Agent-Based Modelling Approach for Developing Enforcement Mechanisms in Spectrum Sharing Scenarios: An application for the 1695-1710MHz band.

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***Abstract*—As radio spectrum sharing matures, one of the main challenges becomes finding adequate governance systems and the appropriate enforcement mechanisms. Historically, these processes were assigned to a central entity (in most cases a governmental agency). Nevertheless, the literature of Common Pool Resources (CPRs) shows that other governance mechanisms are possible, which include collaboration with a private, third-party regulator or the complete absence of central institutions, as in self-enforcement solutions. These alternatives have been developed around well-known CPRs such as fisheries, forests, etc. As argued by Weiss et al [50], and other researchers, spectrum can indeed be considered to be a CPR. In this work we study the two extremes of governance systems that could be applied to spectrum sharing scenarios. Initially, we study the classical centralized scheme of command and control, where governmental institutions are in charge of rule-definition and enforcement. Subsequently, we explore a government-less environment, i.e., a distributed enforcement approach. In this anarchy situation (i.e., lack of a formal government intervention as defined by Leeson [29]), rules and enforcement mechanisms are solely the product of repeated interactions among the intervening agents. For our analysis, we have selected the spectrum sharing framework of the 1695-1710MHz band. We also use the definitions presented by Bhattarai et al. [9], [10] as well as Altamimi [3] for managing the size of the coordination and exclusion zones. In addition, we utilize Agent-Based Modelling (ABM) to analyze the applicability of these governance mechanisms. ABM simulation allows us to explore how macro phenomena can emerge from micro-level interactions of independent agents.**

I. Introduction

Commons is a general term for shared resources in which each stakeholder has an equal interest over a determined resource. When natural resources are perceived as commons, they are typically refered to as Common Pool Resources (CPR). CPRs are natural or man-made resources shared among different users that are defined by two main features: i) it is sufficiently large to make it costly to exclude potential beneficiaries from its use, and ii) it is characterized by a high degree of substractability (i.e., a rivalry of consumption) [37]. We can find many examples of natural goods defined as *"commons"* that have been vastly studied in the CPR literature: fisheries, forests, water systems, pollution, etc. [20]. Nevertheless, a less known example of CPR systems is the use of the Radioelectric Spectrum for signal transmission purposes. Spectrum is a resource that benefits a group of users, benefits diminishes, however, if users independently pursue their own "self-benefit".

As pointed out in [22], [23], [50] the exploitation of spectrum bands can, indeed, be classified as a Common Pool good. We can start by pointing out the substractability feature of radio spectrum bands: if a user transmits using a particular spectrum band, it adds to the noise level for all other users in the same band. Consequently, based on the Shannon-Hartley Theorem, an increase in noise[1] decreases the available channel capacity [28]. Inevitably, the band is no longer a suitable environment for any additional wireless communications in the same frequency, space and/or time. As to the other CPR

[1]As explained by Dytso et al. this noise is defined as Gaussian interference inputs acting as a "foe" of other signals to be transmitted in the same band [19].

characteristic, the exclusion of users, we assert that it is relatively difficult to exclude an arbitrary user from the use of most regions of the radioelectric spectrum. Technologies that exploit spectrum bands made it relatively difficult, complex and costly to do so. For example, it would be a very complex and costly task to exclude any given user for transmitting and receiving signals using, for instance, a Bluetooth or Wi-Fi transceiver. Consequently, based on Ostrom's features for a common good [39], we can see that the exploitation of radioelectric spectrum bands for transmission purposes perfectly fits the definition of a CPR.

When thinking about the most common governance mechanism for regulating the exploitation of spectrum bands in the United States, most answers will surely point out to a *"command-and-control"* system. This approach refers to the case where the government[2] requires or prohibits specific actions or technologies, by imposing fines, sanctions and/or jail terms to rule breakers [18]. This system has been the "de-facto" approach for spectrum allocation and enforcement since the Radio Act of 1927[3]. To keep in line with the adopted command-and-control approach, the main mechanism for spectrum allocation used by the FCC has been "Licensing". These licenses would assign exclusive rights to the assigned frequency bands under given conditions[4] mandated by the FCC. Nevertheless, in recent times the FCC and NTIA are working toward a more efficient use and allocation of spectrum bands. One of the most discussed approaches is spectrum sharing between Federal and Commercial entities. This "non-traditional" allocation approach implies a change in the widely used command-and-control system. Furthermore, a change in the allocation rules would force an evaluation of the enforcement systems that are foreseen to emerge in this new model for spectrum management.

A commonly discussed feature regarding Common Pool Resource systems is, without a doubt, the governance schemes that have emerged in the regulation and control of this type of goods. We can observe different approaches for both governance structures and enforcement systems going from formal institutions in command and control frameworks to self-reporting and self-policing. In the case of the latter, no third party controller or community structures (i.e., third-party agency) are required. These government-less environment constitutes a distributed enforcement approach. Further, in this anarchy scheme (i.e., lack of a formal government intervention as defined by Leeson [30]), rules and enforcement mechanisms are solely the product of repeated interactions among the intervening agents in a given environment.

For almost 100 years, command-and-control has been the de-facto governance mechanism for managing spectrum bands. Nevertheless, we see government alternatives such as self-enforcement as valid choices for new Federal-Commercial sharing schemes. Hence, in our work we explore the two "extremes" of the governance spectrum. Initially, we explore a centralized approach (i.e., command-and-control) where governmental institutions are in charge of rule definition and enforcement tasks. Then, we study a distributed approach with a "government-less" environment with self-enforcement characteristics.

For our analysis we have selected a well-defined and widely known Federal-Commercial sharing scheme: the AWS-3's 1695-1710MHz band. We think this environment constitutes a good fit for our work due to its simplicity and well-defined rules. Additionally, as our main tool, we use Agent-Based Modelling (ABM). This will allow us to analyze the applicability of the governance mechanisms in greater detail, since the utilization of an ABM simulation framework allows us to see how macro phenomena can emerge from micro-level interactions of independent agents. Thus, defining agents (e.g., the primary or secondary users in the sharing interactions), their behavioral rules (e.g., transmission restrictions) and the allowed interactions among them, permits us to evaluate the efficiency of the proposed governance systems at a macro level.

II. The Spectrum Sharing Framework

We focus on the framework of the 1695-1710MHz band as our base sharing model. This frequency band is part of the Advanced Wireless Services (AWS-3) defined by the FCC and the NTIA. We have selected this particular framework for its simplicity (i.e., there is only one primary user or incumbent) and the advantages of working with an existing, widely known and well-defined scheme.

This band was made available to commercial users under the Spectrum Act's mandate to identify new commercial spectrum for auctions by the FCC [43]. The original Incumbents or Primary Users (PU) are the Meteorological Satellites of the National Oceanic and Atmospheric Administration (NOAA), which are restricted to Space-to-Earth (Downlink) operations [49]. Mobile LTE handsets (MS) are the Secondary Users (SU) or new entrants. These users are limited to uplink operations only in the 1695-1710MHz band. A third participant in the selected framework is the corresponding eNodeB for each handset. These final users do not have transmission rights; however, they are in charge of the coordination functions between the Federal Incumbents and the Secondary Users.

Initially, the NTIA and the FCC only defined exclusion zones (EZ)[5] around the 27 Primary Users nationwide. In 2014, the Agencies defined a new zone as part of the sharing rules in the 1695-1710MHz band: Coordination Zones (CZ) [14]. These new zones extend beyond the border of the EZ. Their size is based on several factors, including transmit power, antenna gains in the direction of the interference, time variations of antenna gains, receiver susceptibility to

[2]Usually, a federal agency such as the Federal Communications Commission (FCC) or the National Telecommunication and Information Agency (NTIA).

[3]The Act determined the creation of a regulatory agency, currently the Federal Communications Agency (FCC), to administrate spectrum allocation according to *"public convenience, interest or necessity"* [44].

[4]Type of transmitter, the type of technology to be used and other operational parameters.

[5]Restricted zones where no new entrants are allowed to transmit.

interference, propagation effects of radio waves, mobility of earth station, etc. [10]. Moreover, transmission privileges for SU in this Coordination Zones are granted if, and only if, the proposed transmission will not interfere with the normal operations of the PU.

Based on the definitions of Exclusion and Coordination zones, authors like Bhattarai and Altamimi have developed approaches to especify the characteristics of these new sharing environment. In particular, methods for creating and sizing both resticted zones [3], [9], [10]. These approaches propose a more flexible scheme that the one suggested by the FCC/NTIA. The objective is to reduce the size of both types of zones to increase the value and incentives for potential new entrants. In this paper, we will be using the notation introduced by Bhattarai et al. in their definitions of the *"The Multi-Tiered Incumbent Protection Zones (MIPZ)"* [10]. This proposed framework for geolocation-database-driven spectrum sharing gives the option to the Primary User to adjust the size of the coordination and exclusion zones *"on the fly"*. This adjustments are based on instantaneous interference conditions and result in the definition of three types of zones around the primary users (see Fig. 1):

- **No Access Zone (NAZ):** Defined as the spatial area in the immediate vicinity of the Primary User (PU). In this zone, transmission privileges are limited only to licensed incumbents.
- **Limited Access Zone (LAZ):** This zone is defined as the spatial area surrounding the NAZ. In this region, a limited number of new entrants are allowed to transmit simultaneously. The limit in the number of simultaneous transmissions is determined by the Primary User. This limit is computed using a specific propagation model, such that transmissions outside the LAZ cause negligible interference. Hence, the contribution to the aggregate interference at the PU location can, indeed, be ignored [9].
- **Unlimited Access Zone (UAZ):** Is the region that lies outside the outer boundary of the LAZ. Unlimited transmission privileges are granted to the SU in this area, since they do not represent any "threat" to the PU's transmission in terms of harmful interference.

