Spectrum Sharing of the 12 GHz Band with Two-way Terrestrial 5G Mobile Services: Motivations, Challenges, and Research Road Map

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***Abstract*—Telecommunication industries and spectrum regulation authorities are increasingly interested in unlocking the 12 GHz band for two-way 5G terrestrial services. The 12 GHz band has a much larger bandwidth than the current sub-6 GHz band and better propagation characteristics than the millimeter-wave (mmWave) band. Thus, the 12 GHz band offers great potential for improving the coverage and capacity of terrestrial 5G networks. However, interference issues between incumbent receivers and 5G radio links present a major challenge in the 12 GHz band. If one could exploit the dynamic contexts inherent to the 12 GHz band, one could reform spectrum sharing policy to create spectrum access opportunities for 5G mobile services. This article makes three contributions. First, it presents the characteristics and challenges of the 12 GHz band. Second, we explain the characteristics and requirements for spectrum sharing at a variety of levels to resolve those issues. Lastly, we present several research opportunities to enable harmonious coexistence of incumbent licensees and 5G networks within the 12 GHz band.**

I. Introduction

The availability of spectrum is critical to balance the development of 5G terrestrial mobile services as well as protect existing satellite services. The spectrum band in question, the 12 GHz band, is currently licensed to three different services in the United States. These are direct broadcast satellite service (DBS), non-geostationary orbit fixed satellite service (NGSO FSS), and multichannel video and data distribution service (MVDDS). DBS licensees are authorized as primary users whereas both NGSO FSS and MVDDS licensees are authorized as co-primary users on a non-interference basis. The key focus of this article is to investigate various aspects of spectrum sharing in the 12 GHz band.

In the United States, the Federal Communication Commission (FCC) is the leading regulatory body for the issue of commercial frequency spectrum sharing. As of now, 5G in the United States of America (USA) is mainly being deployed in the licensed sub-6 GHz frequency band. However, beyond 5G networks are expected to have a plethora of use cases, such as self-driving connected cars, smart healthcare, mixed reality, and holographic image/video transmission, to name a few which will require an extreme high data rate ranging from several Gbps to 1 Tbps, ultra-high reliability of 10^{-9}, and ultra-low latency of 0.1 ms or less. We emphasize that the current 5G cellular network has a lack of sufficient bandwidth to meet such stringent quality-of-service (QoS) demands with ubiquitous connectivity [1]. Such a fact motivates the need of allocating more mid-band spectrum for 5G deployments to improve capacity and coverage of 5G cellular networks while avoiding disruptions to the existing licenses.. The 12.2-12.7 GHz spectrum, commonly known as the 12 GHz band, has been subject to considerable interest from both spectrum regulation authorities and service providers. The 12 GHz band combines excellent propagation characteristics with a contiguous 500 MHz bandwidth for cellular uplink and downlink operations, making it ideal for accelerating the deployment of 5G networks [2].

A spectrum coexistence scenario, such as that depicted in Figure 1, can lead to harmful interference for incumbent licensees in the 12 GHz band. There is a fundamental difference between spectrum sharing in the 12 GHz band and the sub-6 GHz band due to the wide variety of receiver characteristics and deployment strategies adopted by incumbents, the difficulty of moving incumbents to different bands, and the often-critical nature and high sensitivity of incumbent applications. Meanwhile, several interest groups are in conflict over interference between 5G mobile technology and existing broadband services in the 12GHz band. A clean-slate spectrum sharing approach and novel PHY, link layer, and policy solutions are therefore needed to resolve such conflicts and ensure harmonious coexistence between terrestrial 5G and incumbent licensees in the 12GHz band.

