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RESEARCH ARTICLE

Evolution Toward Data-Driven Spectrum Sharing: Opportunities and Challenges

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ABSTRACT As the demand for wireless services continues to grow, the need for efficient and effective management of the radio frequency (RF) spectrum becomes increasingly important. A spectrum management approach based on data analysis and interpretation i.e. data-driven, offers a solution as it provides valuable insights into spectrum usage patterns, demand, and the potential for harmful interference in shared spectrum scenarios. This paper focuses on the opportunities and challenges of incorporating diverse data sources into the management of spectrum, with a specific emphasis on spectrum sharing, particularly within database-assisted spectrum sharing systems. The benefits of adopting a data-driven approach to these systems are demonstrated through simulation of specific case studies. These studies indicate the potential for achieving up to a 60% greater density of spectrum use compared to conventional approaches, while also effectively managing harmful interference.

INDEX TERMS Data-driven spectrum management, database-assisted spectrum sharing, dynamic spectrum access.

I. INTRODUCTION

With the increasing demand for wireless services and the advancements brought about by 5G technology, the need for more innovative approaches to effectively manage the radio frequency (RF) spectrum is becoming more apparent. Approaches to spectrum management that leverage both data analysis and interpretation (data-driven) are emerging as promising solutions to address these challenges, as they can enhance processes, improve decision-making and enable alternative methods for spectrum sharing [1], [2]. This is exemplified by database-assisted spectrum sharing regimes that are being implemented globally [3], [4]. Such systems use a geolocation database to coordinate access to spectrum resources and prevent harmful radio interference to existing spectrum users.

However, existing database-assisted systems have some shortcomings, particularly their reliance on limited data sources for decision-making. This becomes a more pressing concern as the demand for spectrum resources continues to grow. According to projections, there will be a deficit of approximately 1GHz of mid-band spectrum for mobile broadband communications by 2030 [5]. Consequently, these systems must evolve to accommodate the many diverse incumbent services operating in different geographical areas and across various spectrum bands.

The opportunity to evolve database-assisted systems is particularly timely with the emergence of various technologies such as big data analytics, cloud-computing and the industry momentum towards network disaggregation and virtualisation, through endeavours such as Open-RAN (Radio Access Network). In tandem, regulatory authorities are increasingly interested in leveraging next-generation techniques and data-driven analysis to understand spectrum utilisation in both short and long-term time frames [6] and to realise greater spectrum sharing in the future [7]. Furthermore, regulatory bodies actively collaborate with industry partners and working groups to set sharing system standards and thus accelerate their implementation. As a result, there is strong regulatory momentum toward adopting data-driven approaches to enhance all aspects of spectrum management with particular emphasis on spectrum sharing.

Previous research on data-driven approaches to spectrum management has focused on specific frequency bands or

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narrow use cases [8], [9], [10]. For example, the authors in [8] explored data-driven spectrum sharing in frequency bands designated for land mobile radios, while the contribution in [9] considered spectrum sharing between network operators in mmWave spectrum. Additionally, the results presented in [10] examined spectrum assignment approaches for autonomous vehicles using measurements, modeling and database information. A common limitation among these studies is the narrow perspective on how various spectrum sharing systems could evolve to increase spectrum utilisation. To address these limitations, this paper takes a more comprehensive approach by building upon the findings presented in [11], which demonstrated that the inclusion of additional spectrum-related data can increase the number of users for spectrum sharing. Specifically, the paper introduces a novel perspective aimed at advancing future database-assisted sharing models. This vision involves harnessing diverse data sources within the decision-making process. The rationale behind this approach is that by incorporating a broader array of data and adopting data-driven strategies for spectrum sharing, it becomes feasible to align with regulatory policy goals, manage interference levels within shared environments and predict future spectrum demand scenarios. Ultimately, these efforts lead to enhanced spectrum utilisation efficiency.