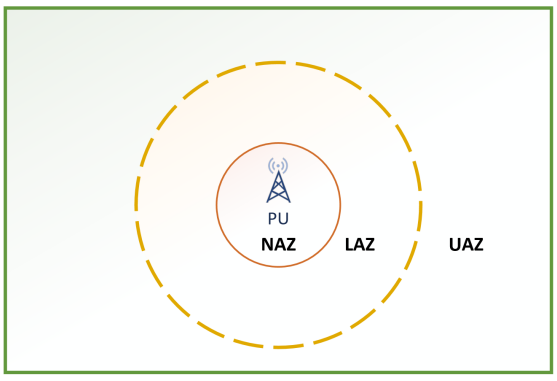

Fig. 1: MIPZ Theoretical environment layout

III. Centralized vs. Distributed Governance Systems

As previously presented, Weiss et. al [50] and other authors in the field have shown that the exploitation of radioelectric spectrum bands can, indeed, be classified as a Common Pool Resource (CPR) system. However, as Ostrom explained, defining governance shcemes for this type of goods is not an easy task [35]. In fact, to achieve a "smooth" governance process of the CPRs we need: i) resources and their uses to be constantly monitored, ii) rates of changes in the resources to be limited, iii) to maintain close face-to-face communications and dense social networks, iv) outsiders to be excluded at relatively low costs and v) users should agree to constant monitoring and enforcement of the rules [18]. Nevertheless, this is not an impossible task. Works by Robert Wade, Elinor Ostrom with Jean-Marie Baland and Jean-Philippe Platteau have recollected information on successful efforts in manners to manage and govern this type of resources [1]. The research in the field have presented several "alternative" arrangements of governance. For instance, in the analysis of Wade and Ostrom [36], [48] central governments participate, but cannot undermine the local authority, while having nested levels of appropriation, provision, enforcement and governance (i.e., a polycentric governance approach). On the other hand, Baland and Platteau [6] found that CPR users and appropiators define the rules wihtout intervetion of an external agent. Further, external agencies only assit the community in sanctioning processes. In our work, we explore the two extremes in the governance and management of CPRs, namely a centralized approach (government-centric scheme) and a distributed approach (self-governing shceme).

A. Centralized Systems

Many political theories frequently assume that individuals are not capable of reaching credible ex-ante commitments. This is especially true when there exist substantial ex-post temptations to break these previous commitments [40]. In light of these assumptions, Hobbes [24] exposed the need of a *"coercive power, to compel men equally to the performance of their covenants, by the terror of some punishment, greater than the benefit they expect by the breach of their covenant"*.

Assuming the weakness of verbal agreements, has led to many authors in other non-political fields to underscore the necessity of external agents to enforce contracts and ex ante agreements. For example, John Nash distinguished between cooperative and non-cooperative games [32]. In cooperative games, players can communicate without any restriction. Moreover, players can make enforceable agreements to improve their mutual payoffs. On the other hand, in non-cooperative games players can do neither. The main assumption behind this distinction is that agents are incapable of reaching enforcement agreements. Even if they reach an agreement, it will be of no benefit, if the probability that the intervining parties keep this agreement is low [21]. Therefore, we need the presence of a "powerful" entity, as argued by

Hobbes in his famous *"Leviathan"*, to maintain equilibrium in the system [24].

Hobbes' ideas, that date back to 1651, have led to the strong belief that without government there is no law to prevent the strong from plundering the weak, to stop the presence and proliferation of "free riders" and the dishonest taking advantage of the honest. Furthermore, Hobbes critical assumption was that *"without government there cannot be governance"*. Consequently, there would not exist a law to protect property rights and support social order [30]. As a result, we all need "the government", as the central entity, to determine and enforce the law to maintain social order.

One widely used definition of "government" dates back to 1919, where Webber defined government as a *"territorial monopoly on the legitimate use of coercion"* [29]. This definition has manny common characteristics with the notion of the "command-and-control" system. These assumptions have also been used for developing regulation and enforcement policies in several fields, including telecommunications. In command-and-control schemes only governments[6] can require or prohibit specific actions or technologies, with possible fines, sanctions or jail terms for punishing rule breakers [18]. In other words, the decision power is concentrated (i.e., centralized) in a single institution, the government, while other participants have little or no control. Many authors in the literature agree that when sufficient resources are made available for monitoring and enforcement, such approach can be very successful [18], [30], [37]. Nevertheless, if there is a lack of resources, these approaches become very inefficient. Not to mention that these mechanisms have also proved to be economically inefficient in many circumstances [18].

B. Distributed Systems

Many CPR examples have shown "alternative" governance systems for an adequate management of goods. Fishers, irrigators, herders, all CPRs' appropriators, have repeatedly shown their capacity to organize themselves, create rules, monitor others and themselves, and successfully enforce the agreed upon rules. These organizations have been able to create self-organized and self-controlled institutions without reference to central authorities (i.e., governmental institutions). Further, the institutions that have emerged have been sustained over long periods of time without participation of any external agency [36].

In the governance literature, a growing body of research suggests that Hobbes assumption, that a life without government is not possible, is wrong. This research path points to a government-less or self-governance approach. It is important to mention that these self-governing or private-governing institutions do not refer to the complete absence of law, instead they refer to the lack of a formal government or state dictating and enforcing the law. The main characteristic behind this idea is that agents, who find themselves in government-less situations or choose to eschew government, develop their own, privately-created law [29].

One of the main reasons for having central governmental institutions is the lack of compromise of the users for keeping ex-ante agreements. Consequently, the natural question in this type of private-governing arrangements is: How such created law is enforced? The short answer to this question is *"Discipline of continuous dealing"* [8], [29], [45]. The idea behind this principle is simple, if you do not behave today, I will take repressive actions. This actions include stopping the interaction with you tomorrow, telling others not to interact with you, reduce your future privileges, etc. Consequently, if you value the future interaction with a given user and his/her social network, you will not break the ex-ante agreements.

It is worth mentioning that contrary to the centralized approach, self-enforcement is not "one model fits all". Different self-enforcement contexts come with different specific problems of property protection and conflict resolution. Therefore, one particular model of private-governing institution will not necessarily be successful in a different context. Most importantly, these emerging institutions are fitted to maximize the "well-being" of the members of the community by continuously adapting their rules, norms and enforcement practises.

IV. The ABM Model

To model the spectrum sharing framework presented in Section II, we have implemented an agent-based model. An ABM consists of individual agents (persons, households, firms, technological equipment, etc.) that are represented as software "objects" having multiple characteristics. These characteristics can be constants (e.g., gender, political affiliation, etc.), variable states (e.g., age, world perception, etc.), and rules of behavior (e.g., utility function, movement, perception functions, etc.). All these independent agents interact with each other and the environment where they are placed to study the potential phenomena that can emerge [5]. Our objective is to show the emergence of global governance setups based only on the interaction of simple agents following a predifined set of rules, norms, and individual beliefs and strategies. ABM allows us to design complex models that are able to capture the effect of a large number of moving factors, which is one of the most important characteristics within Common Pool Resource management systems [20]. Many authors studying CPRs have already successfully explored this management problem through the implementation of agent-based models as we can observe in [17], [20], [26], [27]. In what follows, we describe the different parts of the system.

A. The Environment

The environment of our model is based on the definitions presented in Section II. In this way, the "world"[7], where the different agents will be placed, is divided in three zones (see Fig. 1):

1) No Access Zone (NAZ)

[6]It can be interpreted as the government figure in general terms or particular agencies such as the FCC, which are part of the Federal government.

[7]Defined as the logical or physical plane where the agents are located and interact with each other [12].

2) Limited Access Zone (LAZ)
3) Unlimited Access Zone (UAZ)

B. The Agents

The spectrum sharing framework of the 1695-1710MHz band, using both protection and coordination zones, is composed of three participants: meteorological stations, mobile handsets and base stations. These participants are the agents in our model as shown in Fig. 2. These agents have the following characteristics:

- **NOAA Meteorological Satellite (MetSat Station):** Static agent using the band for downlink communications. Its main function, as the Primary User, is to determine the boundaries (size) of the UAZ, LAZ and NAZ.
- **LTE Mobile Stations (LTE Handsets):** Defined as the new entrants or Secondary Users of the system. The Handsets have the ability to move around the environment while transmitting to their correspondent Base Stations (eNodeBs).
- **LTE Base Stations (eNodeB):** These static agents act as the connection and coordination points between the incumbent and the new entrants.

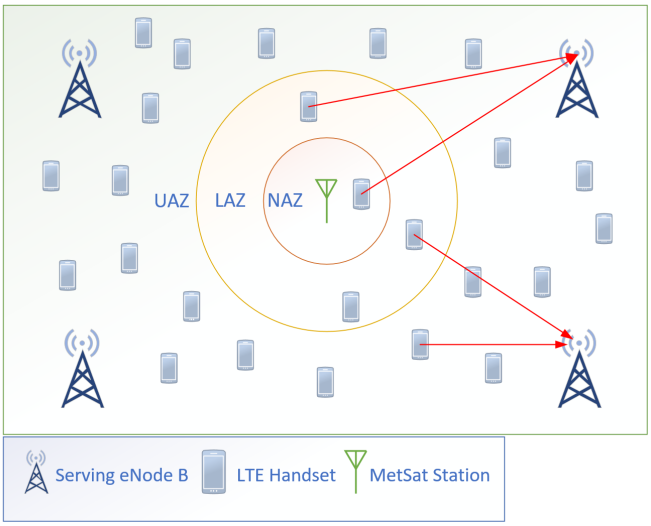

Fig. 2: The agents

C. Agents' Behavior

This section describes the initial configuration, the rules, behavior and interactions of the different agents in our model.

