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A Systems Approach for Solving Inter-Policy Gaps in Dynamic Spectrum Access-Based Wireless Rural Broadband Networks

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ABSTRACT In this paper, we articulate the challenge of multiple intersecting policies for the realization of rural broadband networks employing dynamic spectrum access (DSA). Broadband connectivity has been identified as a critical component of economic development, especially during the COVID-19 pandemic, and rural communities have been significantly (and negatively) affected by the lack of this important resource. Although technologies exist that can deliver broadband connectivity, such as 4G LTE and 5G cellular networks, the challenges associated with efficiently deploying this infrastructure within a rural environment are multi-dimensional in terms of the different dependent policy decisions that need to be considered. To resolve this issue, we describe how systems engineering tools can be used for representing these intersecting policies such that system configurations can be optimized for efficient infrastructure deployment and operations. One technology requiring increased attention is DSA, where licensed and emerging wireless services can coexist together via spectrum sharing. However, implementation of this technology is challenging, where highly efficient Radio Access Technology (RAT), available spectrum, and user requirements need to be precisely aligned. All these elements to be configured are typically described by independent policies. While DSA is more complicated than previously used spectrum allocation schemes, inter-policy gaps occur that ultimately decrease the network's efficiency. Consequently, a systems engineering framework has the potential to obtain the optimal solutions although the systems and wireless communities conceptualize and scope problems differently, which can impede collaboration. We present the use case where 4G LTE RAT technology employing DSA applied to digital terrestrial television (DTT) frequency bands can yield spectral efficiency loss when the different policy dimensions are not sufficiently accounted for within the use case. Numerical experiments have shown that in an example rural scenario the availability of rural broadband can increase from 1% to 21% of locations if the inter-policy gaps are removed.

INDEX TERMS Dynamic spectrum access, systems engineering, iceberg model, policy, spectral efficiency, rural broadband.

I. INTRODUCTION

Wireless communications has become a critical component in many aspects of today's societies, including education, employment, healthcare, social interactions, and entertainment. This increase in demand is reflected by overall bandwidth usage, where studies are showing mobile data traffic increases as large as 17-fold over the last 5 years [1]. Wireless connectivity enables users' mobility and reduces the cost of infrastructure creation. However, existing wireless

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broadband installations often do not support sufficiently high data rates, thus limiting economic development opportunities. New approaches are needed to help the 14.5 million Americans that still do not have adequate high-speed broadband access [2].

It is relatively straightforward and profitable for a wireless network operator to build a few base stations within a densely populated region since there is access to resources required for the network operation (*e.g.*, electricity, backbone fiber network) and a high population density market that justifies the business model for such an investment. Conversely, rural broadband wireless network build-out is more challenging and less economically efficient due to low population densities which leads to low return on investments. Moreover, a wide coverage range requires a base station to have antennas mounted at high elevations (increasing costs) as well as emitting high power at relatively low frequencies due to the physics associated with electromagnetic propagation [3]. Unfortunately, there is an insufficient number of low frequency bands available for rural broadband (*e.g.*, below 1 GHz [4]). This is a result of past spectrum allocation policies providing fixed and long-term licenses to use a given frequency band. However, worldwide measurements revealed these licensed systems rarely utilize their assigned frequency resources efficiently from a time and space perspective [4].

This was the main motivation for the development of Dynamic Spectrum Access (DSA) technologies [5], where more than one system can utilize a given frequency band if the interference between these systems is kept at a sufficiently low level. While this can potentially yield a sufficient quantity of ''low frequency'' spectrum for rural broadband wireless access, it requires precise spectrum management of the spectrum access via designated policies, *e.g.*, Dynamic Spectrum Alliance rules [6] for DSA in the Digital Terrestrial TV (DTT) band (approximately from 470 MHz to 790 MHz), Citizen Broadband Radio Service (CBRS) with Spectrum Access System (SAS) [7] in the 3.5 GHz band.

Efficient rural broadband will need to use DSA technology that will enable access to available spectrum via radio transceivers based on a given standard (*e.g.*, LTE or 5G) while providing connectivity for higher-layer applications (*e.g.*, video calls). All these elements are specified by policies, such as the LTE standard for Radio Access Technology (RAT) or International Telecommunication Union (ITU) standards, *e.g.*, [8]. Each policy plane has to be properly configured while the connection is established. Although each of these policies is typically well defined and provides a high level of efficiency, the intersections between them can have gaps resulting in inefficient resource utilization, thus yielding for end-users expensive, low speed, and/or unavailable wireless broadband in rural areas. While some DSA rules are available for more than a decade (*e.g.*, first standard for DSA in DTT band, IEEE 802.22, was released in 2011 [9]), this technology still presents significant burden in effective utilization of electromagnetic spectrum.

One approach to resolve the gaps is to reframe this challenge as a systems problem to identify a potential solutions. When examined in isolation, each policy can be justified. However, the inter-policy gaps are only highlighted when examining the integration between these policies and new technologies. The field of systems engineering has developed frameworks and tools for addressing these types of integration and interoperability problems [10] (*e.g.*, model-based systems engineering (MBSE), Digital Twins). However, to effectively design and execute systems-level solutions, it is critical to engage experts from multiple disciplines. This type of interdisciplinary research is challenging because disciplines have different conventions, terminology, and ways to scope problems. In this paper, we aim to improve the dialogue between wireless and systems researchers to help uncover the solutions space between these disciplines using rural broadband via Dynamic Spectrum Access as an important use case.