To avoid interference and facilitate fair coexistence between 5G mobile services and incumbents, several spectrum-sharing policies need to be revised. At the same time, there are several dynamic factors in the 12 GHz band, and effective consideration of these factors can create numerous opportunities for harmonious coexistence between terrestrial 5G networks and incumbents. Based on these facts, this article makes the following three contributions. First, we describe the unique attributes and challenges of spectrum sharing in the 12GHz band. Second, we explain the features required at various levels of spectrum sharing in order to adequately address incumbents' characteristics, unique propagation characteristics, and dynamic contexts of the 12GHz band. Finally, we highlight several research opportunities in the areas of radio resource management, spectrum sharing policy, and spectrum monitoring. To the best of the authors' knowledge, this is the first paper to present a systematic study of the challenges

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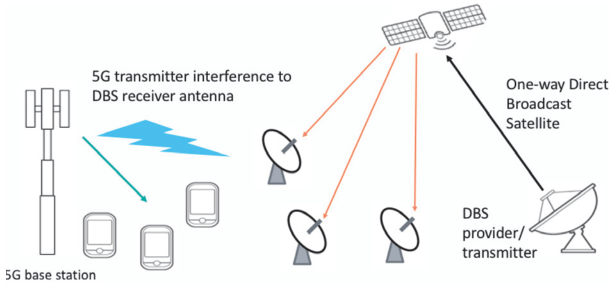

Fig. 1: Interference from 5G wireless system to DBS system in the 12 GHz band (NGSO FSS is omitted for clarity).

and possible solutions associated with the use of two-way terrestrial 5G mobile services in the 12GHz band. The research presented in this article addresses the topics identified in ITU-R Working Party 1B: Spectrum management methodologies and economic strategies. We argue the importance of economic considerations in the development of spectrum sharing policy using the 12 GHz band as a case study upon which additional U.S. and global application can be developed. While this article focuses on U.S. regulatory considerations, we expect similar issues to arise for other countries.

II. The Current State of 12 GHz Spectrum Sharing

The Federal Communications Commission (FCC) allows 12 GHz spectrum sharing between the primary DBS and co-primary MVDDS operations, where a one-way digital fixed non-broadcast service, including one-way direct-to-home wireless service, is permitted for MVDDS licensees. MVDDS licensees must comply with strict coexistence rules, including frequency coordination, maximum effective isotropic radiated power (EIRP), and transmitter locations, to avoid harmful interference with DBS receivers. Meanwhile, NGSO FSS and MVDDS licensees share the 12 GHz band on a co-primary basis. Based on which service is deployed first, these two have priority over one another.

In 2021, the FCC released a Notice of Proposed Rulemaking (NPRM) seeking comments on whether 5G services could be deployed in the 12 GHz band while protecting incumbents from harmful interference [4]. Since the release of the NPRM, several interest groups submitted divergent comments to the FCC. MVDDS licensees strongly recommend that terrestrial 5G networks can co-exist in the 12 GHz band without any or with little coordination. They cite small cell sizes and advanced multi-antenna beam-forming technology as potential solutions. In contrast, both NGSO FSS and DBS licensees contend that terrestrial 5G networks cannot be operated in the 12 GHz band without causing severe interference to their existing operations. An overview of the analyses conducted by the major incumbent licensees of the 12 GHz band is briefly summarized in Table I. The authors do not take a position on the accuracy of the analysis or the veracity of the assertions made by any parties.

III. Key Unique Characteristics of the 12 GHz Band

The FCC recently opened a total of 450 MHz of bandwidth in the sub-6 GHz spectrum, such as (i) 100 MHz bandwidth in 3.45 – 3.55 GHz band [10], (ii) 70 MHz bandwidth in 3.55 – 3.65 GHz S-band [11], and (iii) 280 MHz bandwidth in 3.7 – 3.98 GHz C-band [12]. Compared to these sub-6 GHz bands, the 12 GHz band has several unique properties summarized as follows.