1) Initial Configuration: The model is set to have one PU, a MetSat, and four eNodeBs as coordination points. This number of static agents is fixed in the model to emulate the definitions of the band (see Section II). On the other hand, the number of dynamic secondary users, the handsets, is variable. The total number of handsets is dictated by the observer[8]. Each of the created agents is assigned a risk profile[9]. The assigned profile dictates the bahavior of the mobile user when moving and transmitting in the different types of zones.

2) Main Functions: This section describes the main "responsabilities or duties" assigned to each agent.

- **Primary User:** The MetSat has a central position in the simulation environment. The agent defines the initial size of the zones around it, as well as the maximum number of simultaneous transmissions that can take place within the LAZ. In the case of the centralized scheme, these values are fixed in the simulation setup[10]. On the other hand, the boundaries of the Limited Access and No Access zones are dynamically defined by the MetSat when working within the decentralized scheme. For this purpose, only initial zone sizes are defined for the agent[11]
- **Secondary Users:** The handsets are not assigned to a fixed location. Instead, mobile stations are randomly moving around the environment with no restriction. In addition, in each time period (time step), each mobile station determines whether it has data to transmits. If a transmission is required, the handset proceeds, or not, based on its own "enforcement perception"[12].
- **Coordination Points:** The agents emulating the eNodeBs are also assigned to a fixed position around the PU. Every eNodeB has a variable number of associated hansets at each time period. These stations are in charge of evaluating and defining the allowed transmission power that the handsets can utilize.

3) Interactions: The model is composed of two types of interactions: Handset-to-eNodeB and MetSat-to-eNodeB.

- The first interaction, Handset-to-eNodeB, allows the bidirectional exchange of information between the coordination points, the eNodeBs, and the new entrants, the mobile stations. The information being transmitted includes: size of the LAZ and NAZ, maximum number of transmissions in the LAZ, current number of allowed connections in the LAZ area and association signals between the base stations and the closest handsets.
- The second interaction, MetSat-to-eNodeB, is established between the base stations and the PU. The MetSat sends the size of both, the Limited Access and No Access zones to the different eNodeBs. In addition, it communicates the maximum allowed interference threshold in the LAZ and the number of simultaneous transmissions taking place in this zone. In turn, each eNodeB coordinates with the MetSat the handsets' transmissions within the LAZ.

[8] In ABM, the observer is not an interacting agent. The observer is a "being" that oversees everything that is going on in the simulation process [46].

[9] A risk profile: *"[I]dentifies the acceptable level of risk an individual or corporation is prepared to accept. A corporations risk profile attempts to determine how a willingness to take risk (or aversion to risk) will affect an overall decision-making strategy."* [25].

[10] Adjusted in the Netlogo model using the 'LAZ', 'NAZ' and 'LAZThreshold' controls.

[11] Adjusted in the Netlogo model using the 'InitialSize' control.

[12] See Section IV-D2 for additional details about how each agent measures its "enforcement perception".

D. The Rules

A main component in ABM is the definition of rules, norms and individual strategies. As defined by North in [34] institutions are usually viewed as *"[t]he set of rules actually used by a set of individuals to organize repetitive activities that produce outcomes affecting those individuals and potentially affecting others"*. Based on this definition, we can see that the 1695-1710MHz sharing framework can also be categorized as an *"Institution"*: the actions of the incumbents have an impact on the new entrants and vice versa. This new definition of our sharing scheme is key when defining the rules of the system, since we can now usthe *"ADICO Grammar of Institutions"*. The ADICO model allows us to structure and analyze the constructed institutions in the simulated systems. Further, it permits the definition of shared strategies, norms and rules as institutional statements using five components [15], [20]:

- Attributes: Describe the participants in the situation to whom the institutional statement applies (i.e., the agents of the system).
- Deontic: The deontic operators dictate the actions allowed to the agents. There are three types of operators: *obligated, permitted and forbidden*.
- aIm: Describes the action or outcomes to which the institutional statement applies (i.e., the actions related to the deontic operations for each agent).
- Condition: Are the set of parameters that define when and where an statement (rule, norm or strategy) applies.
- Sanction (Or else): Is the consequence of non-compliance to an assigned institutional assignment.

1) ADICO Definitions for the Primary Users: In Table I we can see the rules that are defined for the Meteorological Satellites (MetSat). It is important to notice the different actions for the MetSats. The ones with the white background apply in all enforcement situations (government-centric and self-enforcement), while the actions with the blue background apply only in decentralized enforcement scenarios.

	MetSat Definitions				
Agent	MetSat	MetSat	MetSat	MetSat	MetSat
Deontic	Obligatted	Obligatted	Obligatted	Permitted	Permitted
aIm	Comunicate LAZ size	Communicate NAZ Size	Communicate LAZ Threshold	Increase LAZ & NAZ size	Decrease LAZ & NAZ size
Condition	All the time	All the time	All the time	Interference Happen	No Interference
Or Else	None	None	None	None	None

TABLE I: ADICO rules for the primary user

As previously mentioned, different rules apply according to the enforcement[13] mechanism. Due to this situation, the strategies for the PU vary in each situation, as explained in what follows.

Centralized Enforcement: In the case of the command-and-control scheme, the MetSat has little control over the parameters that impact its behavior. For instance, the size of the Limited and No Access zones are given by the regulator as a fixed size, and cannot be updated by the MetSat. In the same way, the amount of simultaneous transmissions is a fixed parameter in the model. Consequently, the MetSat's only strategy in this scenario is to communicate these parameters to the coordination points. With regards to the detection rate d in our scheme[14], it is given by the effectiveness of detection imposed by the government enforcer[15]. Further, these are fixed during the complete simulation process.

Decentralized Enforcement: The PU has greater control over the sharing parameters in the self-enforcement scenario. In this case, the MetSat can update the parameters based on the past interference-events as shown in Table I. For this purpose, the MetSat can reduce the size of the LAZ and NAZ areas if it receives a good "signal" from the SU (i.e., if no interference has occurred). Otherwise, it can increase the size of both LAZ and NAZ if an interference event has occurred. However, since the detection part is also done as a self-task, the variation in the size of these zones has a direct impact on the ability to detect interference events (i.e, the detection rate d decreases due to the increase on the monitoring area). For our model, we have selected a simple linear relationship to capture the aforementioned problem, as described in the following expression:

$$d = \frac{MxE}{S} \tag{1}$$

In Equation 1, d refers to the detection rate of interference events in both the LAZ and NAZ. This rate is the product of M, which represents the minimum size of the zone to avoid interference events, and E[16], which is the effectiveness of detection of the equipment being used and divided by S, which indicates the size of the restricted areas around the PU.

One final consideration in the scheme, is the initial size of the LAZ and NAZ. As presented in Section III-B, the decision of the initial size of the areas around the primary user can vary according to past signals from other users [29]. This is also captured in the model, where different sizes (From 10% to 100%) can be utilized for both the Limited and No Access Zones.

In Fig. 3, we can see how the size of the zones, going from minimum to maximum allowed area, and the detection effectiveness of the *"enforcer"*[17] change the detection ability of the system. Therefore, we can see that, as the size of the area increases, the detection rate decreases. In the same way, we can observe that different system effectiveness values[18] produce different curves for the final detection rate in the LAZ and NAZ. In this manner, the strategy for the PU, the Meteorological Satellite, to increase or reduce the size of the areas, S, can be defined using the following expression:

[13]In the case of CPRs, the literature situates enforcement as part of the governance structure and incorporates it into the definition of rules [38].

[14]See Section IV-D2 for additional details about the detection rate in the model.

[15]Adjusted in the ABM model using the 'DetectionRateNAZ' and 'DetectionRateLAZ' controls.

[16]Adjusted in the ABM model using the 'DetectionEffectivity' control.

[17]In the case of self-enforcement, there is not a central entity as an enforcement unit [29]. Instead, there exists a detection system in place.

[18]Adjusted in the ABM model using the 'DetectionEffectivity' control.

$$S = \begin{cases} Increase, & Interference \geq 1 \text{ and } S < 1 \\ Decrease, & Interference = 0 \text{ and } S > 0 \end{cases} \quad (2)$$

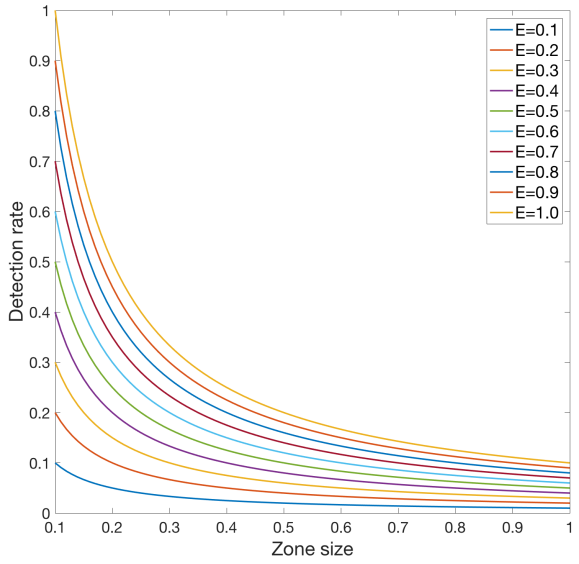

Fig. 3: Impact of the decision parameters in the detection rate

2) ADICO Definitions for the Secondary Users: In Table II we can observe the rules defined for the secondary users or mobile stations. One important thing to notice here is that the defined rules do not vary with the type of enforcement system in place. The reason behind this assumption is that the SU always follow the same rule: only transmit when authorized.