Specifically, we explore one example of how policy gaps inhibit technology innovation. In Section II, we outline the proposed systems framework for approaching this challenge. In Section III, the DSA concept is introduced while in Section IV, we describe policy intersections for the spectrum, RAT and user planes. In Section V, we focus on the RAT and spectrum access plane intersection to present the problem quantitatively. In Section V-A, we present an example of the potential throughput loss as a result of inter-policy gaps for LTE systems accessing the DTT band using Dynamic Spectrum Alliance rules [6]. Finally, Section VI summarizes the conclusions.

II. SYSTEMS THINKING FOR WIRELESS RURAL BROADBAND CONNECTIVITY FRAMEWORK

Systems thinking, originally coined by Richmond [11], is characterized by an ability to see the interrelationships between the whole and the parts. Thus, a systems thinker should be able to understand both the forest and the trees to anticipate how changing the trees will affect the forest. In the context of wireless rural broadband connectivity, this involves understanding: (1) the technologies, (2) the policies that govern those technologies, and (3) the consumer applications and lifestyles that impose requirements on the network operation (see Figure 1). For example, rural consumers tend to live in areas with low population density. Thus, it is advantageous for wireless networks to operate at high power in low frequencies to reach more consumers. However, existing policies restrict access to these frequencies, which ultimately are partially unused.

One tool for encouraging systems thinking is an iceberg model, as shown in Figure 2. The iceberg model is used to facilitate efforts to uncover the underlying structure that contributes to an event. In the iceberg analogy, parts of the system are visible, namely events. However, other elements of the system are less visible or under the water line, namely patterns of behavior, underlying systematic structures, and mental models. Each layer of the iceberg reveals a deeper layer of the system. The iceberg model uncovers the root

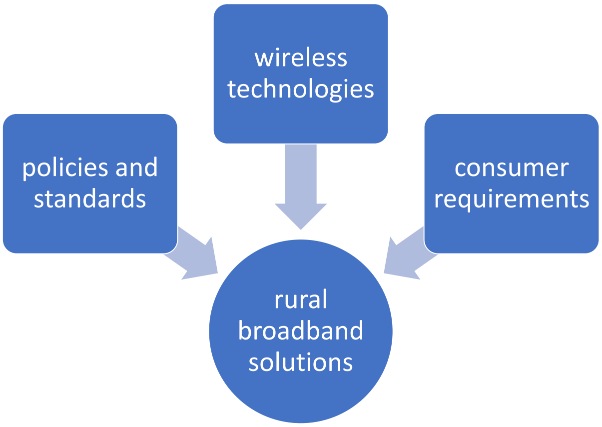

FIGURE 1. Systems thinking can identify better solutions for rural broadband.

causes of an event to support efforts to develop solutions and interventions [12]. Ultimately, the iceberg models helps us understand and contextualize a problem, but does not prescribe a specific solution. In the context of rural broadband, the observable events are the low Quality of Service (QoS), high cost, and digital divide. Lack of affordable high-speed broadband access reduces the economic development potential of rural communities.

The patterns of behavior describe a higher level of system dynamics, which lead to events. Over time, demand for connectivity has increased, making the status quo untenable. Due to the COVID-19 pandemic, many aspects of life shifted to an online environment, from education to employment to healthcare, thus increasing the total Internet traffic volume [13]. In addition, the Internet of Things (IoT) has the potential to radically alter existing industries such as precision agriculture, but this emerging technology requires connectivity over wide areas to be effective [14]. At the same time, rural communities tend to have limited access to connectivity options due to poor economics coupled with low population density.

Underlying systematic structures represent the rules or norms that influence patterns. This is where the inter-policy gaps, which is the focus of this paper, begin to emerge. The existing structures, where different organizations have authority over different parts of the interconnected systems contribute to the gaps. Each organization has independent goals, which no one is responsible for resolving. For example spectrum in TV white spaces is provided dynamically in 8 or 7 MHz channels while the LTE system, that utilizes this spectrum can only use 5 MHz or 10 MHz channels. As a result, some of the spectrum has to be unused to accommodate this mismatch.

Lastly, mental models, which are beliefs that keep the system in place, generate the structures. The emphasis on market-based approaches and the lack of a centralized regulatory authority contribute directly to inter-policy gaps. In addition, there are concerns about spectrum coexistence, which prompt a conservative approach. For example, the broadcasting community has been afraid that Internet Service Providers

TABLE 1. Key systems concepts for wireless experts.