A. Propagation Characteristics

The 12 GHz band has several advantageous propagation characteristics. The 12 GHz band exhibits an order of magnitude less path loss than the commercially deployed mmWave systems in the 28 GHz band. In an ideal scenario, the coverage radius of a base station (BS) in the 12 GHz band is approximately 2.33 times of the coverage radius of a BS in the 28 GHz band [2]. The 12 GHz band has also a much superior building penetration ability than the 28 GHz band. The proponents of 5G in the 12 GHz band argue that the 12 GHz band exhibits almost similar propagation characteristics to the C-band. For instance, the 12 GHz band exhibits 10.2 dB higher free space propagation loss and 4 dB higher foliage loss compared to the C-band, and almost same in-building propagation loss compared to lower Sub-6 GHz spectrum [13]. Such propagation features could theoretically enhance capacity the 12 GHz band, thanks to its large bandwidth gain. A recent study shows that the 12 GHz band can offer 20 Gbps aggregate (peak) downlink throughput due to its ability of simultaneously using five 100 MHz downlink channels, whereas the C and mmWave bands can offer maximum 15.1 Gbps and 9.0 Gbps aggregate (peak) downlink throughput, respectively [14]. In addition, advocates of 5G in the 12GHz band argue that adaptive beamforming and phased antenna arrays will reduce harmful interference at incumbent receivers outside the cell sites. Overall, 12 GHz's propagation traits could determine the coexistence of terrestrial 5G and incumbent networks if executed with a dynamic regulatory framework in mind. Nonetheless, these techniques haven't been tested on existing incumbent systems, which should remain a core consideration for any sharing policy.

B. Novel Operational Settings for 5G

Incumbent wireless services in the 12 GHz band have varied deployment strategies, operational characteristics, and interference tolerance. A DBS receiver typically has one-way communications, so it cannot request retransmission or report harmful interference [8]. According to 5G advocates, NGSO FSS operators can schedule data transmission to downlink Ku-band channels outside 12.2-12.7 GHz [2]. However, NGSO FSS providers contest that this effort would not be cost effective if it were possible [6]. Confirmation in ability and cost either way has not been clearly established. However, if the downlink were possible and within a reasonable cost, different interference protection metrics would be required to protect DBS and NGSO FSS operations based on the receiver's sensitivity to the interference and density of the incumbent receivers in each region. This would require a flexible policy to adjust different parameters, e.g. transmit power limits and down-tilt angles of licensed 5G BSs in the 12 GHz band based on deployment contexts and coexistence scenarios to ensure interference protection for incumbent receivers

TABLE I: Comparison of Industry Specific Assertions on 12 GHz Spectrum Sharing with Terrestrial 5G Networks

Industry	Overview of the Assertion	Key Features of the Assertion	Criticism of the Assertion
MVDDS [5]	• **Coexistence scenario:** Spectrum sharing between terrestrial 5G and NGSO FSS networks • **Key Point:** 5G can coexist with NGSO FSS receivers without interfering with them in 99.85% cases	1) Simulation setup for terrestrial 5G using macro and small cells and point-to-point wireless backhaul links for the continental USA 2) Advanced antenna system at 5G BSs with sidelobe suppression	1) Lack of realistic line-of-sight (LOS) and non-LOS (NLOS) propagation channel models 2) Inaccurate assumptions about the deployment and characteristics of the FSS receivers [6]
NGSO FSS [6]	• **Coexistence scenario:** Spectrum sharing between terrestrial 5G and NGSO FSS networks • **Key Point:** 5G operations in the 12 GHz band can disrupt NGSO FSS receivers, leading to 77% service degradation	1) Accurate modeling of the deployments of FSS receivers 2) Practical antenna gain models for FSS receivers 3) Non-probabilistic modeling of the LOS and NLOS propagation channels and FSS specific clutter loss models	1) A non-representative coexistence scenario of terrestrial 5G and NGSO FSS networks in the context of most of USA 2) Unrealistic assumptions about the distribution of FSS receivers and 5G BSs, as outlined by proponents of 5G in the 12 GHz spectrum [7]
DBS [8]	• **Coexistence scenario:** Spectrum sharing between terrestrial 5G and DBS networks • **Key Point:** 5G operations in 12 GHz band can generate 20-30 dB more interference levels than the limit set by the FCC	1) Practical antenna gain model for DBS receivers 2) Advanced beam forming antenna array at 5G BSs with sidelobe suppression 3) Practical clutter loss models for roof mounted DBS receivers in urban, sub-urban, and rural scenarios	1) Excessive high density of macro BSs, representing a highly conservative coexistence scenario, as mentioned by proponents of 5G in the 12 GHz spectrum 2) Consideration of 10 times larger transmit power from the macro BSs than the nominal values [9]