	Handset Definitions				
Attributes	Handset	Handset	Handset	Handset	Handset
Deontic	Obligated	Forbidden	Permitted	Permitted	Permitted
aIm	Associate with eNodeB	Transmit in NAZ	Transmit in LAZ	Transmit in UAZ	Move around
Condition	All the time	All the time	TXs <Threshold	All the time	All the time
Or Else	None	Sanction	Sanction	None	None

TABLE II: ADICO rules for the secondary users

The behavioral strategy for the SUs is taken from the tax evasion literature. In particular, the works by Bloomquist [11], Mittone and Patelli [31], and Davids et al. [16]. While all agents have a set rules to follow, they might break them from time to time. In other words, they might choose to transmit in the NAZ or the LAZ (when the maximum threshold has already been reached), which will cause an interference event. To account for this decision making process, our model is based on the standard microeconomic theory of Allinghman and Sandmo [2]. This economical theorem says that a given user will break the rules whenever the perceived "caught"[19] rate, p, and penalty rate, f, where $f \geq 0$, take on values that make expression 3 true.

[19]Defined as committing an infraction and being sanctioned for it.

$$p < \frac{1}{1+f} \quad (3)$$

The problem with Equation 3 is that it does not capture many other factors that are involved in the decision making pocess of a given agent. In this light, Bloomquist [11] argues that rule breakers with high compliance opportunity costs (i.e, high discount rates) are more likely to break the rules than other agents. Nonetheless, this is not the only additional factor that influence the decisions of a given agent. For instance, the time lag between breaking-the-rule and the sanction or the detection ability of the system should also be taken into account. Based on these assumptions, we have an alternative decision making expression, which is shown in equation 4.

$$p < \frac{1}{1+cr} \quad (4)$$

$$cr = \frac{fxd}{(1+r_i)^t} \quad (5)$$

With our new parameters a given user will break the rules if, and only if, expression 4 is true. Where the expression cr is the product of the interaction of the most important factors affecting the decisions of a given agent. First, t, is the number of time periods between the infraction and the detection, d, is the detection rate of the enforcer, where $0 \leq d \leq 1$ and r_i is the discount rate for the agent i. This implies that the present value of breaking the rules is inversely related as an exponent to the length of time between an infraction and its detection (see Eq. 5) [11].

Based on expressions 4 and 5, a given user will break the rules whenever the perceived "caught" rate, p, and the agent perception, cr, take on values that make expression 6 true.

$$T_x = \begin{cases} No, & \text{if } p \geq \frac{1}{1+cr} \\ Yes, & \text{Otherwise} \end{cases} \quad (6)$$

Multiple levels for the factors described at 6 are possible. Further, different combinations of these factors can result in distinct situations for the agents as depicted in Fig. 4. Thus, for example, if the detection is immediate, the decision of transmitting depends only in the detection rate, d. Moreover, when only one time period passes between the infraction and the sanction, the transmission decision is based only in the discount rate, r_i, of each agent. Finally, we observe the effect of all the features of the decision making process having different outcomes based on the discount rate, the detection time and the detection rate of the system. Showing, in this way, that the Bloomquist expression captures all the factors involved in the particular decisions of an independent agent.

In our agent-based model, all the aforementioned parameters are included. Thus, as we can see in Table III, the model uses different values for the detection rate in both the LAZ and NAZ, the average discount rate for the agents and time delay between the infraction and the sanction.

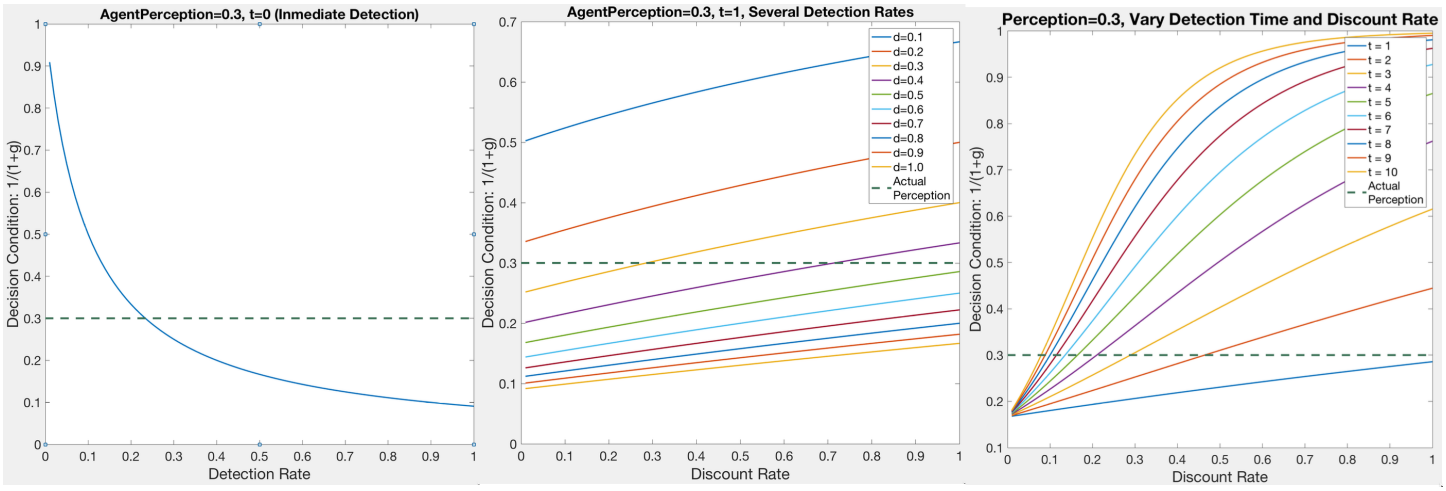

Fig. 4: Effects of the different parameters in the decision making process of a given agent

Our model is based in the perception of the users about the probability of being "caught". As shown in Table III, four types of available functions determine the perception of the agents in our system:

1) Actual: The agents know the exact detection rate, d. All agents have the same perception with no distinctions.
2) Actual + Random: The agents know the exact detection rate, d. Nevertheless, they have different perceptions based on their risk profiles and the known rate.
3) Perceived: The agents do not know the exact detection rate, d. A random perceived rate is assigned to each agent. These rates are based on their risk profiles. It is important to notice that this agent perception is updated based on its own and its neighbors[20] experiences.
4) Perceived + Random: The agents do not know the exact detection rate, d. A random perceived rate is assigned to each agent. These rates vary according to their risk profiles. This perception is not a fixed value. In fact, it is dynamically updated based on the agent's and its neighbor's experiences.

ABM Variable	Name	Levels
PerceptionFunction	Agent Perception: p	Actual, Perceived, Actual+Random, Perceived+Random
DetectionRateNAZ	Detection Rate in NAZ: d	From 0 to 100%
DetectionRateLAZ	Detection Rate in LAZ: d	From 0 to 100%
AverageDiscountRate	Discount Rate: r_i	From 0 to 100%
AdjudicationTime	Time to be sanctioned: t	From 0 to 10 Time Periods
PenaltyRate	Penalty: f	From 0 to 10 Units

TABLE III: Factors included in the ABM model

Andreoni et al. [4], among other authors in the economic field, have exposed that the level of compliance in enforcement situations is actually higher that the predicted by the expected utility (EU) theory. One of the explanations for this phenomenon is the tendency of the users to overweight low probability events [11], [33]. In order to obtain more accurate perception rates, Bernasconi [7] shows that the rates can be transformed using an empirically-derived weighting function based on rank dependent expected utility (RDEU) as denoted in the following expression:

$$p' = \frac{(1-p)^g}{[(pxg) + (1-p)^g]^{1/g}} \tag{7}$$

This new perception rate, p', captures the higher compliance problem in enforcement situations. This "weighted" rate is the product of the original perception rate, p, and a shape parameter, g. We did incorporate this economic notion in our model, using a shape parameter $g = 0.63$[21]. This shape parameter is the result of averaging three independently estimated values: Tversky and Kahneman (0.61) [47], Camerer and Ho (0.56) [13] and Wu and Gonzalez (0.71) [51]. This perception also evolves as the features of the enforcement change. For instance, if the detection rate is increased/decreased, the agents adjust their perceived rates. In the same manner, if an agent or one of its neighbors was "caught" the perceived rates are modified for future transmissions.

Finally, the ABM model includes a "social network"[22] characteristic. This feature refers to the "status" of a given agent's *"neighbors"*. In other words, if any of the neighbors was sanctioned, this has an impact in the agent's perception for future interactions. Consequently, it modifies the behavior and strategy of the agent. This characteristic was included to capture the effect of "social preasure" in the decision making process of the agents. This allows us to simulate what happens when communication and information exchange between agents is added to the governance procedures [37].

E. Implementation

Our ABM model was implemented in the *Netlogo* platform. The selected tool allows for multi-agent programming and

[20]Neighbor influence only present when the 'Social Network' characteristic is activated.

[21]Adjusted in the ABM model using the 'PerceptionWeight?' control.

[22]Adjusted in the ABM model using the 'SocialNetwork?' control.