Concept	Definition	Reference
systems thinking	ability to see interrelationships between parts and the whole	[11]
iceberg model	structure used to uncover the underlying structure that contributes to an event	[19]
system of systems (SoS)	collection of independent systems that provide enhanced capabilities when combined	[17], [18]
model-based systems engineering (MBSE)	the use of formal models as the sole source of truth in a system life cycle	[20]
policy content modeling	process for converting text-based policy documents to simulations	[21]
digital twin	a simulation version of a real-world system to test new policies	[22]

reutilizing their primary spectrum band would cause interference, breaching their license to use the band [15]. The scientific community has expressed concern about how their research would be significantly affected by spectral incursions by existing and emerging wireless technologies [16]. Overall, there is a fundamental challenge for policymakers to keep up with technology advances. At present, policymakers tend to be more reactive than proactive.

The relationship between the parts and the whole can also be described as a system of systems (SoS), if each part is a system in its own right [17]. An SoS is characterized by the level of autonomy, belonging, connectivity, diversity, and emergence [18]. Autonomy is the ability of each sub-system to make independent choices and belonging is the ability of each sub-system to choose whether to be part of the SoS. Connectivity is the ability to be connected or interoperable with the other sub-systems and diversity is heterogeneity between and within sub-systems. Lastly, emergence is the tendency for complex systems to be greater than the sum of their parts. This feature drives unexpected consequences from small changes in inputs. Each input in Figure 1 represents a system within a system of systems. Each input represents a collection of parts that are more meaningful when combined. As a result, the solution space is not limited to the separate circles, but rather it includes the intersections. While rural broadband will not be solved with wireless technologies alone, these technologies must align with the policy process and meet consumer requirements.

Main concepts in the field of systems engineering relative to the rural broadband problem are listed in Table 1.

Systems engineering tools have been used to improve the design of systems by encouraging a model-centric approach. The primary advantage of these tools is in early identification of potential weaknesses in complex systems, where cascading failures can be difficult to predict [23]. For example, MBSE tools such as SysML can be used to anticipate and protect

