Wireless Policy as "Programming of Concurrent Wireless Operations"

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Abstract

The Spectrum Policy community continues to deal with a long standing problem of facilitating effective co-existence of numerous radio operators for diverse use-cases while transmitting and receiving signals over the electromagnetic spectrum. Historically, the regulator has relied on developing a socio-legal construction of "spectrum operating rights" to enforce coordination between concurrent operations with the goal of avoiding all instances of "harmful interference". However, with the recent surge in the demand for radio-use licenses and the consequent risk of disruption in concurrent operation due to harmful interference, the regulator has been forced to search for alternative ways to facilitate spectrum sharing and efficient resource utilization. In this paper, we develop a "spectrum-as-concurrent-programming" metaphor to describe spectrum policy by adopting tools developed within the domain of programming language theory. We develop a methodology that focuses on defining a specification of the radio-frequency(RF) environment which provides the context within which the behavior of concurrent radio-operations may be constrained, to replace the de-facto practice of relying on a description of radio-equipment standards. Additionally, we introduce the

rely-guarantee reasoning framework for automatically verifying the logical consistency of the set of operating rights issued by the regulator to the regulated entities.

Executive Summary

There has been a long standing problem within the spectrum policy community to determine how the regulator should facilitate coordination among numerous radio operators with diverse use cases while they utilize the nation's radio spectrum to promote the social and economic development of it citizenry.

Historically, the regulator adopted the role of a resource allocator to coordinate access among the operators through “spectrum-use licenses” when there seemed to be a large supply of the natural resource and a limited number of radio-operators for each possible use. However, over the last two decades the regulator has found that adopting the “resource-lens” has been ineffective in ensuring the successful co-existence of a large number of radio-operators with diverse uses aimed at maximizing social value. The issues of harmful interference as experienced by incumbent operators due to changes in the spectrum allocations is forcing the regulator to consider newer ways to address the increased fragmentation of the spectrum resource and to possibly facilitate improved spectrum-sharing and introducing receiver performance standards.

The field of programming language theory and distributed systems theory attempt to address the problem of coordination by focusing on the “coordination of concurrent operations” instead of the “scarcity of resources”. In this research program, we propose to introduce the tools and techniques utilized for the design and verification of concurrent computation to address the challenges faced in Spectrum Policy. We develop a methodology that focuses on defining a specification of the RF-environment and the behavior of concurrent radio-operations.

Additionally, we introduce the rely-guarantee reasoning framework for automatically verifying the logical consistency of the set of operating-rights issued by the regulator to the regulated entities.

I. Introduction

As wireless technologies proliferate, the potential for conflicts between concurrent wireless operations via interference increases. Spectrum regulators have the responsibility to ensure the effective co-existence of diverse operators with diverse uses of the spectrum resource. Historically, the regulators have attempted to handle this responsibility by adopting a "resource-centric" policy, in which they identify themselves as resource-allocators charged with the role of ensuring the efficient utilization of a finitely available spectrum resource. They allocated frequency bands to specific uses, created service rules for each band, assigned transmission rights and finally enforced the rules that they promulgated.

A common policy issue discussed over the last couple of decades is the lack of available frequencies to meet the demand by wireless operators due to a "scarcity of spectrum resources". More and more private and public resources are being wasted in disputes about radio operation that cannot be resolved bilaterally and have to be escalated to the regulator. A common thread underlying these disputes is an ambiguity in the rights that govern cross-channel interference across license-boundaries with different adjacent service types and users. To address these challenges, the regulators are actively seeking out strategies to encourage spectrum-sharing among concurrent operations with the goal of maximizing social value, rather than the de-facto goal of avoiding interference. In this vein, the regulator is currently determining ways in which transmission rights may be enhanced with reception protections via interference limits, to meet its responsibility to maximize social value through the management of harmful interference among concurrent radio operations (9).

The FCC Spectrum Policy Task Force (10) shared a widespread sentiment that "the Commission's most difficult, controversial, and unsatisfactorily resolved cases have resulted from situations in which the extent of an incumbent's spectrum rights and interference rights, and its limitation on impacting other bands or uses, were not clearly understood by the incumbent, by a new service provider and even by this Commission." The ambiguous and ad-hoc definition of cross-channel rights and responsibilities has long been recognized as a problem. Adjacent service coexistence problems continue to plague the Commission in both static allocations and within dynamic scenarios witnessed within bands with "dynamic spectrum access" technology.