The remainder of this paper is organised as follows. Section II describes the context for data-driven spectrum sharing including both the related work and a brief review of current database-assisted sharing systems. Next, section III outlines some of the opportunities available to improve spectrum management by leveraging a wider variety of applicable data sources with a particular focus on database-assisted spectrum sharing systems. This is followed in section IV with case studies that highlight the gains that are possible when applying a data-driven approach to spectrum sharing. Section V then presents the simulation results for the case studies. Lastly, section VI discusses some of the challenges that must be overcome in a data-driven system before concluding the paper.

II. DATA-DRIVEN SPECTRUM SHARING

A. RELATED WORK

Regulatory authorities are increasingly recognising the value of data-driven approaches in spectrum management. For example, in the United States of America (USA), the federal communications commission (FCC) recently issued a notice of inquiry [6] that places increasing value on new data sources, technologies and methods to improve how the spectrum is managed and shared. Similarly, the office of communications (Ofcom) in the United Kingdom (UK) has described how the reliance on better data is underpinning their efforts towards greater spectrum sharing in the future [7]. As a result, the application of data-driven methodologies to boost spectrum sharing is a novel concept for many international regulatory bodies. This concept aligns particularly well with modern cloud-based technologies, enabling increased automation of regulatory tasks and the judicious use of limited regulatory resources.

Recent research has demonstrated the potential of data-analytics for spectrum insights. In [12], the authors combine mathematical models with diverse data sets to inform spectrum policy decisions, especially regarding national spectrum pricing policies. Further, the authors in [13] use big data analytics and sensor data to derive insights on how to manage the RAN for cognitive systems. Lastly, commercial systems such as [14] offer analysis on the spectrum usage patterns that enable evidence-based decisions on when and where to allow other users to access the spectrum, the latter a key enabler for dynamic spectrum access.

Taken together, these findings indicate that applying data-driven methods to spectrum management and sharing is an emerging area of investigation. This is distinct from cognitive radio systems, which rely on spectrum environment data to make informed sharing decisions. Instead, as regulatory trends lean towards utilising a database to manage and coordinate sharing and the interference environment, this paper presents a viewpoint on how database-assisted sharing models can evolve. This evolution involves harnessing diverse and abundant data and adopting data-driven approaches to enhance decision-making. The concept is illustrated through relatively straightforward examples that showcase how a range of data sets, including those not conventionally linked with spectrum sharing, can advance current database-assisted sharing systems.

B. DATABASE-ASSISTED SHARING

Recognising that large portions of the spectrum are exclusively allocated to primary or incumbent services and are potentially underused, many regulatory bodies and industry stakeholders have implemented spectrum sharing models that involve the coordination of spectrum access via a database. These database-assisted models vary in terms of the licensing schemes, with some bands licence-exempt while others require specific licences for shared usage. For example, in the USA, the citizens broadband radio service (CBRS) sharing model is a three-tier system that operates in the 3550-3700 MHz band. The model uses a geolocation database as part of a spectrum access system (SAS) [4] to administer and enforce access between primary incumbent users, priority access licensees and license-exempt general authorised access users. Moreover, the CBRS model uses an environmental sensing feature to identify when the incumbent system is in use and redirect lower-priority users to a different section of the band.

Similarly, the European Telecommunications Standards Institute (ETSI) uses a two-tier database model for licensed shared access (LSA) in Europe [3], [15], enabling mobile network operators to share spectrum with priority incumbent systems. Initially, the LSA model was designed for access in the 2.3-2.4 GHz band, but it has since been adapted for use in other frequency bands [16]. Unlike the CBRS model, the LSA scheme does not permit dynamic, short-term access. Instead,