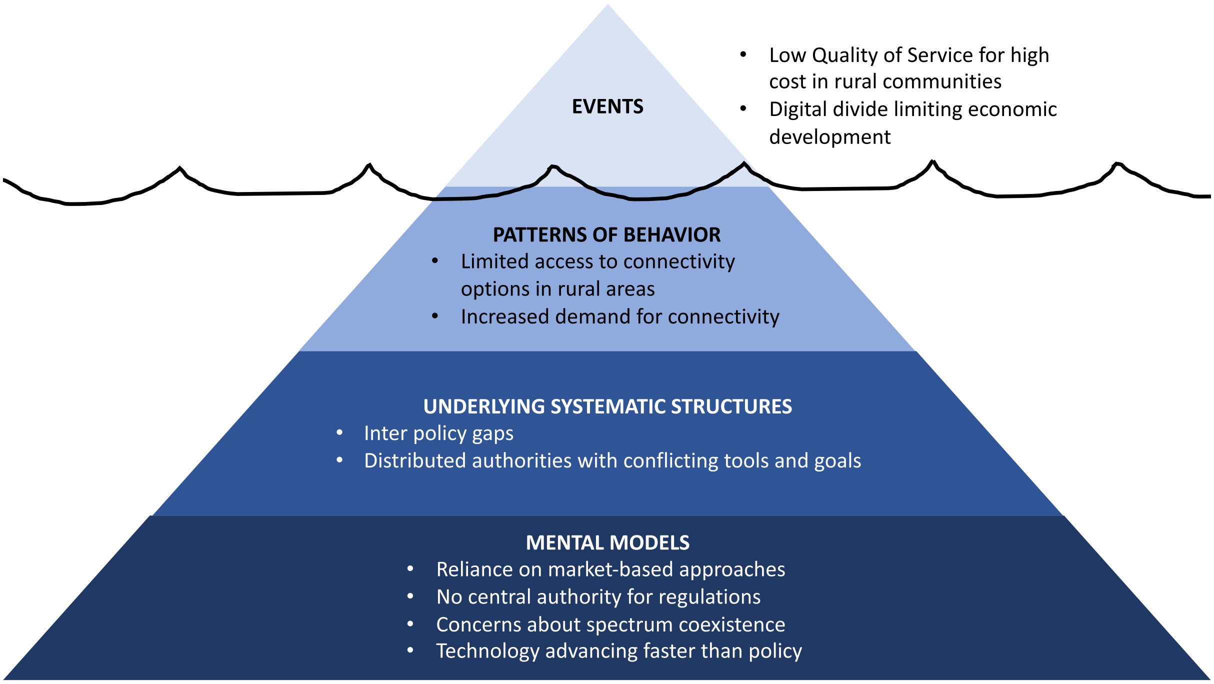

FIGURE 2. **Iceberg model for rural broadband problem uncovers root causes.**

potential vulnerabilities in the energy system [24], analyze the impacts of policy and trade decisions in international natural gas markets [25], and identifying cyber-physical vulnerabilities in additive manufacturing systems [26]. In the aerospace industry, MBSE approaches have been extensively adopted [27]. For example, NASA spent two years evaluating the effectiveness of MBSE tools before deciding to move forward with an enterprise-level application because of the observed benefits across multiple tasks. They found that MBSE tools identified design constraints earlier, improved communication across teams, reduced errors and increased workflow efficiency [28], e.g., the proposed post-processing procedure of a rocket engine tests cut the required time from around 8 hours to 1 hour. This effort continues at NASA as part of the MBSE Infusion and Modernization Initiative (MIAMI) [29]. A NASA-led evaluation of the state of the discipline interviewed industry professionals, who reported benefits such as ‘‘20-25% cost savings on managing change’’ and ‘‘at least 20%, maybe up to 40%, time reduction for early phases of the project’’ [30]. There is increasing interest in using MBSE tools to analyze the impacts of policy gaps. One of the challenges with analyzing policy gaps is that policies are articulated in documents, rather than models. In [21] authors demonstrate an approach for conducting policy content modeling to create a machine-readable digitized policy model to analyze gaps and quantify the negative impacts of gaps. A promising approach is to estimate the policy toxicity of the gaps to prioritize efforts to resolve these issues. Policy toxicity is defined as a weighted average of observed gaps. In an analysis of Veteran's Affairs policies, there were gaps in policies ranging from conflicting time targets to misplaced information. The policy toxicity ranged from 0.13 to 1 across various documents, where high numbers indicate higher numbers of gaps in general as well as higher numbers of important (or more highly weighted) gaps. This approach can structure efforts to revise policies by prioritizing gaps that could have the biggest impact if they are resolved [21].

MBSE has begun to be slowly adopted in the wireless community. For example, wireless researchers have developed a policy architecture to support dynamic management in the design of cognitive radio networks [31]. A MBSE approach to developing IOT architecture can also be found in [32].

III. USING DYNAMIC SPECTRUM ACCESS FOR RURAL BROADBAND CONNECTIVITY

New wireless standards (*e.g.*, 5G [33]) are seen as key factors for supporting an increase in user demand and data traffic. However, while new, highly spectrally efficient RATs (*e.g.*, Massive MIMO [34], channel coding [35]) are used, these networks cannot operate without a sufficient amount of available wireless spectrum. This is readily observed in 5G specifications that require devices to cover 27 bands in frequencies from 600 MHz to 5 GHz [36], and 4 bands in frequencies from 24 GHz to 40 GHz [37]. For rural broadband, high-frequency bands cannot support wireless connectivity over large distances between the base station and the end-users due to poor propagation characteristics. As a result, the amount of available spectrum resources to consider drops rapidly, requiring efficient resource management.

A device can access spectrum either via an exclusive license or by spectrum sharing. Licensed spectrum requires an operator to buy an exclusive license for a given frequency band and a given area. While relatively simple in terms of required spectrum access policy and well established for many years, this approach may not provide high spectral efficiency (*i.e.*, many frequencies are underutilized in many locations over time [4]). On the other hand, shared spectrum access allows many wireless systems to utilize the same band, increasing spectrum utilization. Typically, shared spectrum access is less costly in terms of licenses. However, unsupervised spectrum sharing can lead to interference between coexisting systems and potentially significant degradation of Quality of Service (QoS), which is unacceptable for providing commercial services. Therefore, complex spectrum access policies have been designed to allow for coexistence with guaranteed QoS (*e.g.*, CBRS with SAS in the 3.6 GHz band or Licensed Shared Access in the 2.3 GHz band [38], [39]).

These policies are steps towards realizing DSA using transceiver platforms refered to as Cognitive Radios [40]. The cognitive radio is a wireless transceiver capable of sensing its electromagnetic environment and adjusting its operating parameters to transmit in unused spectrum chunks or ''white space''. This innovation required advances in many fields including spectrum sensing for detection of other spectrum users [41], policy-based description of the devices and environment utilizing proper architecture and language [42], flexibility of signal processing in a transmitter [43], [44], and interference rejection capabilities in a receiver [45]. Transmission trials have confirmed the high performance of this framework [46], although there are still many problems that have not been solved and impede implementation (*e.g.*, detection of licensed systems with sufficient reliability or certification of devices and preventing stand-alone dynamic spectrum access). To correct this, regulators have proposed specific bands to be shared using geolocation databases (*e.g.*, 5G CBRS).

DSA is a step towards more efficient resource utilization in wireless communications systems. While in the past, a specific RAT (*e.g.*, LTE) and operator were assigned to a given band, DSA now makes this arrangement more dynamic. Conversely, DSA needs to be accurately specified in policies defining the interfaces with databases, transmission power, bandwidth, and spectrum emission mask. To provide interference-protected and RAT-independent access, these policies are general and restrictive. This simplification aims to protect other users, but leads to reduced spectral efficiency. For instance, a field test was conducted in the 3.6 GHz band in Poland utilizing a commercial cellular network and CBRS protocol [47]. From this test, it was observed the transmit power allowed by the database in most locations was below the maximum power level causing harmful interference to other devices (based on measurements). This can be improved by feedback information sent from the victim/interfered receivers as proposed in [48]. To increase implementation of innovative technologies, a more flexible approach to policy definition and interference calculations is required.

Main concepts in the field of wireless engineering relative to the rural broadband problem are listed in Table 2.

TABLE 2. Key wireless concepts for systems experts.

