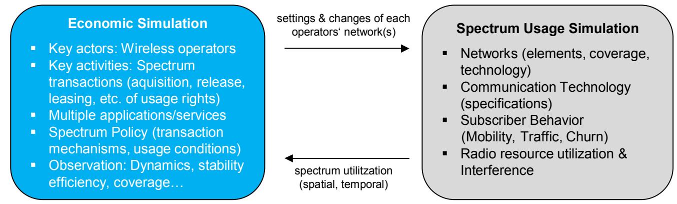

Fig. 1. Interworking of Strategic and Network Simulations

C. Regulatory Perspective

The regulatory perspective is addressed as an external perspective, as in spectrum management ecosystems regulators can be assumed to play a supervising role. The configuration of the simulation itself (e.g. allowing for certain mechanisms to be available for spectrum transactions) already constitutes a (simulated) regulatory decision. The simulation must enable altering all parameters which can also be influenced by regulators in real-world scenarios, such as assignment periods, spectrum usage conditions, entitled users, etc. Furthermore, the technical and economical simulation is required to produce results which are in line with market observations as they are usually conducted and published by regulators. The temporal resolution chosen for the simulation depends on the mechanisms to be studied. Whereas real-time auctions would require intervals for determining spectrum demand in the range of several minutes, other forms of dynamic spectrum access could be based on e.g. daily or weekly values. The same applies for the spatial resolution, which depends on the services (and network technologies) modeled and their considered radio link distances. The basic feature of the simulation approach is the provision of an environment, in which actors in their respective domains (see Fig. 2) behave as specified by the rules provided in form of dedicated libraries. Theses libraries contain e.g. the spectrum assignment algorithms, but also mobility and channel usage models, link scheduling algorithms, or spectrum valuation methods, etc. Regulators are to be given a tool, where specific rules within these libraries or variations of the latter can be tested in terms of stability, equilibria and impact on stakeholders prior to a regulatory decision.

IV. Entity Modelling

Within a model, central elements of a spectrum economy must be represented. They can be divided into actors (i.e. decision making units within the simulation) and libraries, providing the required methods and data. Further, they can be classified according to the domains that constitute the ecosystem, which is depicted in Fig. 2. The breakdown into three domains follows the division of responsibilities in spectrum management ecosystems, where regulators provide rules for spectrum access and policies for all frequency bands and applications according to international standards and supranational agreements. From a legal perspective, assignment mechanisms will always be under control of the regulator, who is assumed to be entitled to supervise all kind of spectrum sharing platforms, even if they are operated by third party providers. Therefore, the transaction platform is attributed to the regulatory domain and all assignment procedures are simulated here.

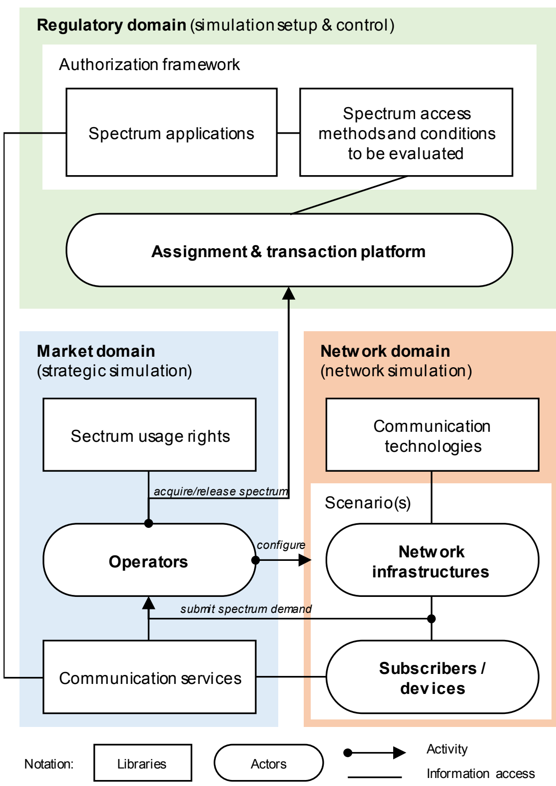

Fig. 2. Basic Entities of a Spectrum Management Ecosystem

A. Economic Simulations in the Market Domain

The market domain focuses on spectrum users, which are denominated as operators of wireless communication systems. The term "operator" here refers to an entity offering at least one communication service related to any wireless application by providing and operating the necessary infrastructure of a determined technology in a predefined area to a certain number of subscribers. This broad definition of operators enables simulating heterogeneous constellations of applications in the same scenario as demonstrated in table I.