We believe that some of these challenges may be effectively addressed if the Commission transitions from adopting a "resource-centric" lens to a "concurrent-operations" lens for wireless policy and spectrum management. This paper proposes a model for defining rights with the goal of maximizing social value through maximizing concurrent operations rather than minimizing or avoiding harmful interference altogether. This approach would also simultaneously avoid the delusion of "scarcity of spectrum resources" that continues to plague current spectrum policy. Though similar to the "spectrum-as-radio-operation" model (1), we enhance it with a methodology that focuses on defining a specification of the RF-environment and the behavior of concurrent operations, to replace the de-facto practice of relying on a description of equipment standards. Additionally, we introduce the rely-guarantee reasoning framework for automatically verifying the logical consistency of the set of operating-rights issued by the regulator to the regulated entities.

In the next section, we shall introduce "concurrent programming" as a suitable metaphor for spectrum policy, followed by a description of the formal framework based on rely-guarantee reasoning in Section III. We have attempted to minimize the use of mathematical equations, without losing out on communicating the ideas involved in this approach. In Section IV, we describe, using a logical framework, how the specifications of wireless operations, that are executed in isolation, can be used to derive the specifications of the system when they are made to operate concurrently. We then describe the future directions of research that we envision in Section V, followed by Section VI to capture our conclusion.

II. Programming of "Concurrent wireless operations" : A metaphor for Spectrum Policy

In the "wireless-as-concurrent-operations" frame of reference, the "resource" that is consumed and shared across operations is analogized to a real-number indexed "variable" that can be assigned a value. This is in contrast to viewing the "frequency-interval" of electromagnetic radiation as a resource within the "spectrum-resource" frame. In the following description, we use the constituent elements of a programming language to capture various aspects of radio signal processing. A radio signal is analogized to a data-value contained within a variable of a type associated with electromagnetic(EM) radiation. While one may parameterize the EM-wave at a particular frequency 'f' as a sinusoidal signal that varies over time with

$$y(t) = A(t) * \sin(2\pi f t + \phi)$$

which is characterized by the data-tuple (A, ϕ) representing the energy and phase of the signal respectively. Let a variable parameterized by real-valued frequency f be represented as x_f. The parameterization could be generalized to be the tuple (frequency, space, polarization, angle of incidence, polarization, etc) as $x_{(f, s, i, p, \ldots)}$ to capture different dimensions of 'spatial representation' that the regulator is interested in. The choice of the set of parameters is guided by Matheson's electrospace model (7) and one can assume that there exists an unbounded number of registers with one register associated with each variable x_f. . An electromagnetic wave is a transport wave that transfers energy and linear momentum without the requirement of a material-medium to propagate through. Since electromagnetic waves do not interact with each other during the propagation between the transmitter and the receiver, each variable x_f, can be understood to represent a list of values representing a set of sinusoidal signals originating from n-different transmitter sources, represented by their parameters as follows:

$$x_f = [\,(A_1, \phi_1), (A_2, \phi_2), \ldots (A_n, \phi_n)]$$

If we are to consider the representation of a signal originating from transmitter-k as a fourier series of complex-valued coefficients indexed by discrete valued j, we may consider a signal with ($\omega_j = 2\pi f_j$) to be represented as:

$$y_k(t) = \Sigma_j\ A_{jk}(t) * e^{i(\omega_{jk} + \phi_{jk})} = A_{jk}(t) * (\,cos(2\pi f_{jk} t + \phi_{jk}) + i \sin(2\pi f_{jk} t + \phi_{jk})\,).$$

For ease of notation, the variable x_f may then be represented as x_ω by replacing $\omega_j = 2\pi f_j$. If we are evaluating a set of signals originating from n-different sources, we shall have a single variable corresponding to frequency(f_j) to be

$$x_{\omega j} = [\,(A_{j1}, \phi_{j1}), (A_{j2}, \phi_{j2}), \ldots (A_{jk}, \phi_{jk}) \ldots (A_{jn}, \phi_{jn})\,]$$

Note that the contents of a variable is represented as a "list of tuples" and not just a single tuple, to capture the phenomena of multiple concurrent signal values being inserted by different transmitters. And the phenomena of interference at a receiver occurs when a receiver has to read from this "list of tuples". Ideally, in a scenario where one wishes to avoid interference altogether, each receiver would prefer to have to read a list with only one tuple entry. The fact that the list may have multiple tuple-entries signifies that at the current location of the register, there is concurrent irradiation from multiple Tx-source and that this shall be some form of interference at the receiver.