Concept	Definition	Reference
Dynamic Spectrum Access (DSA)	concept of using electromagnetic spectrum if needed and when available, more flexible than traditional fixed licenses	[40]
Citizen Broadband Radio Service (CBRS)	one of DSA-based spectrum access policies designed for 3.5GHz band in the USA	[7]
LSA (Licensed Shared Access)	one of DSA-based spectrum access policies designed for 2.3GHz band in Europe	[38]
Radio Access Technology (RAT)	method that allows transmitters and receivers to communicate over allocated band, e.g., 5G, LTE	[33]
Digital Terrestrial Television (DTT)	method of distributing TV signal to households using a set of radio transmitters (every few tens of km) and UHF frequencies (typically from 470 MHz to 790 MHz)	[15]
TV white spaces (TVWS)	unused electromagnetic resources in between DTT transmissions that can be utilized using DSA-based spectrum access policy, e.g., specified by DSAL using prefered RAT, e.g., 5G	[46]
Out-Of-Band (OOB) radiation	effect observed in wireless transmitters causing some of the transmitted signal leaks to adjacent bands, measured at the transmitter typically by Adjacent Channel Leakage Ratio (ACLR)	[49]
Adjacent Channel Selectivity (ACS)	parameter of wireless receivers measuring how prone they are to be distorted by signals transmitted in adjacent bands	[15]

IV. POLICY INTERSECTIONS FOR WIRELESS CONNECTIVITY

DSA issues can be viewed more globally as spectrum efficiency degradation issues resulting from imperfections at the ''intersections'' of various policies. Successful wireless communications require adequate configuration of three ''planes'' (see Figure 3): (1) user plane, (2) RAT plane, and (3) spectrum plane. The user plane specifies the traffic requirements for a given service and application, such as throughput, delay, and jitter for successful Voice-over-IP (VoIP) service. This is specified by policies for a given service or some general rules (*e.g.*, ITU recommendation [8] provides maximum acceptable end-to-end delay for voice transmission in a network). The requirements of many users can be aggregated and visible from the network level perspective as a virtual Mobile Network Operator or a slice, which are important aspects of 5G systems [50]. Additionally, the output of the user plane can be the cost of providing such a service (*e.g.*, energy utilized for transmission and processing, cost of spectrum lease). The RAT plane specifies the configuration of a given RAT (*e.g.*, number of subcarriers,

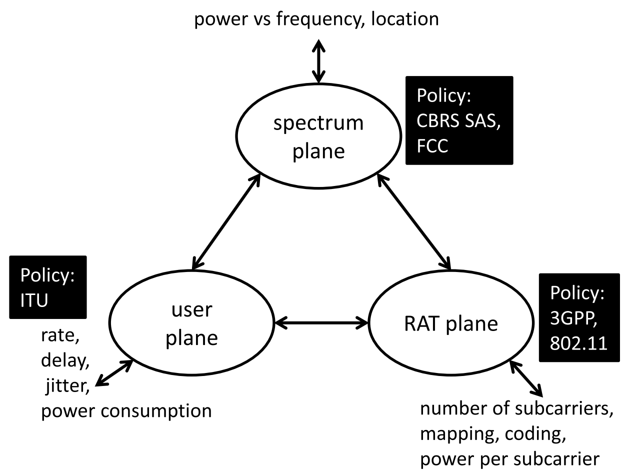

FIGURE 3. Policies and their parameters required for wireless connectivity.

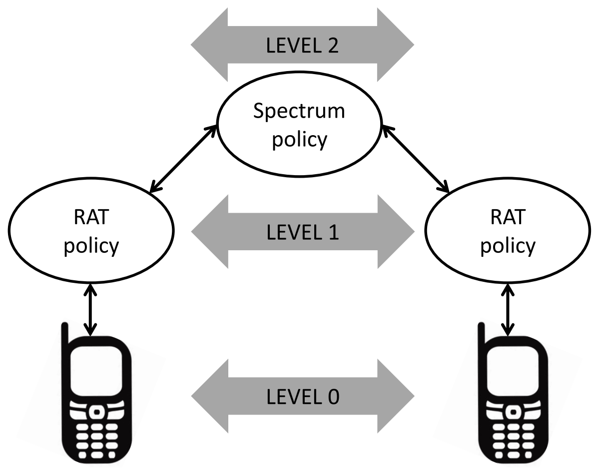

FIGURE 4. Policies in RAT and spectrum plane enabling/restricting connectivity.

constellation, coding, power allocated to each subcarrier) that satisfies the requirements of the user plane and utilizes the spectrum resources provided by the spectrum plane within specified limits. The RAT plane is typically limited by the technology and available configurations specified in policies (*e.g.*, 3GPP specifies that an LTE carrier can occupy the 1.4, 3, 5, 10, 15, or 20 MHz band). Additionally, a given RAT configuration results in a given power spectral density or spectrum mask that is essential for the spectrum plane. The spectrum plane specifies the allowed transmission band and maximum transmission power in addition to coordinating interference among spectrum users adjacent in space and frequency. The rules of spectrum utilization are typically specified by spectrum regulators using policies (*e.g.*, FCC or CBRS alliance [7]).