TABLE I. CLASSIFICATION OF OPERATORS, EXAMPLE

No.	**Spectrum Users, Offered Services and Technologies**		
	Application	***Service***	***Technology***
1	Mobile	Voice	GSM, Rel. 99
2	Mobile	Data	LTE, Rel. 8
3	PPDR	Data	TETRA, Rel. 2
4	Broadcast	TV	DVB-T2

For each operator the area covered, the subscriber base for each of the services offered and the configurations for each operated network have to be specified. Additionally, operators must be assigned an initial set of spectrum usage rights. Usage rights can be represented in different forms and relate portions of spectrum with authorization mechanisms and usage conditions previously set by the regulator (regulatory domain). This way, it can be implemented e.g. that 800 MHz spectrum can be used for mobile services on an exclusive basis and has to be auctioned by using a certain auction format (which has to be implemented, too) and that minimum coverage obligations have to be met. Likewise, options for trading or leasing can be set as available for license holders. However, usage rights do not need to be exclusively awarded; i.e. some spectrum can be accessed by multiple operators, such as spectrum for short range devices (SRD). The tenure of spectrum usage rights can be modeled in form of generic assignments indicating frequency units (blocks), operator(s), duration of assignment (if limited), region of assignment (if regionally limited), etc. Throughout the simulation, usage rights are awarded, exchanged and released between operators, and/or a regulating entity according to the specifications set independently for each spectrum application. The simulation then can be considered as a repeated game between operators who compete for spectrum. Depending on their spectrum applications and services, they may value certain bands differently and may also be subject to externalities arising either from spectrum scarcity in particular bands and/or economic competition, e.g. between commercial operators. Based on their individual payoff function, they try to acquire/release spectrum usage rights. The game is repeated in fixed intervals, which coincide with license periods. Within one license period, operators may use their spectrum according to the provisions specified in the license. The network usage within such period is simulated based on smaller sub-intervals.

B. Network Simulation

Operators of wireless services who have access to spectrum can implement their services according to the specified usage conditions by operating networks of a certain technology covering a predefined area. Note that the term "network" is to be considered in a broad sense here: It comprises all types of implementations of a service, ranging from nationwide cellular networks, to local point-to-point links (e.g. microwave links). Within a simulation, multiple overlaying networks of different services, operators and technologies need to be modeled in order to address heterogeneous spectrum usage scenarios. Scenarios are populated by subscribers and require generating a subscriber base for each network. Subscribers use the network according to service specific demand and mobility models, which have to be provided in the form of model libraries related to the offered services. Throughout the simulation, the network domain is configured and altered in certain intervals according to parameters transmitted by operators, such as coverage, available spectrum, size of subscriber base, technologies used and services implemented, etc. According to these parameters, representative hypothetical network scenarios are created and simulated. Depending on the technology chosen for network implementation, specific parameters such as channelization or functionalities, e.g. link scheduling must be provided within the network domain. However, the requirements on the latter can be relaxed, as for spectrum valuation only the *average aggregate* demand (and its variation) per time interval is needed. Having chosen the technology, a network simulation can be created by placing infrastructure (e.g. base stations) and subscribers within the scenario. With the start of the usage simulation, subscribers begin to move and use the network according to the models related to the chosen service. From the network usage, the required number of radio channels (and therefore spectrum usage), transmit power etc. is calculated on a per link basis. All relevant parameters and functions are provided by technology libraries. The aggregate spectrum usage is stored and handed back to the economic domain, where operators based on that take decisions on their ensuing activities on the spectrum transaction platform. A simple exemplary scenario is depicted Fig. 3, consisting of two mobile network operators (MNO) who's networks have different cell sizes. The figure illustrates how subscribers move through the scenario and connect to the nearest base station.