The regulator, in this paradigm, is like the compiler and the run-time engine that conducts static and dynamic checks of correctness on the operation of the concurrent programs. Rights to own and use a resource (the variables) is obtained by the program by ensuring that the variables lie within the scoping context of the operation, or by satisfying the conditions imposed by the run-time engine. In the context of radio-operations, the RF-spectrum serves effectively as a global shared-resource, to which every operation has concurrent read and write access.(This is similar to the way concurrent users can edit a shared Google-Doc.) The operating rights represent the permissions that shall be imposed on the operations, to enable them to coordinate access to the variables, in a manner that permits maximal concurrent operation (representing maximal social value), with constraints that help manage the extent of interference lies within permissible limits, or even to avoid "harmful interference" altogether. These permissions may be imposed by adopting a type-system for the program or by defining a logic that can be used to specify the correctness criteria of the program.

The situation in which the regulator has assigned rights to concurrent radio-operations to operate in a certain manner, is analogous to having a concurrent program generate executable code after compilation. However, the occurrence of a run-time bug during execution of the program, is representative of the "harmful-interference" based conflict in the wireless domain. The regulator thus operates as the programmer who adjudicates which operation is responsible for the violation of the operating-permissions (bug), and then modifies it's permissions to ensure safe coordination between the conflicting parties in future. The metaphor mappings of how concurrent programming metaphor can be used to represent wireless concepts is as described in Table 1:

Target Domain	Source-Domain
WIRELESS	CONCURRENT PROGRAMMING
Spectrum	Global context of real-number indexed variables
Signal	List of tuple-values assigned to a variable
A resource	An indivisible variable whose access is managed between concurrent operations
Radios	RD/WR Commands/Instructions
Frequency	Index of a variable
Wireless Operation	Programs
Interference	Data-race between concurrent operation
Authorization to Operate	Permissions
Regulator	Programmer developing concurrent program
Usage/Access Rules	Context and ownership of a variable
Resource Use	Reading/writing into variables
Resource Utility	NA. Determine if a variable is utilized in program or not
Resource Scarcity	NA. Availability of distinct variables for the computation

Environment	Collections of actions and behaviors of other radio systems operating concurrently.

Table 1: Mapping between metaphor of "concurrent programming" and concepts used in Wireless Policy.

Every dominant framework adopts a set of self-evident concepts and develops a set of perspectives based on these assumptions. The value of a new metaphor fundamentally lies in its ability to provide novel perspectives regarding both the premises and the conclusions of a dominant framework. For example, the 'wireless-as-a-spatial-resource" expounds the idea that "spectrum-is-scarce"; However, there is evidently no constraints on the number of real-number indexed variables that may be created in a program, nor on the number of operations that can operate upon a variable over different time durations. This feature of the model invites the analyst to re-examine the 'scarcity of spectrum' concept, but also calls into question as to what a resource is and what factors truly contribute to "harmful interference", even within the context of an abundantly available resource. A further comparison of the two types of models is presented in Table 2.

Attribute	Concurrent Programming-Inspired	Resource-Inspired
Worldview	Process/Program (Radio-Operation)	Substance (spectrum)
Ontology	Variable, Value, RD/WR Commands over Registers	Spectrum, signals, radios
Resource	Variables	Spectrum

Division of resource	RD/WR access to variables - based on context and ownership	Regions in frequency and space-time
Scarcity	Scope of Concurrent operations	Frequencies
Over-use	Not-defined	Over-occupation of the spectrum band with signals
Regulatory Approach	Static (compiler) and dynamic(run-time) determination of correctness	Agency defined property rights to spectrum assets; conflict resolution-via administrative decision-making/courts
Rights	Ownership rights and permissions via type-theory. Constraints imposed by the run-time engine	Primarily transmitter parameters in frequency and geography. Duration typically 15-20 years; non-renewable in some places, renewal expectancy in others; sold at auction
Non-engineering conditions	Not included in the definition	Common (easily imposed by analogy to real-estate)
Incumbent protection	NA. Transfer of ownership of variables/ updating of context. All operations are treated equivalently, in the interest of maximizing concurrent operation	Implicit in the political process to define transmit parameters in spectrum usage rights

Table 2: Comparison between “spectrum-as-concurrent-radio-operations” and the de-facto metaphor of “spectrum-as-resource”.