Wireless transmission is performed after the configuration of each plane (*i.e.*, after meeting each plane's policy). Since the policies for each plane are prepared separately, restrictions applied by each policy intersection can introduce inefficiency in resource utilization, *e.g.*, a user application requiring a maximum connection delay of 3 ms and 20 Mbps of throughput. The user plane policy maps this traffic to a class guaranteeing 2 ms of delay. At the same time, the RAT plane decides this throughput can only be supported by a minimum of 15 MHz of bandwidth for a given signal to interference and noise power ratio. However, the spectral plane provides frequency channels of 10 MHz bandwidth each, requiring 20 MHz of bandwidth to be allocated. This example shows how fixed policies, which are not coherent with policies used on other planes, can reduce the efficiency of resource utilization. This is especially important for applications such as wireless rural broadband, where the amount of available spectrum resources are limited and high spectral and economic efficiency is valuable. This challenge is further described via examples highlighting the intersection of the RAT and spectrum planes.

V. POLICY INTERSECTION CASE: SPECTRUM AND RAT POLICIES FOR DSA

DSA allows many transceivers belonging to various RATs to access a specific frequency band. For simplicity, let us assume two neighboring transceivers are willing to utilize the same or adjacent frequency band as depicted in Figure 4. However, this situation will give rise to mutual interference. If both systems know their transmission and reception parameters, as well as the channel characteristics (*e.g.*, power spectral density, receiver selectivity, antenna patterns, channel attenuation, and frequency characteristic), the exact interference power can be calculated. While this data is difficult to obtain *a priori*, the precise *interference coupling* can be measured after transmission begins [47]. The devices have to adjust their mutual interference (*e.g.*, by adjusting their transmission power). Each device has to follow some optimization strategy in order to meet throughput requirements or provide priority to access the given spectrum. This DSA method is denoted as "LEVEL 0" in Figure 4, where exact devices and radio environment characteristics are used such that it is not limited by RAT or spectrum policies. However, it is difficult to achieve for real systems, where tens or hundreds of transceivers need to exchange transmitter and receiver parameters.

LEVEL 1 coexistence occurs when both RATs are the same (*e.g.*, both transceivers use LTE, or both RATs' coexistence was foreseen while designing the RATs specification). This requires the transmission and reception parameters of the target transceiver to satisfy the minimum requirements specified in the RAT policy. With these assumptions, the estimated interference will not be higher than the real interference. Additionally, LEVEL 1 coexistence can allow for some additional transceivers coordination embedded in the RAT policy (*e.g.*, Inter Carrier Interference Coordination messages sent in LTE between the Base Stations to optimize power allocation between Base Stations). However, there is a potential spectral efficiency loss as a result of the *worst-case* transceiver parameter assumptions (*i.e.*, minimal requirement based on RAT policy). Furthermore, LEVEL 1 coexistence reduces flexibility in RATs considered. It can only account for a single RAT or RATs that have been foreseen to coexist while preparing RAT policies.

Increasing flexibility to enable additional RATs can be achieved using the next level of coexistence, which is denoted as "LEVEL 2". This is obtained by an additional DSA spectrum policy in between RAT policies as depicted in Figure 4. In this scheme, awareness of the existence of other transceivers has to be built-in. It is typically obtained by periodic operations performed by transceivers to sense for channel occupancy or contacting the database to check if the allocated spectrum is still available. Implemented DSA schemes often use geolocation databases storing pre-calculated spectrum availability data. In this case, the policy provides a specific algorithm for how to calculate the allowed transmission parameters for a given location and a given frequency. These calculations are typically performed before a transceiver even registers in a given location as these are typically highly computationally complex. On the other hand, the calculations need to assume the properties of the devices (*e.g.*, powers spectral density shape and receiver immunity to interference). As such, the transceiver RAT specification cannot be used, as its type is not known before registration. The most commonly used approach is to specify a set of device classes (*e.g.*, ETSI specified 5 of them for operation in DTT band [49]). A given RAT's transceiver is later mapped to one of these classes. The spectrum efficiency loss (*i.e.*, a bitrate that can be achieved using a given bandwidth) can be caused here by the two required mappings. First, a transceiver of possibly high quality is assumed to fulfill only minimal requirements of the RAT policy (device to LTE policy mapping). Next, the spectrum policy cannot utilize a RAT policy to specify its device class (LTE to ETSI emission classes mapping). It is worth mentioning that some spectrum efficiency degradation is caused inherently by some randomness in the wireless channel rather than by the inter-policy gap (*e.g.*, typically the interference between both transceivers is estimated using a channel propagation model that can result in errors on the order of several decibels from the real path loss between devices). Moreover, the DSA policies have to use safety margins in case of numerous interfering transceivers affect the victim receiver. Finally, as a result of lack of knowledge about precise locations and specification of the victim receivers in many spectrum policies, it is required to protect many locations even if in practice the victim is either not present or not active within the vicinity (*e.g.*, protection of all areas where DTT reception is possible for DSA in DTT band or protection of wide-area if naval radar is detected in the case of CBRS).

In summary, the higher "LEVEL" values used result in more generalized policies, enabling various RATs to access the same spectrum band. Spectral efficiency decreases as the number of non-aligned policies that need to be satisfied increases.