C. Dynamic Contexts

Several dynamic contexts must be considered when sharing the 12 GHz spectrum, including weather, channel conditions, spectrum occupancy, and traffic types. These factors provide a picture of possible coexistence states of wireless networks. A context can be classified into static or dynamic, where the former is fixed, while the latter varies spatially and temporally. Spectrum sharing rules for the 12 GHz band must be aware of underlying contexts. In Table II, we summarize important contexts for the 12 GHz band. We emphasize that the presented list of contexts in Table II is not exhaustive, and will be enriched by incorporating the regulatory, economic, and standardization aspects of the 12 GHz band. Additionally, our proposed spectrum sharing policy examples are potential solutions for reducing interference in the 12 GHz band and they require further investigations.

D. Economic Aspects

The 12 GHz band has a significant impact on the economy. In the continental USA, there are approximately 20 million DBS subscribers. However, there are over 400 million mobile subscribers, including enterprise and Internet-of-Things (IoT) subscriptions [8]. Proponents of terrestrial 5G claim the economic benefit of introducing 5G connectivity in the 12 GHz band in multiple markets – for rural, urban, and suburban environments – is potentially vast. The terrestrial 5G network is also frequently lauded to be the key building block of deploying vital inter-device connectivity and automation across a wide range of industries in the 12 GHz band [15].

At the same time, one cannot overlook the equally important considerations of moving or restricting incumbent use of the 12 GHz band. NGSO FSS providers have pushed toward progressing rural broadband initiatives that are necessary for equitable access in an increasingly digitally connected economy. There is no guarantee at this time that mobile terrestrial deployment on the 12 GHz band would offer an effective output in this endeavor. In addition, incumbent use on the band represents existing corporate investments, established job creation, and successfully deployed functional systems. It would be an unwise policy endeavor to change the access of the band without a framework to ensure that no more than reasonable risk would fall on the incumbent providers.

A mutually positive outcome, namely the coexistence of incumbent providers and the terrestrial 5G mobile services in the 12 GHz band, will create a unique environment of opportunity from the economic perspective. Such a mutually positive outcome is theoretically possible. The endeavor of creating tools to drive a policy framework that adapts to the changing nature of "best use" in the context of spectrum sharing is a worthwhile effort. This prospective tool is explored in greater detail in Sections IV and V.

IV. Essential Components for Spectrum Sharing in the 12 GHz Band

In the 12 GHz band, 5G terrestrial mobile services will include macro-cells, small-cells, and wireless backhaul connections. In such a dynamic scenario, suitable mechanisms are required to determine priorities for coexisting services, identify and assign available channels, evaluate and adjust allocation policies. In Figure 2, we envision a context-aware spectrum sharing architecture that would determine suitable spectrum sharing decisions according to the network's dynamic states