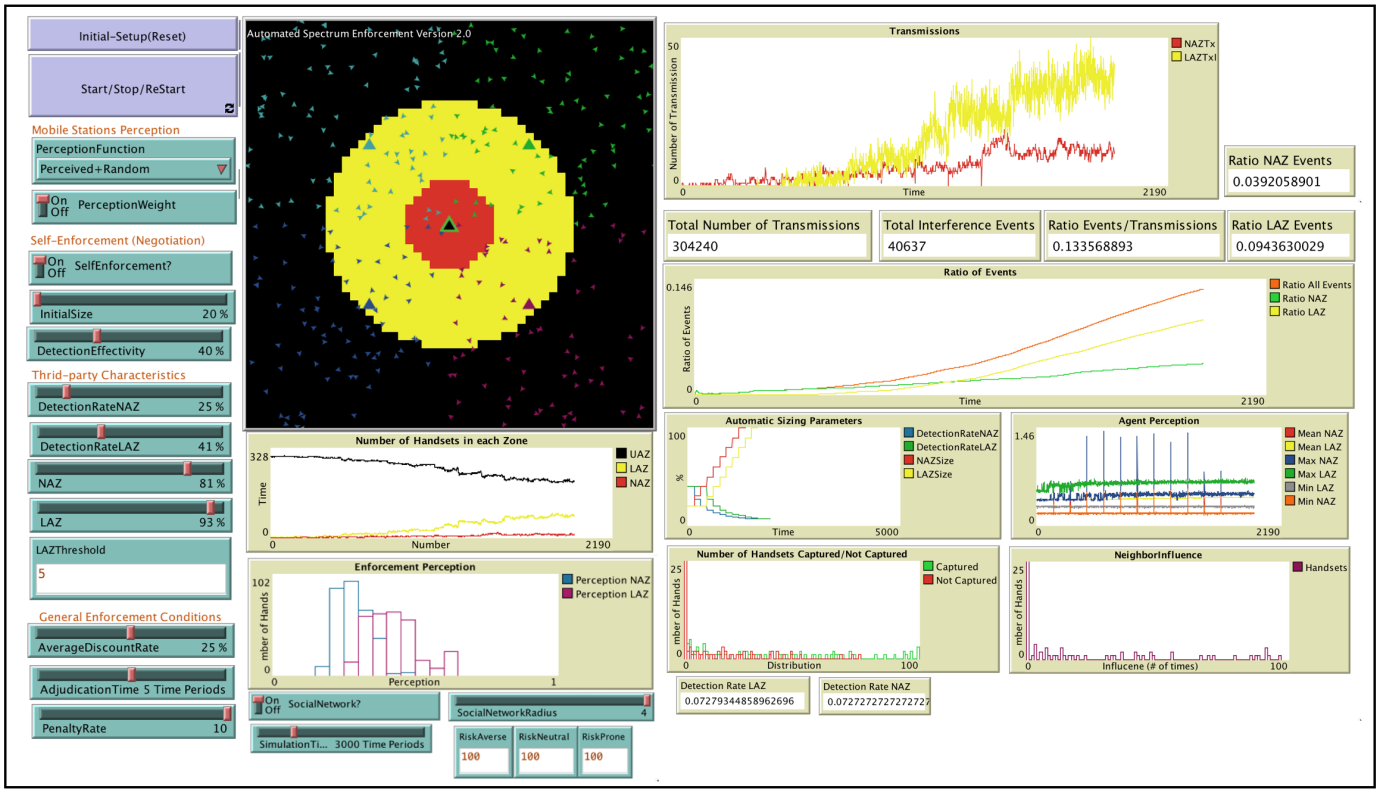

Fig. 5: Screenshot of the user interface of the model implemented in netlogo

modelling environment for simulating natural and social phenomena. One of the main characteristics of NetLogo is that it is particularly well suited for modelling complex systems evolving over time. The tool also facilitates the exploration of connections between micro-level behaviors of individuals and macro-level patterns that emerge from their interactions [46]. The resulting model is the product of the agents and their corresponding rules, norms, strategies and interactions as it is shown in Fig. 5 and described in Section IV.

V. Experiments and Results

A. The Experiments

To capture all the possible combinations of the factors of the model we use a *"Full Factorial Experimental Design"*: All combination of levels, assuming k factors, every i_{th} factor with n levels and r repetitions for each level being tested, as shown in expression 8. For our setup we have chosen a total of 10 replications[23] for each experiment to guarantee that the variance in the model is captured. As described in previous sections, both enforcement mechanisms are based in different assumptions. Nevertheless, there are some features in our model that are common to both governance systems, as depicted in Table IV.

[23]The total number of experiments, TNE, using the independent variables (i.e., factors and their levels) shown in Tables IV, V and VI is 11,520.

$$TNE = r[\prod_{i=1}^{k}(n_i)] \tag{8}$$

Independent Variables	
Factors	**Levels**
"Risk Averse" Handsets	100
"Risk Neutral" Handsets	100
"Risk Prone" Handsets	100
Average Discount Rate	10, 20 and 50
Adjudication Time	0, 1, 5 and 10
Penalty Rate	0, 10
Social Network	ON and OFF
Perception Function	Actual, Perceived and Perceived+Random
LAZ Threshold	1, 5 and 10

TABLE IV: Experiment design: Common factors

In the case of the government-centric system (i.e., the centralized framework), the agents have little or no control over the different parameters in the model. In this manner, a centralized organization is in charge of specifying the variables for the simulation process. Furthermore, the ability to detect an event (i.e., detection rate in the LAZ and NAZ areas) is a fixed value determined by the same entity with no intervention of the other agents. All these factors and their corresponding levels are detailed in Table V.

For the self-enforcement system (the decentralized framework), the different factors of the system are coordinated

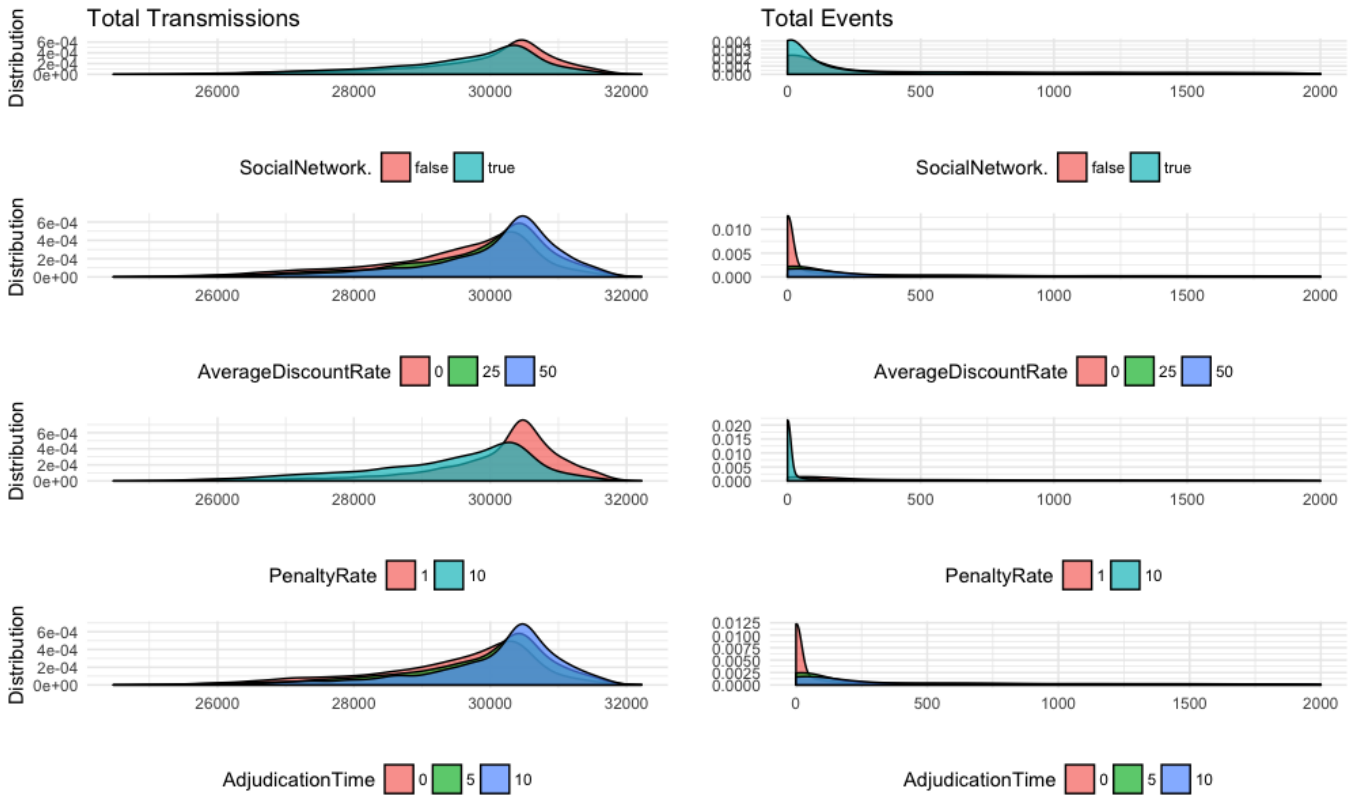

Fig. 6: Government-centric: Impact of the different factors in the number of transmissions and events in the system

Independent Variables	
Factors	**Levels**
Detection Rate NAZ	25 50 75 100
Detection Rate LAZ	25 50 75 100
NAZ Size	25 50 75 100
LAZ Size	25 50 75 100

TABLE V: Experiment design: Government-centric factors

between the agents simulating the Primary and Secondary users. Nevertheless, as an initial setup of the system, the model requires the input of two key factors: Initial Zones Size (LAZ and NAZ) and Detection Effectiveness (see Table VI).

Independent Variables	
Factors	**Levels**
Initial Size LAZ	20 40 60 80
Initia Size NAZ	20 40 60 80
Detection Efectiveness	25 50 75 100

TABLE VI: Experiment design: Self-enforcement factors

B. The Results

1) Government-centric system (Centralized framework): We will start the discussion of our results by talking about the main findings regarding the government-centric scheme. The first thing we would like to discuss about in this environment is the number of transmissions and number of events in the system. These variables are the product of varying the principal components in the enforcement framework. We can observe in Fig. 6 the impact of factors such as the influence of the peers (i.e., social network), the average discount rate of the SU, the penalty rate and the adjudication time over the total number of transmissions and the corresponding interference events in the system.