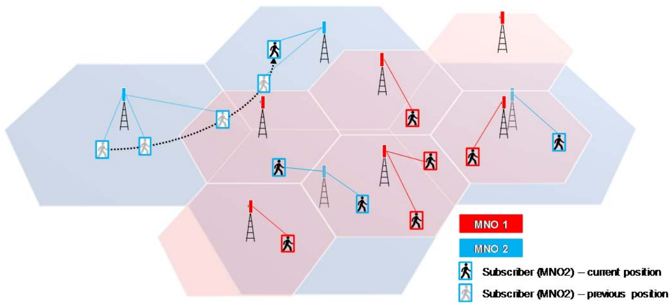

Fig. 3. Link based modelling in a 2-MNO overlay scenario

As the overall simulation focuses on the total amount of spectrum needed (locally and temporarily), a detailed network modelling (e.g. simulating the full protocol stack) is not required here, which simplifies the usage simulation, especially in heterogeneous scenarios.

C. Scenario Generation

In order to capture the variety of possible constellations in spectrum management ecosystems with respect to the presence of operators and services, subscriber density, terrain type, etc., multiple spectrum usage scenarios should be considered and independently simulated in the network domain (see Fig. 4).

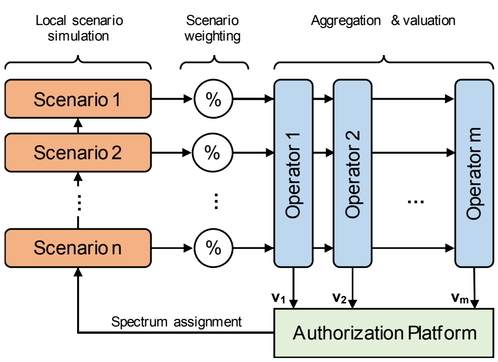

Fig. 4. Multi-Scenario Ecosystem

Local results could be provided in the form of local time-frequency maps (LTFM) as suggested by [13]. Afterwards the results need to be weighted according to their proportional occurrence in the entire ecosystem and aggregated by operators who derive a valuation for spectrum based on that information for each scenario area. The valuation is considered when operators become active in spectrum transactions implemented on the authorization platform. Transactions may result in altered spectrum configurations, which will available in the subsequent simulation round. The simulation and aggregation of multiple scenarios allows capturing the heterogeneity of real spectrum management ecosystems.

Basic configurations such as operators' footprints and network usage, socio economic and terrain factors, but also the introduction of local licenses can be modeled independently, which in turn allows for simplifying assumptions in local scenarios. As the establishment of libraries providing methods and parameters for spectrum access is an essential part of the simulation, a formal notation is needed to describe various elements of spectrum access and developed in the following.

V. A Formal Notation of Spectrum Access

Radio spectrum can be considered as an excludable economic good, if appropriate solutions for monitoring and licensing are in place [21]. We assume this to be given in the following, as excludability is a precondition for the definition of individual or shared usage rights associated with certain usage conditions. Formally, any form of spectrum access can be interpreted as a grant of usage rights subject to a particular award mechanism in combination with related usage and return conditions applied to particular portions of radio spectrum.

A. Spectrum Units

According to [2], radio signals can be described by frequency (F), time (T), location (X,Y,Z) and direction (of travel). The hyperspace spanned by these orthogonal dimensions is called electrospace and orthogonality implies that disjoint subsets of the electrospace do not interfere with each other, if signals stay within their defined bounds. To govern interference, it must be ensured that signal power falls below a certain level outside the area authorized for operation and does not exceed a certain level within that area [22]. For that reason, signal and interference power are sometimes also referred to describe radio spectrum [1], but will not be considered as independent here, as allowed power levels can also be derived from the size of the area covered. Additionally, the direction of travel will also be neglected here, as only few applications would make use of it.

Hence, the total spectrum S is formally represented by the dimensions $S = F \times T \times X \times Y \times Z$. Accordingly, an atomistic spectrum unit is defined as a 5-tuple of basic units of frequency, time, width, length and height, written as $\Delta s = \langle \Delta f, \Delta t, \Delta x, \Delta y, \Delta z \rangle$.