TABLE II: Proposed Dynamic Contexts for Spectrum Sharing in the 12 GHz band

Context Variables	Relevant Sub-Variables	Category	Source of information	Context-aware Spectrum Sharing Policy Example(s)
Weather	Precipitation, type, and rate (e.g., sun, clouds, fog, rain, snow)	Dynamic	Public weather database	Transmit power regulation of 5G links to maintain the threshold signal-to-interference-plus-noise ratio at the incumbent receivers in different weather
User diversity	Private, commercial, scientific, government, and emergency	Static	User registration information	Priority of users to access the available radio channels
User defined parameters	Quality-of-service (QoS) and quality-of-expectations (QoE) of different types of traffic	Dynamic	Network traffic monitor	Assignment of users in different channels to maintain the QoS and QoE requirements
User locations	Indoor and outdoor	Dynamic	Location server	Uplink and downlink transmit power limits of the users
Incumbents' information	Location, density, and type (DBS or NGSO FSS)	Static	Public database of incumbents	Geophysical information specific priority settings for the incumbents
Spectrum status	Current and predicted spectrum usage of the incumbents	Dynamic	Measurement reports from the spectrum monitoring sensors	Available radio channels for sharing with 5G radio links
Radio links' information	Downtilt angles at the BSs; beamforming pattern; interference rejection capability at the users	Static	Active/registered radio links' database at the BSs	Novel operational settings of 5G radio links for harmonious coexistence
Users' dynamic behavior	• Mobility: Static, pedestrian, and vehicular • Channel state information	Dynamic	Users' status and channel quality indicator reports at the BSs	Radio resource management decisions [11]
Band characteristics	Channel evacuation time	Static	Policy database	Policy of moving interfering radio links to alternative band within the prescribed duration [11]

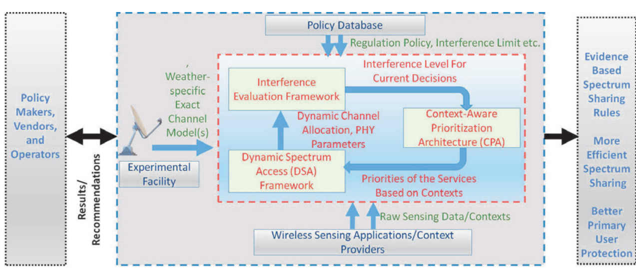

Fig. 2: Envisioned spectrum sharing architecture for the 12 GHz band with different components.

and feedback from external sources. These include outside experimental service facilities and established policy parameters via a policy database. The essential components of the context-aware spectrum sharing architecture are highlighted inside the dotted red rectangle in Figure 2. The required features of these components are explained as follows.

A. *Interference Evaluation Framework*

A compatible interference evaluation framework is essential in evaluating the effectiveness of existing and future interference-mitigating solutions in the 12 GHz band. The existing interference evaluation frameworks of the 12 GHz band [5], [6], [8] have several limitations. First, the existing studies approximate channel models of the 12 GHz band according to static 3GPP settings and thus fail to incorporate the dynamic propagation contexts present in the 12 GHz band. The 3GPP channel models rely on probabilistic modeling of line-of-sight (LOS) and non-line-of-sight (NLOS) channels based on statistical propagation characteristics, not based on site-specific local factors. Based on realistic scenarios, the realizations of LOS and NLOS channels may differ greatly from the probabilistic model predictions. The effects may vary as a result of different shapes and heights of buildings, vastly different deployments and heights of incumbent receivers compared to typical 5G users, as well as weather-specific effects, such as rain-related scattering and absorption. Second, existing interference evaluation frameworks do not consider the potential impact of different types of traffic on the interference to incumbent receivers. Third, the existing interference models use only predefined system parameters, and are therefore incompatible with the dynamic adjustments of different radio transmission and scheduling parameters. A flexible interference evaluation framework for 12 GHz is essential to address these limitations. The interaction between transmitted signals and different elements in the propagation path must be accurately emulated using realistic models of the propagation environment, user mobility, and practical measurements. The interference evaluation framework also needs to compatible with the remaining components of Fig. 2 so that it can incorporate adaptive radio transmission and scheduling as well as policy decisions provided by the DSA framework and policy database, respectively. Finally, the trade-off between accurate interference modeling and the required near-real-time computational complexity needs to be addressed.