The presence of a social network (neighbor influence) reduces the number of interference events without a reduction in the total number of transmissions. In the same manner, if the users have a lower "valuation" of the future (i.e., less discount rate, r_i) the number of interference events is considerably reduced. This phenomenon is also true for the penalty rate and adjudication time. Thus, we have that with higher penalty rates the number of events is visibly reduced. Comparativly, when the time between the infraction is committed and the sanction is adjudicated is reduced from 10 to 0 time periods, the total number of events is also reduced. Even though all the parameters described in Fig. 6 have a direct impact in the number of transmissions and also the number of enforceable events, factors such as the average discount rate, the penalty rate and the adjudication delay present a more noticeable ifluence in the total number of interference events.

One of the main components in the decision making process of our model is the perception of the Secondary Users (see Section IV-D2). As shown in Fig. 8, the SUs' perception influences the number of interference events in our system. If the users know the rate of detection (i.e., actual perception

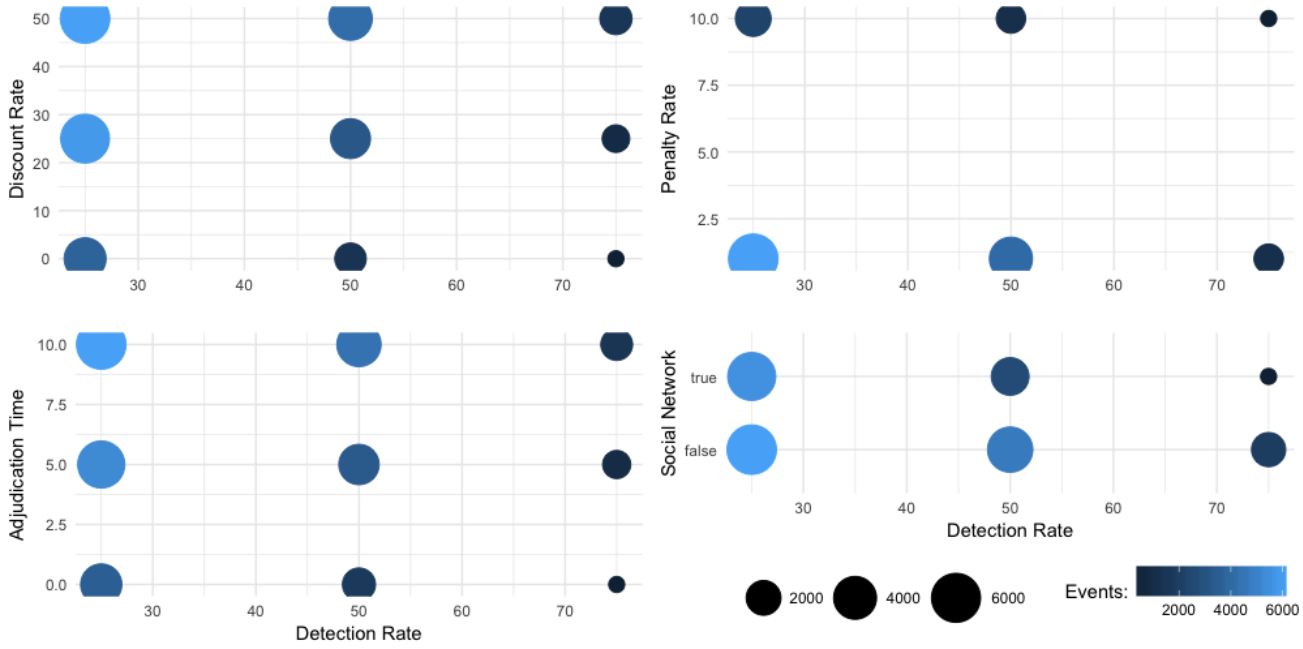

Fig. 7: Government-centric: Number of events and system factors

function), more infractions are committed. On the other hand, when the agents have only a perception of the detection rate, the number of events is considerably reduced. Nonetheless, when the detection rate is considerably high there are still some users transmitting when only a perception of reality is given, which does not happen when users known the exact rate.

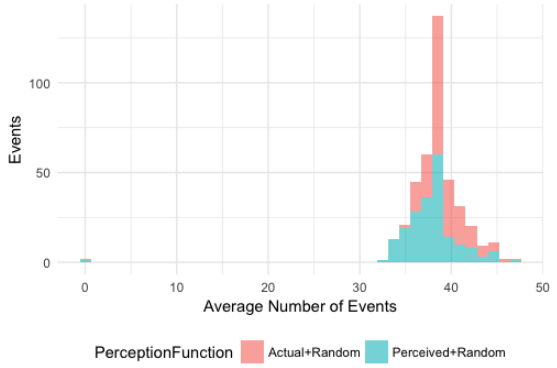

Fig. 8: Government-centric: Effects of the SU perception function

Fig. 7 shows how the number of enforceable events is correlated to the detection ability of the system and the different factors for the agents. For instance, as the penalty rate is increased, from minimum to maximum, there exists a considerable reduction in the number of enforceable events. This is also true for all other factors in the environment. Thus, if an agent has a high discount rate and knows that the adjudication time is the highest possible, it will generate more interference events. Finally, the presence of a social network has a very visible impact. In this case, we can see that when neighbors have been caught and the agent discovers this situation, the number of events is clearly reduced compared to scenarios where there is no peer influence.

One of the main characteristics in the government-centric framework is that the detection rate of enforceable events is given by an external agent, the central entity. Further, this value is fixed during the whole simulation process to emulate governmental processes of evaluating and monitoring the environment. As it can be observed in Fig. 9 this has the expected impact: as the detection rate increases the number of events is reduced in both zones, LAZ and NAZ. In fact, we can observe a stable behavior with regards to the detection rates in the system. Nevertheless, even with high detection rates (e.g., 75%), we still have several events occurring in the system.

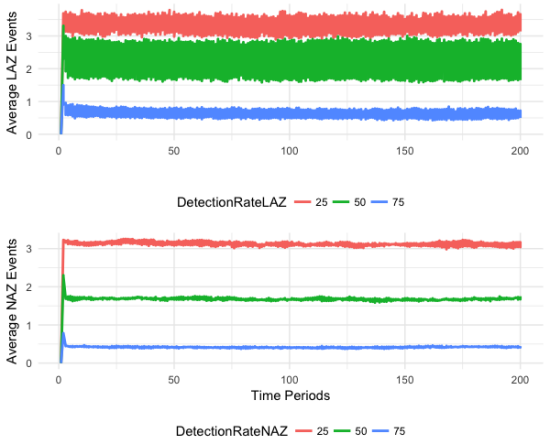

Fig. 9: Government-centric: Detection rate and events

The final part of the analysis regarding the centralized enforcement approach covers how the combination of environment factos can influence different system behaviors. In Fig. 10, we can observe the worst, middle and best case scenarios for the government-centric enforcement system. The best case scenario implies that the enforcement parameters are at their "best". In other words, the adjudication time is 0 (no delay between infraction and sanction), the penalty rate is the maximum possible and the discount rate for the users is 0. The worst case scenario, on the other hand, is the complete opposite: time delay is 10, highest discount rate and lowest penalty possible. Lastly, the middle case captures an intermediate point between the two previously described scenarios. As we can observe, only in the optimal situation, best case scenario, we have a very low number of events. Otherwise, even in the "middle scenario", we have almost as high interference events as in our worst case scenario.

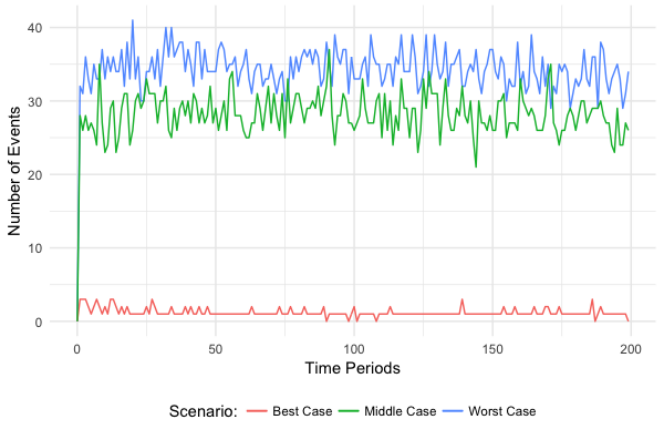

Fig. 10: Government-centric: Enforcement scenarios

2) Self-enforcement system (Distributed framework): In what follows, we will explore the main findings regarding the self-governing framework. As descibed in Section IV-D2 the size of the restricted zones LAZ and NAZ stems from the interactions between the incumbent and the new entrant. In the same manner, the ability to detect an interference event is based on the area to monitor and the effectiveness of the method used to detect potential events. In this manner, in Fig. 11, we can talk, first, about the increase in the number of events as the size of the NAZ increases. On the other hand, we can see that the resulting detection rate in the zone has a negative impact in the number of interference events. Finally, in the same manner as centralized mechanisms, the perception function influences the number of events. Hence, when agents know the detection rate, there is a higher number of events. Nonetheless, we can see that the kwonledge of the actual detection rate avoids certain unauthorized transmissions, which do occur under the uncertanty of only perceiving the rate.