Basic units of time and frequency should be chosen equal to the greatest common divisor of the respective time slots and channelization of the services intended to be modeled. A particular spectrum unit s_i is thus given by $s_i = \langle s_{i,min}, s_{i,min} + \Delta s \rangle$ with $s_i \in S$, and $i \in \{1, \dots, K\}$, where $s_{i,min}$ contains the lower bounds of each element of s_i. Further, all spectrum units are disjoint in S, i.e. $s_i \cap s_j = \emptyset$, for all $j \neq i$ and S is completely defined by atomistic spectrum units, therefore $S \setminus \{s_1, \dots, s_K\} = \emptyset$.

B. Spectrum Packets and Assignments

Before spectrum can be transferred to users, spectrum units are grouped into packages for which further rules must be set (assignment mechanisms, usage and return conditions). A spectrum package therefore represents a common set of spectrum authorization rules. It can be dedicated to a single user (by individual exclusive assignment) or to a group of users (shared access, or commons). Each spectrum unit can be part of only one package, but usage rules may allow for splitting packages in order to enable sub packaging, so that parts of it can be assigned to different users. Note, that for all assignments originating from a particular package, the same set of rules applies. In the following, an assignment is defined as the attribution of a spectrum package to either individual or groups of entitled users, which may have different access priorities. This allows modelling individual, shared (co-primary, hierarchical), or common use.

C. Modelling Assignment and Secondary Transactions

Initially, it is assumed that all spectrum is held by the regulator, who awards it to spectrum users. For modeling secondary transactions, i.e. when spectrum is transferred between spectrum users an index k, with $k \in \{1, \ldots, N\}$ is introduced, which increases with each transaction and represents the so-called depth of an assignment A_k. It is specified for each atomistic spectrum unit s_i and therefore well-defined. Distinguishing between different assignment depths allows the previous spectrum holder to add supplementary rules on spectrum usage and return conditions, which may, for example, represent the outcome of bilateral negotiations between operators. In general, the term negotiation is to be understood in a broad sense, i.e. it may refer to personal negotiations between operators' staff members or denote the invoking of a bargaining procedure in an electronic spectrum market. The state diagram in Fig. 1 illustrates how individual spectrum units can be shifted to form new assignments.

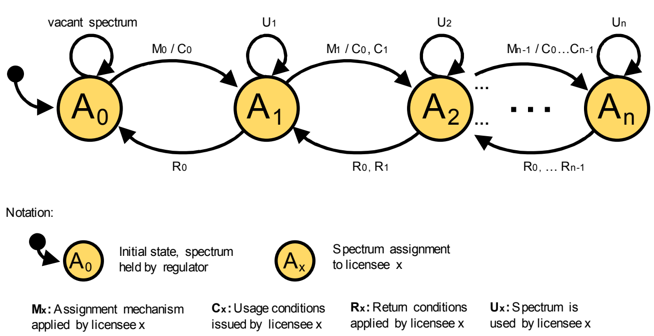

Fig. 5. State diagram of atomistic license units

The state A_0 represents the initial state, where spectrum is not assigned to any user. As long as it is not awarded, the spectrum remains vacant. After the first assignment (A_1), it can either be used or transferred. A transfer, however, can only be conducted if the current assignment is specified as exclusive to the actual spectrum holder, and the permission for the transaction is stated in the usage conditions. In general, spectrum transfers can be permanent (trading) or temporary (leasing). As regulators would award spectrum only for certain period of time, assignments by regulators are always temporary, and trading by individual licensees also implies that spectrum must be returned latest by the of that license period. In the case of leasing, spectrum is returned to the lessor within a shorter period. Traded spectrum has to be returned to the regulator by the last spectrum holder. In order to manage spectrum assignments, the entitled users, award mechanisms, as well as usage and return conditions have to be specified. These elements are described in the following.

1) Entitled Spectrum Users

Each assignment must specify the entitled spectrum users. To model individual exclusive assignments, entitlement refers to a single user, otherwise to groups of users, if general authorizations, or shared uses of spectrum are to be modelled. Additionally, access priorities among users can be set to model primary/secondary spectrum access. Some users may be given privileged rights, such as selling or leasing spectrum or imposing additional usage conditions (e.g. for sub-licensees).