B. Context-Aware Prioritization Architecture

To enable effective spectrum sharing between incumbent and proposed 5G mobile services, a context-aware prioritization architecture (CPA) is necessary. The CPA extracts dynamic contextual information from the surrounding radio frequency and geophysical environment and determines priorities for coexisting wireless services based on the acquired contexts. Unlike existing spectrum sharing architectures, which typically consider fixed and context-agnostic user and traffic prioritization, CPA leverages diverse operational settings and electromagnetic characteristics of the shared radio frequency band to improve spectrum coexistence. In particular, CPA can prioritize different types of traffic based on operational contexts, enabling the DSA framework or coexisting BSs to schedule suitable sets of users and types of traffic over the 12 GHz band. However, implementing a robust CPA for the 12 GHz band presents several challenges. First, the CPA needs to obtain contexts from raw data collected from a variety of sensing applications. The acquisition of relevant and accurate dynamic contexts from the astronomically increased raw sensing data is extremely challenging, requiring integration of tools from big data processing, edge computing, and artificial intelligence (AI) to extract the required contextual information. Second, the CPA needs an intelligent framework to efficiently combine different dynamic contextual information, possibly having different levels of importance, in order to determine priorities of coexisting services and suitable network resource management decisions. Third, appropriate interfaces must be standardized to facilitate rapid information exchanges between the CPA and the physical network entities (e.g., BSs, edge controller, and core network) for real-time link adaptation and synchronization. Finally, the CPA must be scalable for large networks. A centralized implementation approach approach can provide global information about a network at the CPA at the expense of high overhead and latency. A decentralized implementation of the CPA improves information collection/dissemination latency at the cost of local-optimal decisions due to the availability of partial network information. Therefore, the CPA needs to judiciously balance centralized and decentralized deployment to balance scalability and efficiency.

C. Dynamic Spectrum Access Framework

In order to effectively allocate spectrum resources available on the 12 GHz band based on prioritizations and operational contexts, a dynamic spectrum access (DSA) framework is required. Several commercially available DSA frameworks, including TV white space (TVWS), licensed spectrum access (LSA), and spectrum access systems (SAS), do not adequately address the unique properties and dynamic contexts associated with the 12 GHz band. As defined in these DSA frameworks, exclusion zones (EZs) are areas where in-band radio links are forbidden from transmitting harmful interference. As opposed to sub-6 GHz, 12 GHz incumbents are ubiquitous and significantly large in number. This makes it difficult to identify interference sources and track them in real time. As a result, static EZs do not offer the best protection for incumbents. The 12 GHz band is also affected by the weather. Thus, DSA frameworks for the 12 GHz band need to incorporate flexible EZs that can change according to weather conditions and user mobility. DSA frameworks also use spectrum databases. The location and dynamic settings of incumbents need to be recorded and coordinated with various stakeholders using a comprehensive database. In order to track and predict spectrum coexistence in real time, database-based spectrum sharing and intelligent spectrum sensing in the 12 GHz band should be combined. This would enable dynamic adaptation of spectrum-sharing rules. Additionally, due to their negligible interference with outdoor incumbents, indoor restricted users are usually accommodated in the shared band as needed. However, as incumbents such as DBS in the 12 GHz band are installed in consumer homes, indoor users can cause harmful interference as well. Effective spectrum access rules therefore need to be developed for indoor users in the 12 GHz band as well. It is worth noting that the development of DSA frameworks is typically carried out by industries in accordance with rules established by the FCC, which is responsible for verifying the integrity of these frameworks.

V. Research Opportunities and Policy Considerations

Spectrum sharing research in the 12 GHz band is in the infancy stage and requires innovations in radio resource management (RRM), spectrum sharing policies, as well as spectrum monitoring and management frameworks. Some promising research directions in these areas are summarized as follows.