A. USE CASE: LTE BASE STATION UTILIZING DTT BAND

To quantitatively describe possible spectral efficiency loss resulting from inter-policy gaps, we use an example of an LTE base station utilizing a DTT frequency band. This use case is especially important for rural broadband applications as frequencies in the DTT range allow base stations to achieve large coverage.

One spectrum policy that is valid for this scenario is specified by the Dynamic Spectrum Alliance [6]. Let us consider an empty DTT channel that is to be used by the LTE base station. As the next channel is utilized by the DTT signal, the base station has to shape its signal so that the interference to DTT receivers is limited. The coexistence calculations are specified in [6] assuming the RAT meets one of the ETSI device classes [49]. First, these class definitions assume that the broadband transceiver utilizes some multiple of 8 MHz bandwidth. While LTE can be configured to work with 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz, or 20 MHz configuration, the most spectrally efficient scheme that obeys this rule is a 5 MHz LTE configuration.

A 5 MHz LTE base station has to satisfy LTE policies [51] regarding its characteristics (*e.g.*, occupied bandwidth, emitted power, and Out-of-Band (OOB) emission). The standard specifies that maximum transmission power equals 24 dBm assuming the base station belongs to the Local Area base station class. At the same time, the OOB radiation is limited by a set of constraints. In this scenario, the most important is Adjacent Channel Leakage Ratio (ACLR) and operating band unwanted emission. The ACLR is the ratio of the filtered mean power centered on the assigned channel frequency to the filtered mean power centered on an adjacent channel frequency [51]. For LTE, the minimal requirement is to obtain 45 dB in adjacent and next to adjacent channels. In Figure 5, an example of an LTE signal that conforms to the LTE regulations is shown in blue. Its ACLR, calculated according to [51], equals 46 dB in the adjacent band and 61 dB next to the adjacent band. The unwanted emission is specified as an absolute emission power that should not exceed a given level if measured with a 100 kHz filter in the frequency range from the channel edge over the next 10 MHz of the band. After scaling base station emission power, the spectrum Emission Mask-like curve is obtained as presented in red in Figure 5, where the LTE signal power spectral density conforms with this constraint.

However, to allow for the transmission of this waveform in the DTT band, the geolocation database compliant with Dynamic Spectrum Alliance rules has to assign this base station's parameters, such as power. The database assumes that a given device complies with one of the ETSI emission classes [49]. Definition of classes is required to allow for precalculation of allowed power maps. However, the database is unable to measure the real power spectral density of the LTE carrier. As such an assignment can be based on LTE specifications assuming worst-case scenarios (*i.e.*, that LTE power spectral density meets the LTE requirements with

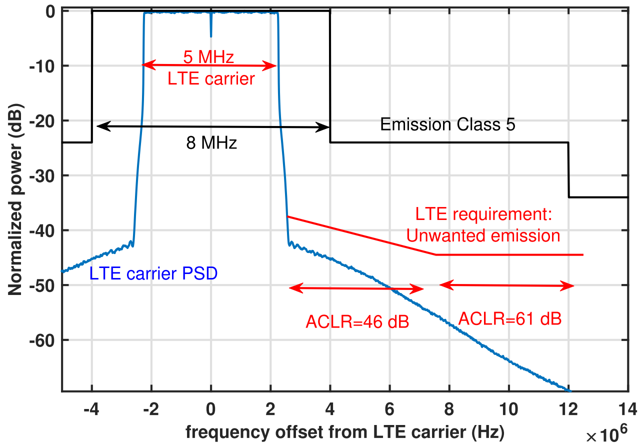

FIGURE 5. **Power Spectral Density (PSD) of a 5MHz LTE BS along with spectrum leakage constraints.**

equality). In this case, the geolocation database assumes the LTE base station only meets requirements for emission class no. 5, which is depicted in Figure 5 in black. This is the same emission class obtained for an LTE base station in [52]. This results in ACLR over the 8 MHz band assumed in coexistence calculations and equals 24 dB as specified by the emission class. At the same time, the calculation of ACLR using real power spectral density emitted results is 49.3 dB. Thus, the real OOB interference will be about 25 dB weaker than assumed for the chosen ETSI emission class. This maps to the LTE base station allocated power being about 25 dB (more than 300x) smaller if using LEVEL 2 coexistence in comparison to the real interference calculations (LEVEL 0 coexistence). At the same time, the transmission utilizes 5 MHz bandwidth while reserving an 8 MHz DTT channel.