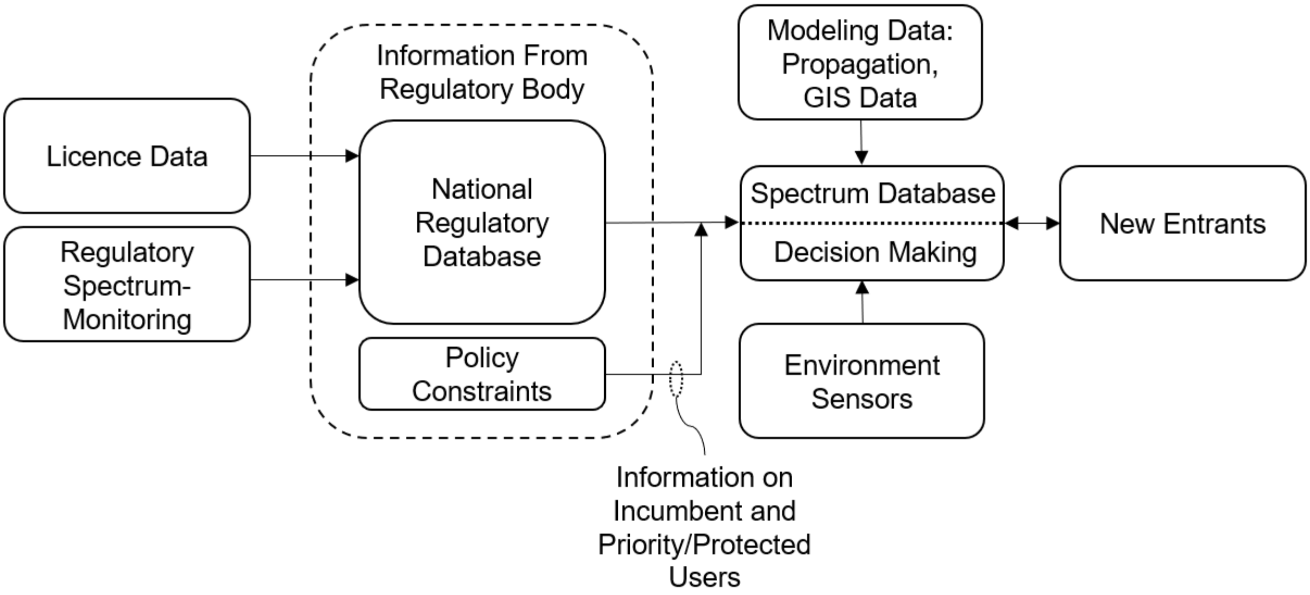

FIGURE 1. Block diagram of a generic spectrum database model including the flow of information in the system. The left hand side shows information administered by the National regulatory body. The data includes licence information, applicable spectrum monitoring data and policy constraints. On the right hand side, the spectrum database is administered by a third party and uses a variety of data including geographic information systems (GIS), new entrant information and potentially sensor data to make spectrum sharing decisions.

it relies on a centralised geolocation database containing static information about incumbent users.

Other spectrum sharing models adopted by various national regulators include the opportunistic use of the TV white space (TVWS) spectrum and license-free access to the 6 GHz band. For TVWS, unused channels of the TV broadcast bands are accessible for license-free broadband devices in certain geographic regions. In these cases, a location-specific database is employed to coordinate access of the secondary systems with the existing primary services, mainly TV broadcasters.

Similarly, many nations have identified the 6 GHz band, from 5925 to 7125 MHz [17], for various low and standard power license-free usages. For instance, in the USA, access for standard power transmission in this band is controlled through a database-assisted automated frequency coordination (AFC) system to safeguard existing fixed microwave operators.

Irrespective of the specific method employed, the overarching principle of a database-assisted tiered system is to automate the process of receiving spectrum requests from new entrants, conduct electromagnetic compatibility (EMC) analysis and make a decision on whether to approve the new entrant based on the regulator's guidelines and objectives [17].

A model for a database system and its relationship with a National regulatory database is shown in Fig. 1 [18]. The regulatory database serves as a central repository for data related to spectrum management. It contains information on current license holders, their spectrum rights and usage, which is collected through monitoring operations or obtained from external vendors. The database also takes into account policy constraints such as restricted and protected areas, which helps guide database administrators in managing the spectrum in accordance with relevant regulations. The spectrum database also maintains a list of registered secondary users with their location and operating parameters. It employs algorithms to process new entrant requests and uses geographic information systems (GIS) data to perform interference assessments. In some cases, environmental radio sensors may also complement the interference analysis to enhance the decision-making.

From a data-standpoint database-assisted systems manage interference between incumbent and lower priority users using two main categories of data, namely, regulatory and spectrum-related. The regulatory data typically informs the database administrator on the conditions of use for the spectrum; whereas the spectrum-related data is used to manage both existing and new spectrum requests to minimise the risk of harmful interference. Table 1 summarises the types of data and their use in existing spectrum database sharing systems.