The programming-language model adopts a representation of both the resource and the operations(processes). The resources are variables. The intention is not to purely focus on the allocation of resources(i.e. Mapping a resource to an owner among the operations); But instead, the focus is on ensuring the correctness (validating both safety and liveness properties) of the operation which is related to the "spectrum-as-radio-operation" model (4).

In the domain of programming language theory, there are two types of content that can be held within a variable : "Expressions" and "Values". A "value" is a technical term, unlike in common usage. "Values" are the final data-assignments of standard data-types like integers, strings, etc. "Expressions" are the entries on which further computations can be conducted to finally obtain a value.

In this model signals are different from spectrum. Just the way 'signals are carried by spectrum' in the physical world, 'values are assigned to variables’ within the programming language context i.e. (RF-Spectrum Frequency, Signal) = (Variable, Value).

Radios perform the function of the read and write operations in a programming language. In this model, we analogize the mechanism of receiving and transmitting signals over spectrum to read/write operations into a physical register in a computer. A wireless operator’s deployed infrastructure can be considered to be analogous to a concurrent program that operates over the machine-infrastructure. Harmful radio interference is like a data-race interference that occurs between the concurrent-operations in a concurrent program that have read and write permission to the same shared set of variables . However, an important difference of radio-operation within this context is the fact that a read operation implements a computation of summarizing the list of tuples associated with each variable, in contrast to just copying a value from a memory-register into a variable within traditional abstract machines used in programming languages.

Additionally, a write-operation simultaneously updates multiple registers associated with a set of frequencies with signal-parametric values, in contrast to modifying a single register at a time in traditional von-Neumann architectures.

We are thus attempting to define a new computational model that's based on electro-magnetic wave propagation and its interactions with matter. The unique feature here is that the "true-state" of any variable is a list of tuples. Whenever any receiver subsystem attempts to “read” from a set of variables, it does not simply access the entire list of tuples. It can only obtain a "computational summary" of the information contained within the lists associated with multiple variables. This "summary" is representative of the "computation" implemented by the filters of a receiver antenna. The "read-operation" is itself a computation that can be represented mathematically as a function

$$\text{read-operation} : (\text{list of tuples}) \rightarrow \text{value}.$$

The ‘read-operation' is implemented in practice by the receiver-subsystem of a radio. Conversely, we can understand the write-operation as one in which the different sinusoidal components of a signal (obtained from the Fourier decomposition of the signal) are simultaneously appended into the list-value stored within the respective frequency-indexed variables. Thus, it is in the definition(semantics) of the `read-operation` and the `write-operation` that we capture the dynamics of "interference" and "energy leak" , as observed in the physical world.

III. Rely-Guarantee Reasoning : A unified framework for the formal verification of Transmission Permissions and Receiver Protections

Concurrency is a crucial element in modern software systems that operate on multicore processors or distributed systems. The correctness of concurrent programs is notoriously difficult to verify because of the non-deterministic interleaving of concurrently running operations and the exponential size of the state-spaces that need to be examined for exploring these interleavings. Additionally, if we wish to extend the analysis for a system with unbounded number of concurrent operations, it is important to develop a scalable reasoning framework that is compositional.

Before we examine the methodology that we intend to use, it might help to consider a situation of concurrent operation that we are all familiar with. Consider that you are driving a vehicle on a three-lane road, along with four other vehicles, one ahead of you by 30ft, one behind you by 40ft, one on the right lane in front of you and one on the left-lane slightly behind you. The description of the current configuration of the vehicles on the different lanes, with respect to your vehicle's location, can be understood to be a description of the "state of the environment". Now, to ensure the safe operation of your vehicle it is necessary to know the arrangement of the vehicles around you. But, this information is not sufficient to ensure your safety. You also need to be able to "rely"-on the neighboring drivers, to "indicate their intent to change lanes" before they change lanes. Similarly, they need you to provide a "guarantee" to them that you shall also use the left-/right- indicators to express your intent to change lanes before actually changing lanes. Thus, only when you are empowered with this collection of rely-/guarantee- conditions that help to summarize the behavior of your neighbors and yourself, can the road-transport regulator ensure the safe and concurrent operation of all vehicles on the shared-resource of the road-lanes.

Existing mechanisms being considered within current regulatory practices, for the purpose of improving the efficiency of spectrum utilization, include transmission rights and the reception protections based on interference limits. These mechanisms make the assumption that characterization of the RF-environment, possibly through a probabilistic description of electro-magnetic energy over a frequency interval, is both necessary and sufficient for avoiding harmful interference. Sadly, it is only necessary, but it is not sufficient. About three decades of research within the programming language community has helped us realize that it is not sufficient to have a methodology that "only describes" the state of the system (RF-environment). There needs to be a mechanism by which the behaviors of the concurrent wireless operations can be specified with respect to the state (RF-environment).