This difference in allowed power can be presented as a difference in throughput available over some area. Three LTE BSs are considered operating in rural area at the same carrier frequency of 700 MHz, with bandwidth of 5 MHz. These BSs are placed on a typical hexagonal grid assuming call radius of 3 km. While the BS antenna height is 45 m and its gain is 18 dBi, the user equipment (UE) antenna height is 1.5 m and has 0 dBi gain as assumed in [53]. The UE is characterized by noise figure of 12 dB [53]. The downlink throughput is calculated according to scaled (by factor 0.6) and truncated to maximal spectral efficiency of 4.4 bps/Hz Shannon formula as suggested by 3GPP for LTE systems [54]. The path loss is calculated using COST 231 model [55]. Figure 6 shows a map of the maximal throughput over this area both for Level 0 coexistence and Level 2 coexistence. It is assumed that the while the Level 0 coexistence allows for the maximal emission power for this class of LTE BS, i.e., 24 dBm, the emitted power for Level 2 coexistence is 25.3 dB lower. The difference comes from the ACLR difference derived above. It is visible that Level 0 coexistence allows for much wider area being covered by the broadband access. Assuming the broadband access has to guarantee throughput of at least

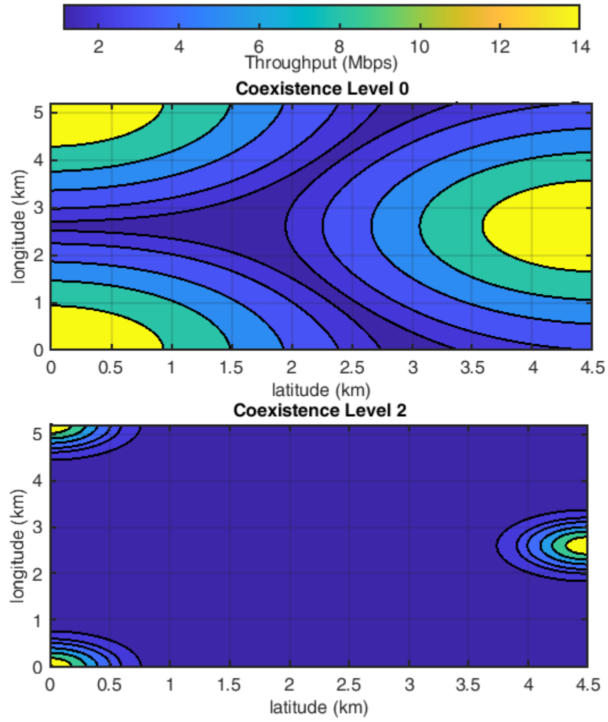

FIGURE 6. **Maximal throughput vs location for three 5MHz LTE BSs transmitting according to Coexistence Level 0 (24 dBm emitted power), and Coexistence Level 2 (-1.3 dBm emitted power).**

10 Mbps [2], it is available in 21.3% and 1% of locations for Coexistence level 0 and Coexistence level 2, respectively.

While this example proves that policy gaps drive spectral inefficiency, spectral efficiency loss can be even greater if the DTT receiver characteristic is also considered. The wireless receivers can attenuate interference obtained outside of their operating band. This is typically measured by Adjacent Channel Selectivity (ACS). The British spectrum regulator, OFCOM, took measurements of 50 of the most popular DTT receivers [15] and found that their ACS varied from about 50 dB to 75 dB for the same scenario. The Dynamic Spectrum Allience rules [6] use the 30th percentile of this parameter distribution. This means that 70 percent of DTT receivers will provide stronger interference rejection than the one considered in coexistence calculations at LEVEL 2.

VI. CONCLUSION

The paper has shown that while the DSA technology can be a key enabler for wireless rural broadband, its deployment is limited by inter-policy gaps. Over the years, systems engineers have developed tools to design and manage complex systems. Wireless rural broadband can be framed as a classic system design problem, where all parties' needs and constraints can lead to conflict. Model-based system engineering (MBSE) tools can articulate and highlight these conflicts. The core concept behind MBSE is that the system is captured in a model that represents the sole source of truth over the course of the system's life cycle [20]. This model can portray multiple perspectives to address the needs of different stakeholders, but this ensures there is a consistent set of assumptions used across disciplines. Typically, this model is realized using Systems Modeling Language (SysML) [56]. Most importantly, this model need not be limited to the technology parts of the system. This process can coherently represent the technological, political, and social aspects of the system. Using model-based system engineering for policy description and inter-policies connection optimization may reduce gaps in future policy development.

From MBSE, other tools have emerged, such as policy content modeling and digital twins. Policy content modeling [21] can be applied to develop a machine-readable policy, which can be exported to XML and deployed in simulation tools for testing conformance between proposed policies and implementation of flexible spectrum utilization. This policy model can be treated as a Digital Twin [22] to improve understanding of the emergent and dynamic aspects of this engineered system. Expert systems can also help develop rule-based policy alignment for high spectrum utilization. A digital twin can also be used to shift existing approaches for policy creation. A structured model can be used as the single source of truth that contains all technical, structural, and behavioral content of the resulting policy.

Policy intersections can create a significant challenge for wireless rural broadband deployment. This policy intersection framework can be further extended by considering various business models for the creation of a rural broadband network with dynamic spectrum allocation (*e.g.*, short-term auctions). However, the high number of possible policies combined with the high number of internal configuration options causes the design and validation (checking of consistency and correctness) of policies and their intersections to be a non-trivial task.

This should allow making policy at each plane more flexible, allowing for many configuration options. Allowing for more degrees of freedom should make the various systems coexistence closer to LEVEL 0 (in Section V) to increase spectral efficiency and support the wide deployment of DSA for wireless rural broadband. The internal correctness of policies and lack of inter-policy gaps can be systematically evaluated using computer simulation tools from MBSE.

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