A. AI-based RRM for the 12 GHz Band

RRM is an effective method for mitigating interference among coexisting wireless services by optimizing radio transmission, scheduling, and routing parameters. By selecting appropriate beamforming parameters (e.g., beam direction, 3D beamwidth, antenna down tilt angles) and transmit power of BSs, RRM in the 12 GHz band can establish dynamic EZs around incumbent receivers. In addition, RRM in the 12 GHz band optimizes spectrum sensing parameters and dynamically allocates time-frequency resource blocks (RBs) among 5G links. This approach maximizes the performance of the 5G network while avoiding harmful interference at incumbent receivers in a given region by selecting non-interfered RBs and scheduling active 5G devices to those selected RBs. However, the envisaged RRM problems are computationally intractable, and a variety of factors affect the optimal solution, including wireless channels, user activity, and dynamic effects. Hence, traditional optimization methods cannot be applied to large-scale 12 GHz networks to implement interference-aware RRM schemes. AI methods, such as reinforcement learning (RL) and federated learning (FL) are useful to solve high-dimensional RRM problem. However, slow convergence rates for RL and FL mechanisms in dynamic wireless environments pose a key

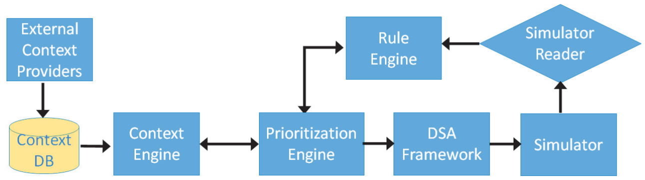

Fig. 3: End-to-end Unified spectrum monitoring and management (SMM) architecture.

challenge. Further research efforts are required to develop AI-based RRM schemes for the management of interference in the 12 GHz band while ensuring robustness of AI models in the face of highly dynamic spectrum-sharing scenarios that generate out-of-distribution data.

B. Development of Dynamic Policies for 12 GHz Band

Standard spectrum sharing policies are heavily optimized towards worst-case coexisting scenarios and are unable to effectively address the dynamic nature of practical wireless networks. To maximize spectrum sharing for best use, dynamic policies that vary based on spatially and temporally varying factors are essential for spectrum coexistence on the 12 GHz band. We visualize dynamic policy as a set of tools that will empower policymakers to make key decisions based on the true best usage, not strictly based on the incumbents' usage. A few examples of these tools are as follows. A *service-level agreement* tool can be used for negotiation between spectrum owners and consumers and provide incentives for the incumbents to share spectrum resources. A *risk assessment* tool can be used to evaluate the potential impact of different policy-level decisions and recommend the most suitable decisions. A *deployment and approval* tool can be used to approve the installation of new incumbent receivers and secondary BSs and inform terrestrial 5G providers how to adapt their strategy for the deployment of new installations. Today, a fixed structure based on the FCC's analysis of the technical arguments made by rulemaking participants is adopted for these tools. However, the existing forms of these tools are not globally optimal. It is required to integrate the capability of performing different "what-if" analyses in these tools as such they can adapt to case-by-case scenarios in a cost-efficient manner. This requires further investigation through interdisciplinary collaborations among policymakers, service providers, market analysts, and wireless communication researchers that will result in tools that reflect the dynamic nature of the 12 GHz band (e.g., weather), as well as policy directives (best use, priority communications, etc.). As this process is further developed, additional considerations for the roles of industry, universities, and research facilities will need to be established.

C. Spectrum Management and Monitoring for 12 GHz Band

To enable the spectrum sharing architecture described in Section IV. A, an integrated framework is required that can rigorously monitor the shared spectrum while addressing dynamic operational settings and satisfy the diverse quality of service (QoS) requirements of both incumbent and proposed terrestrial 5G users. We call such a framework as spectrum monitoring and management (SMM) framework, and Fig. 3 shows a high-level SMM architecture. The key feature of the envisioned SMM architecture is that it synchronizes spectrum sharing decisions with the upper layer controller and spectrum sharing policies while being aware of the impact of spectrum sharing decisions on the network. As such the SMM architecture can dynamically monitor and manage spectrum resources in the 12 GHz band. A detailed description of the functionalities of different components of SMM architecture is given as follows.