2) Mechanisms

Award mechanisms summarize all existing procedures to transfer usage rights from one entity to another. In case spectrum is awarded by the regulator, this refers to the established methods, such as auctions, general authorizations (coordinated and uncoordinated), individual licensing, license exempt use, etc., and also involves related procedures, such as type approval or equipment registration. In case spectrum (i.e. usage rights) is held and awarded by another entity, e.g. a mobile operator, then additional procedures need to be considered, such as trading, leasing, light licensing, sublicensing, opportunistic or co-primary sharing (pooling).

3) Usage Conditions

The obligations of a spectrum user throughout the assignment period are contained in the usage conditions. This refers to basic provisions, such as allowed transmission and/or interference power levels, assigned spectrum units, coverage obligations, etc., but also to sharing and secondary usage conditions. However, the more service specific conditions are imposed, the less flexibility remains for spectrum transactions, as other users would have to comply with the same rules. It is therefore beneficial for facilitated spectrum sharing or transactions, when usage conditions are specified service agnostic, and service specific requirements would be shifted to separate service licenses instead, which has also been suggested by [21]. If spectrum transactions shall be enabled, the regulator may also specify, which mechanisms are allowed for secondary assignment procedures. Further, it must be stated that users are given the right of disposal for their spectrum, which authorizes them to pass on parts or all of their usage rights, and whether or not they are allowed to alter usage and return conditions in the course of transferring usage rights. The disposal of spectrum usage rights can be given to primary licensed users only.

4) Return Conditions

Typically, spectrum usage rights are granted for a limited period of time. In exclusive assignments, an expiry date is stated in the spectrum license, but also the periodic revisions of frequency bands for unlicensed access can be interpreted as temporal delimitation. Hence, each assignment is subject to a certain duration, and its expiry automatically triggers the return of spectrum, unless the assignment period is extended. Additionally, premature returns of licensed spectrum may occur on withdrawal by the issuing entity or the regulator (e.g. as penalty due to a breach of license conditions) or on user's own decision. Return conditions can also be related to the occurrence of certain circumstances, e.g. when leased spectrum is reclaimed by the lessor, or a primary users start utilizing spectrum which was opened for secondary users on a light licensing basis. The acceptance of ad hoc return conditions, however, entails unreliable spectrum access and thus unpredictable service quality. Such early return claims could be offset by compensation agreements attached to return conditions. In the case of unlicensed and uncoordinated access (e.g. WiFi), return conditions reduce to the expiry of the assignment period, as mentioned above.

5) *Summary*

The elements introduced above allow for a description of the spectrum assignment and transfer process. As in most of the current spectrum management scenarios transactions are not applied, assignment would be limited to level A_1, i.e. when the regulator awards spectrum according to its policy considered for the respective band. However, the notation is designed that spectrum could undergo several stages of sub-assignment, either in the form of leasing and sub-leasing or trading, and that at each stage individual agreements on the usage and return conditions can be made. Note that these conditions are hierarchically transitive, i.e. in the course of a transaction, all conditions (potentially) imposed by previous spectrum holders must be preserved (unless stated otherwise in these conditions). In Fig. 5 this is captured by the notation $\langle C_0, C_1, \dots C_{n-1} \rangle$ or $\langle R_0, R_1, \dots R_{n-1} \rangle$, respectively. Of course, it is not required that at each stage, additional conditions are specified. This allows the regulator to define limits, e.g. on the number or frequency of transactions, the systems to be used for transactions (such as electronic markets or spectrum brokers), applicable trading mechanisms, etc., as well as imposing constraints regarding additional conditions that could be imposed on receiving users in the course of spectrum transactions. Finally, all information on usage and return conditions, mechanisms, and entitled users is attached to a spectrum assignment. Assignments can be newly created (award by regulator or transaction), merged (acquisition of additional spectrum, if conditions are compatible, e.g. by transaction), split (e.g. sale, lease or return of parts of the spectrum held), or deleted (return).

VI. USE CASES

In the following we present potential use cases for dynamic spectrum management simulations. First, we focus on Authorized Shared Access (ASA) and Citizen Broadband Radio System CBRS, as they have gained particular importance for dynamic spectrum access in the EU (ASA) and in the US (CBRS). The last subsection contains an outlook on further use cases, to the assessment of which ex-ante simulations of the related ecosystems could provide valuable input.