In the Limited Access Zone, we have the same phenomena as we saw before (see Fig. 12). The size of the area increases as interference events and the corresponding negotiotions occur. This increase, nonetheless, is translated into an increment of

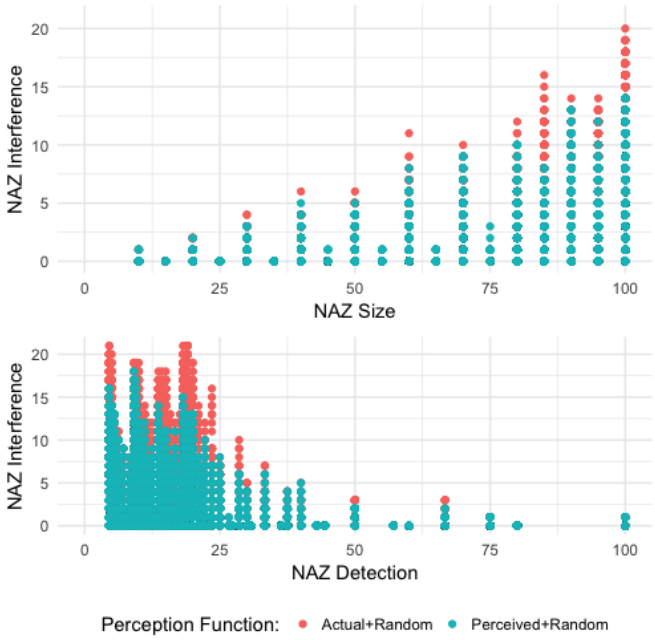

Fig. 11: Self-enforcement: Events in the NAZ

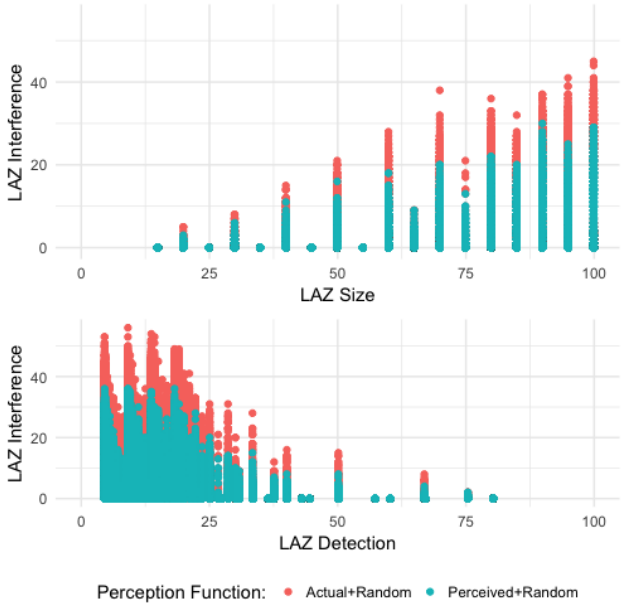

Fig. 12: Self-enforcement: Events in the LAZ

events in this area. With regards to the perception function of the SU agents, we can observe the same trend: when the detection rate is known, the number of interference events goes up. However, as shown before, the perception of the rate lead up to interference events in situations where full knowledge does not.

While negotiations of the different enforcement parameters take place dynamically between the agents during the execution of the model, two initial parameters are still necessary: the

initial size of the LAZ and NAZ and the detection effectiveness of the enforcement system. In Fig. 13 we explore the influence of these initial parameters. The initial size has the greater effect in the number of events. When considering the smallest size, the biggest signaling gesture, we can see that almost 25% of the time there were no interference events in the restricted zones. On the other hand, for bigger initial areas we see a higher number of interference events. This is more evident when the initial size is a its maximum possible size, the detection rate causes an immediate peak in the number of events from the first time period.

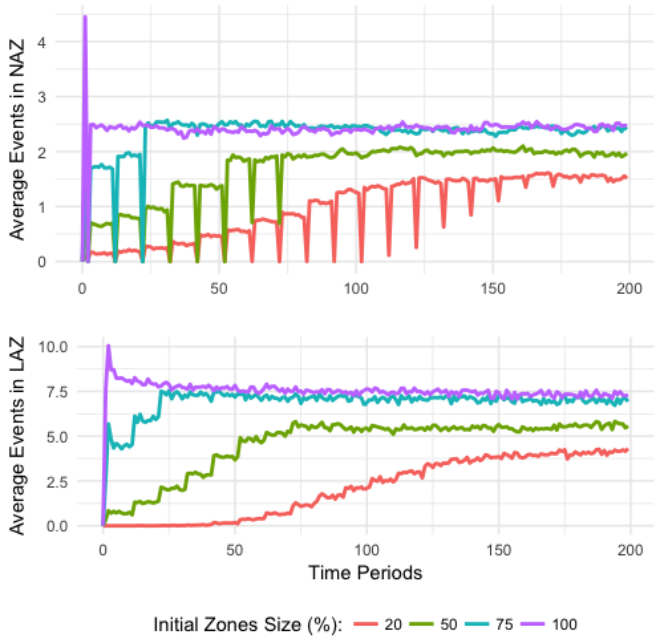

Fig. 13: Self-enforcement: Effects of the *'Initial Size'*

The other initial parameter in our self-enforcement scheme is the detection effectiveness of the system. In Fig. 14 we can observe how the"effectiveness"[24] shapes the environment. As depicted, the effectiveness alone does have an impact in the number of events. Nonetheless, it is not as clear as the initial signaling (i.e., initial size). In this case, all the scenarios have at least some interference events. However, as expected, the number of events is inversely proportional to the effectiveness: as it increases we see fewer interference events happening.

From the interaction between the initial parameters in the model and the behavior of the system, it is worth mentioning the fact that signaling is a more important characteristic in the self-governing framework. When comparing Figs. 13 and 14 we can clearly observe that the initial size has a bigger influence in the number of enforceable events than the

[24]It is important to mention that this value refers to the actual equipment effectiveness or the ability of the utilized method to detect potential interferences. It does not refer to the detection rate in the restricted zones, which is the product of the effectiveness and the size of the LAZ and NAZ areas (see Section IV-D2).

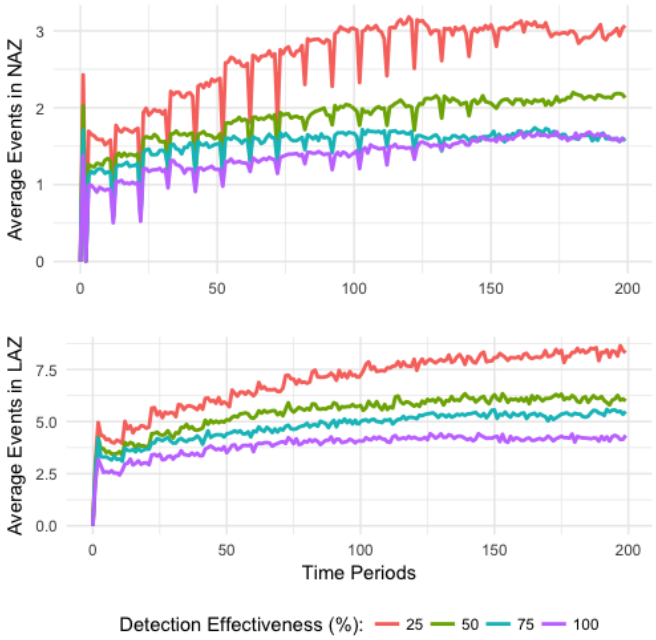

Fig. 14: Self-enforcement: Effects of the *'Detection Effectiveness'*

detection effectiveness. This beahavior agrees with other self-governing signaling[25] examples in the literature [29].

To guarantee the "discipline of continuous dealing", the agents negotiate a key characteristics in the framework: the size of the restricted areas, LAZ and NAZ (see Fig 15). The first thing to notice is that the proposed negotiation of increasing and reducing the restricted areas takes place in almost all scenarios. When talking about the initial signal between the PU and SUs (i.e., the initial size), we can see that all values converge to a stable state in which they agree to a proper area size. In addition, we can notice that when the sizes are over 50% of the maximum allowed, they are reduced to more manageable sizes. On the other hand, if the initial signaling is of a "higher trust" level (i.e., starting with smaller sizes), there is an increase in the area.

When analyzing the detection effectiveness of the system, it is also shown that it has an impact in the negotiation process. This is due to the fact that when a higher number of agents are "caught" or their neighbors were sanctioned, their perception about the enforcement mechanisms changes. Consequently, the number of interference events is reduced and the negotiations take place to increase or reduce the size of the restricted areas. In the particular case of effectiveness, we can see that when it is very low, we can expect only an increase in the LAZ and NAZ. However, for values over 50% of detection we can see a reduction in the areas, which is even more evident in very high effectiveness rates. Finally, it is important to point out that in

[25]The PU signals to the SU trust by choosing different area sizes for the NAZ and LAZ. A smaller area sends a message of trust in the SU and vice versa.

the same way as the initial size, the cases with effectiveness alone take a little more time, but they do reach a stable state.

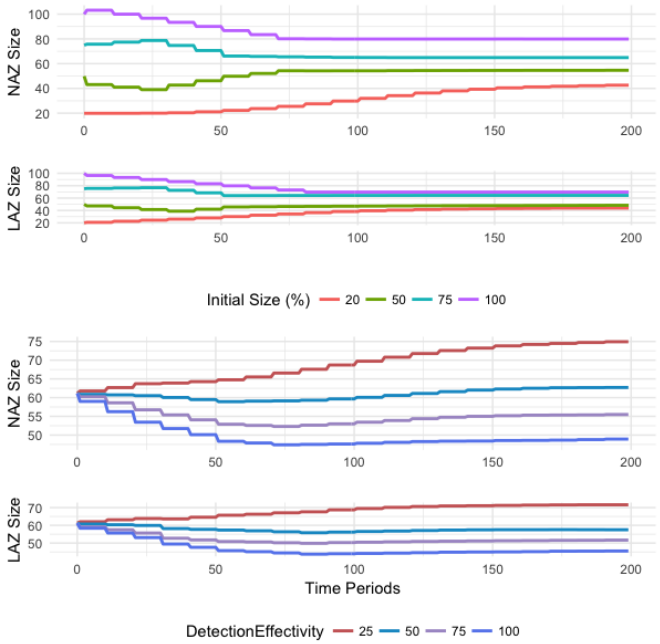

Fig. 15: Self-enforcement: Effects of the model factors in the NAZ and LAZ size

In Fig. 16 the x-axis depicts the initial signaling (i.e., initial size) and the y-axis shows the detection effectiveness of the system. The first thing to notice is the combination of a very high detection rate and the smallest initial size produces the best result in the system (i.e., the lowest number of enforceable events). Further, for all cases with a smaller area we observe the lowest number of events in the system. For higher values of the area size we observe an interesting phenomenon: although the detection effectiveness increases, the number of events is not reduced in the same proportion. This shows, again, that in the self-enforcement scenario the signaling between users has a greater impact than the effectiveness of "catching bad agents".