From Table 1, one obvious opportunity to enhance the performance of current systems is to improve the accuracy and reliability of the data in both categories. For example, more accurate licensing data on antenna heights or the location of the incumbent system can provide more precise protection contours for incumbent systems. Additionally, more accurate path loss models, with higher resolution terrain and above-ground clutter data would allow current systems to make better decisions on when and where to allow lower priority users to operate.

Despite their potential benefits, current database-assisted spectrum sharing systems have several limitations that impede their effectiveness. One major issue is that the interference criteria used to determine harmful interference is based on RF power levels assessed at the victim receivers front-end radio equipment, which can be difficult to accurately assess. Another limitation is the creation of restricted or protected boundaries or zones based on worst-case power level assumptions, resulting in overly conservative estimates of the spectrum available for sharing. Finally, current systems often estimate the usage and RF coverage of existing spectrum users based solely on geography, resulting in static and inflexible coverage estimates that do not account for conditions that vary over time.

III. OPPORTUNITIES

Expanding the types of data used in database-assisted sharing systems offers significant opportunities to overcome current limitations and improve spectrum usage. Aligning with the vision to evolve these systems, complementing existing data with information on the applications or services in operation, network traffic, the radio equipment being used and the potential spectrum use in different geographical areas can provide a more holistic approach to coordinating and managing spectrum resources.

For instance, in most cases, the level of harmful interference is predetermined by the spectrum regulator and measured at the RF level without consideration of the impact on system performance or the types of applications used in different locations over time. By incorporating additional data on the types of applications along with their target performance criteria, the interference criteria can be determined on a case-by-case basis. This approach would allow areas and wireless systems to have different tolerances to interference, resulting in more effective spectrum sharing.

Furthermore, in dense urban environments, where interference is the limiting factor, auxiliary data capturing the RF equipment being used by victim devices, the network (traffic) type and operating margins of the existing users could all assist in defining more realistic exclusion / protection zones. Ultimately, allowing more robust interference criteria to be used based on system performance rather than RF-power.

To further enhance database systems, improving estimates of spectrum coverage and usage is a promising area. Current estimates often fail to align with potential demand areas and ignore the temporal spectrum use. Estimating the temporal and spatial use or demands of multiple services in any geographic area is a challenging task. Assuming there is enough spectrum available, the demand at any given time and place depends on various non-spectrum-related factors such as the services being offered, end-user behavior and the type of industries and businesses being served. For instance, the demand for mobile broadband services can vary greatly depending on the location and the type of activities taking place. In densely populated urban areas, demand may peak during high-traffic events such as cultural festivals and events. On the other hand, in rural areas, the intensity of spectrum usage is more widely spread and the demand may be more seasonal, with peaks coinciding with agricultural activities. By including data such as the offered services, historical traffic patterns, technology advancements, population growth and local community events it becomes possible to anticipate spectrum use in both time and space. This enables geographical areas with demand surges to be better served and has the potential to characterise interference in both spatial and temporal domains.

Table 2 provides examples of various capabilities, the relevant data and opportunities that could be exploited in future database-assisted sharing systems. It is worth noting that the potential opportunities and associated data sets are highly dependent on the intended use and amount of spectrum being managed by the database administrator. For example, current SAS systems for CBRS primarily support mobile broadband services as a secondary licensed tier over large geographic areas. As a result, there is limited value in leveraging data indicating areas of intense business activity. However, with the growing trend towards more localised spectrum access [22], it is expected that database-assisted systems will play a crucial role in administering spectrum over smaller geographic areas to meet the demands of local businesses and industries. In this light, current SAS-type systems are not well-suited to provide localised spectrum access to meet time-varying demand from vertical industries or markets. Rather, these systems tend to provide mobile broadband technology supporting multiple vertical markets. Consequently, current systems do not cater to customers with specialised needs or niche business activities.