Rely-Guarantee reasoning (6) is a well-known method for the verification of shared-variable concurrent programs. Under this reasoning framework, each process (wireless operator) views the set of all other processes in the system as its environment. The interface between the process and its environment is specified using a pair of rely- and guarantee conditions. The rely condition R specifies the process's expectations of state transitions made by its local and global neighbors (other concurrent wireless operators / regulated entities). Since the rely-condition specifies all possible behaviors that might interfere with the process, it serves as concise and compact representation of the exponential size of permissible interleavings of the independent transitions of each one of its neighbors. The guarantee condition G specifies the state transitions made by the thread itself, thus signifying the extent to which it will interfere with its neighbors. R and G are predicates (mathematical function over a set of variables that returns either true or false) over a pair of states i.e. the state at which the transition begins and the resultant state into which the transition terminates. The specification of a program is thus a quadruple (p, R, G, q), where p and q are unary-predicates describing the pre- and post-conditions of the operation. A process satisfies its specification if, given an initial state satisfying p and an environment whose behaviors satisfy R, then each atomic transition made by the process satisfies the guarantee-condition G and the state at the end satisfies the post-condition q. Thus, for the purpose of formally specifying the correctness of a radio-operation, one requires:

1. Pre- and Post- Conditions: Unary predicates over the initial and final states achieved as a consequence of the operation.
2. Rely- and Guarantee- Conditions : Binary predicates that summarize all the transitions that may be executed by the local and global concurrent operations.

For the purpose of considering the correct functioning of an independent wireless operator (say T-Mobile), each one should define its own pre- condition and post- condition as the minimal expectation it has regarding the state of the RF-environment. However, the wireless operator will be dependent on the regulator, i.e. FCC, for guidance regarding its rely- and guarantee- contracts, as these are specifications of the behaviors of other agents. These contracts impose constraints over a pair of states of the system, with the first state capturing the RF-environment at the beginning of their transitions and the other state capturing the conditions of the RF-environment at the end of their permissible transitions.

Let's assume that the RF-environment state is represented by a frequency-interval s. In the current regulatory scheme, we may compare the pre-condition(P(s)) and post-condition(Q(s)) to be associated with the description of transmitter rights and reception permissions within the concept of "interference limits". However, we do not currently have a mechanism for specifying and summarizing the behaviors of the neighboring entities, or of an individual wireless operator as binary predicates - Rely (R(s,s')) and Guarantee (G(s, s')) conditions, where s and s' are representative of the starting state and terminal state of the RF-environment due to a neighbor's behavior. Thus, the challenge for the FCC is to facilitate a mechanism of defining operating contracts that incorporates not just the definition of interference limits, akin to the pre- and post-conditions, but also to define a mechanism to summarize the behaviors of the concurrent operations that contribute to interference.

IV. Parallel composition for scalable verification

To ensure two parallel processes can collaborate without interference, we need to check that their interfaces are compatible in the sense that the rely-condition of each thread is implied by the guarantee of the other. The rule to handle this can be understood as follows. Assume that we have two concurrent processes C1 and C2 each with their respective specifications as (p1, R1, G1, q1) and (p2, R2, G2, q2). Also, let's assume that the programs when operated concurrently (expressed as C1||C2) have the following specification (p,R,G, q). Then we can guarantee that the two programs shall operate correctly when they are forced to execute concurrently only if the following conditions are satisfied:

a) $p1 = p2 = p$
b) $R1 = R \vee G2$
c) $R2 = R \vee G1$
d) $G = G1 \vee G2$
e) $Q = q1 \wedge q2$

where we understand the binary operators ($\vee$ and $\wedge$) as Boolean OR and AND respectively. The rely and guarantee conditions for C1 and C2 can be understood to be compatible with each other, since: (a) $G1 \Rightarrow (R \vee G1) = R2$, and (b) $G2 \Rightarrow (R \vee G2) = R1$.

Thus, the rely-contract of each process in isolation (R1 or R2) captures the behavior of both: (a) its neighbor operating in isolation (G1 or G2) and (b) its rely-contract when run concurrently with its neighbor (R). This methodology provides an alternative interpretation to the requirements for modularization and compositional analysis that were identified in the spectrum consumption models (SCMs) (8).