In Fig. 17 we can observe the relationship between factors such as Social Network, Average Discount Rate, Penalty Rate and Adjudication Time with the number of transmissions and events in the framework. In the same manner as the centralized approach, we observe a direct influence in the number of events for each of the aforementioned parameters. In that way, we see the biggest effect for the penalty rate and the adjudication time. When the penalty rate goes from minimum, 1, to maximum, 10, the distribution in the time periods with zero events is evidently higher. This is also true for the adjudication time, when the time between the infraction and the sanction is higher, there is a more uniform distribution with less "zero-events" cases. Although the social network and average discount rate seem to have a less evident impact, we can still see how these parameters influence the number of "interferences".

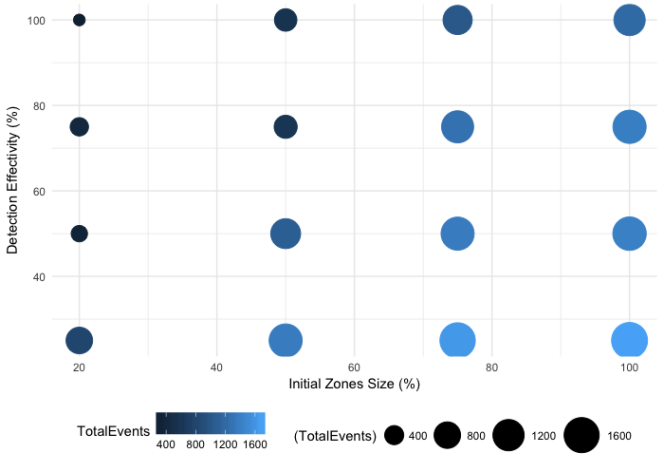

Fig. 16: Self-enforcement: Initial Size vs. Detection Rate

VI. Conclusions

We first want to highlight the construction of the ABM for spectrum sharing scenarios. It is true that Agent-Based Modelling has been vastly used in other CPR examples including fisheries, forests, water systems, etc. Nevertheless, little work has been done to explore spectrum sharing scenarios using both ABM and its CPR spectrum definition. Therefore, we showed the feasibility of constructing such a model and, moreover, the exploration of findings, while simulating governance/enforcement systems applied to our sharing framework.

This work has a different approach than other papers analyzing enforcement mechanisms. We used microeconomic concepts from tax evasion based on the perception of the users rather than, for example, utility functions. This approach has shown to be quite beneficial, since it captures characteristics such as future value of transmissions and the time delay between infraction and sanction introduced by the "enforcer". In addition, we were able to capture the effect of agents havimg full knowledge of the enforcement system in place. This was achieved by applying multiple "user perception functions" in our framework. This alternative between full-knowledge and user perception showed a strong influence in the number of enforceable events in both, centralized and distributed schemes.

In the government-centric (centralized) framework, we first need to point out that all the enforcement parameters influence the number of transmissions and number of events in the system. For instance, we observe that the presence of a social network considerably reduces the number of enforceable events. Comparativly, if the enforcement agency is agile enough to reduce the time lag between infraction and sanction, the number of events is also significantly reduced.

Our results showed that only when all the parameters are at their best (i.e., best-case scenario): low adjudication time, social network influence, high penalties, etc. we have an efficient system with a low number of enforceable events. Nevertheless, if the factors are not only at their worst, but

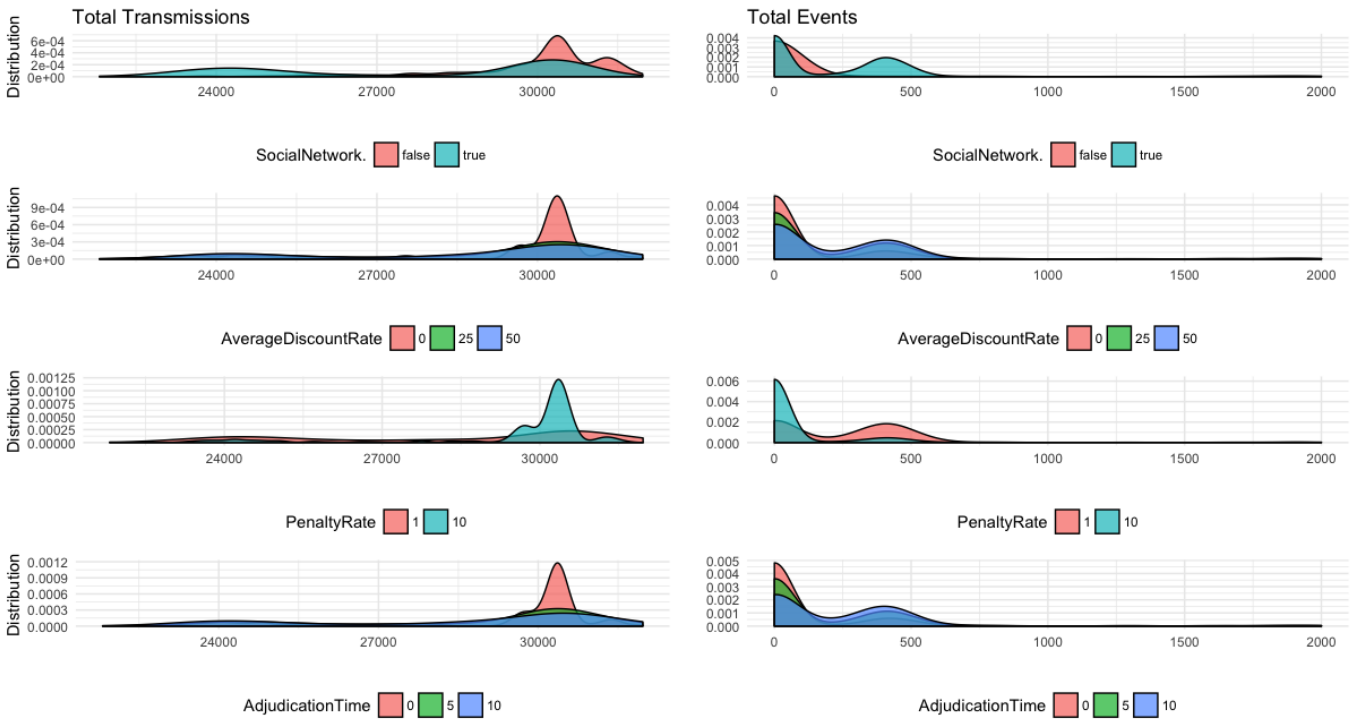

Fig. 17: Self-enforcement: Impact of the different variables in the number of transmissions and events in the system

also in an intermediate point the system has a high number of ”interference” events.

As we specified in Section III-A, in the centralized scheme the governmental agency is in charge of defining and enforcing the rules. Consequently, an external agent is responsible for determining not only the size of the restricted areas, but also the detection effectiveness within them. In this situation, we found that to guarantee a successful result, the system needs to achieve a high detection rate in both the NAZ and LAZ. With low “catching” rates of 50% and 25% the number of events is almost double of those occurring with high 75%, or more, detection rates. These results show the amount of resources needed by the central agency to monitor and control the created restricted areas.

In the case of the self-governing or distributed approach the most important aspect to point out is the successful interaction between the primary and secondary users. As we observed, the size of the areas and consequently the ability to detect “bad guys” within them stems from the negotiation process between the agents. Further, we can see that irrespective of the initial parameters, most of the time the system reaches a “stable state”.

Regarding the initial signalling (setting up the initial LAZ and NAZ sizes and the detection effectiveness of the system) we can see that the trust signal of reducing the size from the starting point has the biggest impact in the environment. Indeed, when starting with the smallest size, we can expect little or no interference events in the system. This is consistent with the “Discipline of continuous dealing” principle: A good gesture by the PU is retributed by the SU and vice versa (see Section III-B) and other examples of signaling in self-governing systems.

The perception characteristics also had a great impact in the case of the self-governing framework. In this work, we showed four different perception functions for SUs. From our results, we can see that if the users know the rate of detection, more ”infractions” are committed. On the other hand, when the agents only have a perception of this rate, the number of events is considerably reduced. Nonetheless, the solely perception of a rate leads to interference events happening where full knowledge scenarios do not.

VII. Future Work

For future additions to this work, we would like to explore additional rules of association and negotiation in the self-enforcement approach. For instance, we are interested in exploring other type of negotiations such as maximum number of LAZ simultaneous transmissions, assignment of property rights, etc. Moreover, we aim to study additional strategies and rules in the agent’s behavioral space that may influence the stability of the system.

In this work we explored the two “extremes” of governance/enforcement systems. In future works, we are interested in exploring additional options for governance frameworks. In particular, we are curious about collaborative systems appearing in the literature of CPRs. One example of this type of enforcement is the “polycentric” approach studied by Ostrom [38]. Moreover, we are interested in community enforcement systems, where the task of “catching bad agents”

is a collaborative effort of multiple agents in the same level of hierarchy.

In our model, the decision making process is based on the perception of the users. However, there are other approaches that we can explore. For instance, the utility functions and processes presented by Polinsky et al. in [42] or the considerations about enforcement characteristics introduced by Polinsy and Shavell in their work *"Punitive Damages: An Economic Analysis"* [41].

ACKNOWLEDGEMENTS

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