A. *Authorized/Licensed Shared Access (ASA/LSA)*

Authorized Shared Access (ASA) refers to spectrum sharing, where mobile network operators (MNO) can access bands identified for International Mobile Telecommunications (IMT) but currently encompassing other type of incumbent use [23]. The generalization of the concept is known as Licensed Shared Access (LSA), where the focus is widened to other spectrum applications [24]. As a key feature, primary license holders (incumbent users) grant spectrum access rights to one or more other users which may then use the band under specific conditions [25]. ASA has gained importance, as it has undergone a certain process of standardization and is also considered as a potential means to enable spectrum sharing in 5G in quality sensitive use cases [26], but also for the extension of LTE coverage in the 2.3-2.4 MHz band [27]. The latter represents a scenario based on property rights with vertical sharing, where LTE networks a given secondary access on request by the ASA controller. Access can be limited to a certain time, region and sub band. Such assignment would be at level A_2, as it is granted by an ASA controller. Theoretically, applicable mechanisms for such access grants may range from a simple registration to real time auctions, especially when multiple secondary users compete for the same spectrum. The modelling framework presented previously could provide ex-ante insight in the evolution of the system under the application of different types of mechanisms which potentially involve payments between spectrum users – a feature which cannot be tested in technical field trials as they are conducted in [28].

B. *Citizens Broadband Radio Service (CBRS)*

CBRS is a complex 3-tier spectrum sharing approach in the 3550-3650 MHz band, where, similar to ASA, incumbent users (here: military and satellite users) share the band with lower priority users. Among the non-incumbent users, either priority (protected) secondary licensed access or general (unprotected) unlicensed access is available. Spectrum for protected secondary users (3G/4G services) is awarded on the basis of auctions, whereas unprotected users are permitted to use opportunistically any portion of the CBRS band not assigned to a higher tier user. Spectrum is centrally coordinated by a spectrum access server (SAS) [29]. Here, the usage conditions of the regulator (C_0) state the three tier architecture under A_1 and enable further mechanisms (M_1, here: spectrum auctions) to award portions of the spectrum on a protected basis to mobile operators (A_2). Note that the protection of the incumbent users is transitive, and thus is imposed on protected secondary users. With the help of the suggested simulation approach, the effect of changes of important features of the CBRS ecosystem could be assessed, such as varying degrees of incumbent protection, altered auction mechanisms or a reconfiguration of the multi-tier architecture.

C. *Outlook on Testing Future Spectrum Management Systems*

The previously presented use cases have in common that as of today they are widely standardized, tested and considered ready for implementation on a larger scale in the near future. Consequently, simulative assessments would focus on alterations in the existing ecosystem, rather than the decision on their introduction. However, there are additional use cases where simulations could provide detailed evidence already at the stage of development. New concepts such as pluralistic licensing, where spectrum users negotiate on interference tolerated [30] could be simulated in a realistic scenario setting and evaluated e.g. in terms of compatibility with other dynamic spectrum access approaches. Generally, a large scale introduction of spectrum trading and leasing, assignment and pricing algorithms could be tested as well as the introduction of new technologies. A more imminent example would be the introduction of unlicensed LTE access in the 5 GHz WiFi bands, which is often feared to degrade the service quality of WiFi networks, and where fair allocation algorithms might provide a solution to efficiently and fairly managed spectrum access [31].

VII. Conclusion and Future Work

In the light of the ongoing trend towards more dynamic and increasing automation of spectrum authorization regimes, we derived the need for simulative assessments prior to regulatory decisions related to the introduction or alteration of fundamental parts of future spectrum management systems. For that purpose, a modeling framework has been proposed, which enables the creation of simulation models which meet the requirements of regulatory decision-making. Furthermore, a notation for the description of spectrum transactions has been introduced in the form of assignment states and related transition conditions. Based on that we demonstrated how the framework could be applied in the context of upcoming flexible spectrum access regimes (ASA, CBRS) and that such simulations would support the development of future spectrum access regimes (e.g. pluralistic licensing) by adding early feedback on the behavior in real-world scenarios. Based on the framework presented here, a first simulation will be developed for an isolated spectrum management ecosystem, which will be successively extended towards a generalized approach for testing spectrum management algorithms and systems.

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