To help understand the concepts that have been introduced in this section, it might help to reflect on them in the context of the Receiver Interference Immunity NOI (9). We can model the differences between specifying equipment standards and specifying the RF environment as follows:

1. Specifying the equipment-standards is equivalent to defining the semantics of the `read-operation`
2. Specifying the RF-environment corresponds to defining the unary pre- and post-conditions for the radio-operations.
3. Specifying the interference within the system corresponds to:
    a. Semantics of the ‘read-operation’
    b. Summarization of all possible interleavings of the behavior of the neighbors within the binary-predicate Rely- and Guarantee- conditions

V. Benefits of Rely-Guarantee reasoning for Wireless Policy

The benefit of this methodology is that we have a reasoning framework that can be used by the regulator under different scenarios. From a given set of rely-conditions and guarantee-conditions that are chosen by the regulator, it can verify ex-ante whether these constraints are logically sound and consistent for all the participating entities. Additionally, it can avoid or minimize some of the pitfalls that arise from only defining interference limits - for example, scenarios in which both transmitter and receiver-devices operate in conformance with the regulator prescribed transmission rights and reception protections, but still experience harmful interference.

If the regulator has received a set of rely- and guarantee- conditions provided independently by the concurrent wireless operators then, the regulator can use the automated reasoning framework, based on rely-guarantee reasoning, to determine instances where conflicts or harmful interference can possibly occur. The conflict scenarios are determined ex-ante, by the existence of logical inconsistencies in the rely- and guarantee- conditions specified by the participating operators i.e. neither the regulator, nor the regulated entities need to wait until their systems are deployed to determine instances of harmful interference. Additionally, the regulator can derive or infer a verified minimal set of rely- and guarantee- conditions that may be assigned to each of the conflicting wireless operators to ensure that they shall not experience harmful interference. These new sets of conditions can then be either packaged into assets (or operating rights) that are traded between the wireless operators, or it may provide an instrument for conducting negotiations between the conflicting parties.

VI. Future Research Directions

In the earlier sections, we have introduced a possible bridge between two domains that have existed isolated from each other - spectrum policy and programming language. However, we expect that the methodologies developed within the PL-community cannot be used in a plug-and-play manner within spectrum policy, as they were developed with different use-cases in mind. This suggests that we have identified a fertile ground with various interesting research questions that invite the engagement of scholars and practitioners from these two different fields.

In particular, a reasoning framework that is based only on the description of the unary-predicates (pre- and post- conditions) may be defined to be compatible with the use of interference limits in wireless policy. However, this has been found to be suitable only for verification of the correctness of programs that operate in isolation from each other with no mechanism for interfering with each other i.e. for programs that run on different desktops. The verification system thus defined, corresponds to the system of Hoare Logic as applied to the verification of sequential programs.

In a scenario where there are concurrent programs operating on the same desktop such that they share resources like computing power and memory, it is imperative that the correctness conditions are defined based not just on the state of the system, but also, with a mechanism to describe the behaviors of an operator's neighbors. The Rely-Guarantee reasoning framework introduced earlier helps to address this gap in the current practices of the regulator.

However, one of the challenges that exists with this methodology, is that it is difficult to formulate in practice the rely-guarantee conditions for each program. We would need to conduct more research to determine how these conditions can be defined formally for wireless operations. New automated reasoning tools, specialized for the purpose of reasoning about concurrent wireless operations, need to be designed and developed before it can be adopted by the regulators and the diverse set of regulated entities providing diverse services.

VII. Conclusions

In this paper, we present a metaphor and a formal methodology that shall enable the regulator to promote effective co-existence and tunable co-ordination between wireless operators as they operate over shared spectrum resources. We have presented our formulation of the "spectrum-as-concurrent-programming" metaphor as an alternative to the de-facto resource-centric view adopted within Spectrum policy. We adopt tools developed within the domain of programming language theory to derive a formal methodology that focuses on defining a specification of the RF-environment and the behavior of concurrent operations for guiding effective co-existence. This method seeks to replace the standard practice of relying on regulatory mandates that describe equipment standards - both transmitter and receiver standards that should be used by the different operators. Additionally, we introduce an ex-ante strategy for avoidance of harmful interference, that is based on rely-guarantee reasoning. This framework is amenable to automated reasoning and can be used to verify the logical consistency of the set of operating-rights issued by the regulator to the regulated entities. We thus propose a research program that seeks to bridge the two historically isolated fields of Spectrum Policy and Concurrent Programming.

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