a) Context Engine: The context engine collects the required information from the appropriate context information providers, filters the data to remove inaccurate, anomalous, and expired data; stores the processed data to its own database; and provides readable data for prioritization engine and simulator tools. An interface between the context engine and simulator also exists to update contextual factors based on the real-time network status. The information provided by context engine to both prioritization engine and simulator tool includes at least environmental and user context; channel conditions and spectrum occupancy information; policy considerations; and network operator constraints. This information is stored in context database, which is a database allocated within the context engine itself.

b) Prioritization Engine: The prioritization engine encapsulates the overall CPA functionalities described in Section IV. B. It sets the weights for different parameters in the system and obtains user priorities while taking spectrum-sharing rules and contextual factors, obtained from the rule and context engines, respectively, into consideration.

c) Rule Engine: The rule engine implements algorithm(s) to govern the prioritization engine assigning priorities. To this end, it exploits both static and dynamic rules based on upper-layer policy and dynamically varying network status.

d) DSA Engine: The DSA engine implements the DSA framework, described in Section IV. C, and provides the simulator dynamic RRM decisions such as PHY/link layer parameters and channel allocation among coexisting users based on the user priorities set by the prioritization engine.

e) Simulator tool: The simulator tool is an interference evaluation framework based on realistic simulations and real-time experimental analysis. In particular, the simulation tool implements the decisions provided by the DSA engine while taking the contextual factors obtained from the context engine, tests the result of these modifications by analyzing the throughput and outage probability of the system, and provides the results as feedback to the system.

f) Simulator reader: The simulator reader takes the results from the simulator tool as input, compares the results with benchmarks, and provides yes and no Boolean decisions to the rule engine implying whether it is required to update the spectrum sharing rules or not, respectively.

An overview of information flow in the SMM architecture is explained as follows. (1) At first, the context engine extracts contextual information, e.g. weather in a given location and time from a public weather feed and provides this information to prioritization engine. (2) Using this context information and existing rules, prioritization engine determines priority scores of different coexisting users and provides them to the DSA engine. (3) DSA engine determines RRM decisions, e.g., transmit power and suitable channels for these users by plugging priority scores, context variables, and site-specific channel models to a scheduling algorithm and provides the updated decisions to the simulator. (4) Simulator implements RRM decisions, evaluates interference, and simulator reader checks the effectiveness of the decisions. The RRM decisions are forwarded to the secondary users (i.e., BSs) for implementation given that the interference criterion is satisfied, o therwise, a re u pdated b y r epeating S teps 1 -4. The aforementioned information flow a mong v arious components is supervised by a controller. Therefore, using SMM, dynamic policies and context-aware automatic frequency assignment can be implemented with full consideration of the impact on physical networks.

This leaves the following for further research: We are in the process of completing our end-to-end implementation of the SMM for spectrum sharing in the 12 GHz band. As we are implementing the SMM, we are determining the tradeoffs and characteristics in how much of the SMM must be centralized versus distributed, and how that may change for different deployment scenarios. Finally, it is our goal to increase the flexibility a vailable t o p olicy m akers a s t hey d etermine how to enable sharing in the 12 GHz band, as well as others where dynamic context can make sharing more efficient, make more spectrum available over time, or make sharing possible.

VI. Conclusion

As a result of its large bandwidth and favorable propagation characteristics, the 12 GHz band offers an attractive opportunity for terrestrial 5G networks to expand capacity and coverage. The spectrum sharing scenario in the 12 GHz band is unique compared to sub-6 GHz bands and thereby requires innovative spectrum sharing solutions. Most importantly, dynamic contextual factors must be incorporated in different levels of the spectrum sharing solutions. In addition, innovations in context-aware radio resource management, dynamic policies, and spectrum monitoring present promising possibilities for facilitating coexistence between terrestrial 5G and the incumbent services on the 12 GHz band.

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