To address this deficiency, geospatial data linked to areas of business activity can be generated by extracting data from satellite imagery and cross-referencing with data from open, online sources such as OpenStreetMap [23]. The extracted polygon data, as shown in Fig. 2 corresponding to a shopping mall and hospital, can serve as proxy locations for anticipated spectrum demand in that particular area. Moreover, automation of the extraction process can yield localised data that can be used to generate insights into short-term spectrum demand. For example, Fig. 3 shows several vertical businesses and industries for the Peel Region of Ontario, Canada, that have been extracted from OpenStreetMap and plotted as coloured polygon data. For reference, Fig. 3 also plots the smallest service area for spectrum licensing, known as tier-5, which is currently being used by the Canadian regulator. It shows that if a tier-5 license is issued for the region depicted, it may not be well adjusted to meet the demands of many small businesses and vertical markets. This type of data can be leveraged by regulatory bodies to predict areas of potential demand and adjust policy objectives to provide spectrum licenses tailored to diverse business needs. Table 3 outlines various industries and corresponding subcategories of data types that can be readily extracted from open sources and utilised in this analysis, ranging from small-scale areas for schools to larger areas for mining sites and farming.

A different GIS data set that can shed light on potential spectrum demand contains information on the employment business counts [24], [25], [26], [27]. Depending on the specific country, the data sets can consist of either multiple

TABLE 1. Data used to manage interference in current database-assisted sharing systems.

Data Type	Description	Current Usage of Data
Regulatory		
Licensing	Captures a mixture of both technical and non-technical information on the licensed users of the spectrum and their authorised geographic areas of operation	Data on authorised spectrum user used for billing, compliance, interference resolution Technical parameters including location, antenna heights and operation (fixed or mobile) used in EMC analysis
Available channels	Defines the frequency range of operation and the minimum contiguous frequency block or channel that can be allocated	Data used to match spectrum requests with available channels
Policy	Defines authorised users of the band and their relative priority	Data used to pre-empt lower priorty users and manage interference
Incumbent technical	Part of the reported licensing information containing RF-related data such as: bandwidth, carrier frequency, antenna heights and pattern	Parameters used as an input to the EMC analysis to estimate coverage and estimate potential interference
Exclusion/ Protection zones	Geographical areas with defined deployment conditions for new services to protect various incumbent services e.g. airports	Polygon data incorporated into the database decision making to manage new entrant requests
Interference criteria	Defines how interference is determined and the maximum allowable level	Typically measured as an interference power level or ratio, relying on reported or assumed thermal noise floor values and bandwidths to determine if the level of interference is harmful
New entrant	Consists of applicant information/registration data and technical parameters	Technical parameters including location, antenna heights and operation (fixed or mobile) used in EMC analysis
Spectrum-related		
Terrain	GIS data used for many applications, captures topographical features such as mountains, streams and ridges	The majority of database systems calculate the path loss values, for interference analysis, using a propagation model and digital terrain elevation data
Above-ground clutter	Consisting of building, foliage and other structural information above the terrain or elevation data	Current database systems combine the terrain elevation data with statistical above-ground clutter models e.g. International Telecommunication Union - Recommendation (ITU-R) 2108 for AFC [19]
Separation distance	Distance required between different priority users	Database systems use the distance in the EMC analysis to either define the type of propagation model that is used in the path loss calculation e.g. AFC [19] or to set a minimum distance from the incumbent system within which a new licence will not be granted e.g. TVWS [20]
Sensor	RF power level measurements taken from sensors	Current sensor-assisted database systems aggregate the sensor information from multiple spatially separated sensors to detect the presence of a higher priority system e.g. CBRS
Spectrum usage (spatial)	Estimates of the spectrum use, typically defined as the RF power over a geographical area	Combination of technical parameters, path losses and RF measurement data to determine coverage and potential interference scenarios used by the decision making in the EMC analysis

years' worth of census data or a single snapshot of the count of active and registered businesses augmented with additional data such as the number of employees. An example of how this type of data can be exploited by future database systems is shown in Fig. 4 using the "Canadian business counts, with employees" data set from Statistics Canada [26]. The figure displays the concentration of manufacturing industries in Southeastern Canada using the location quotient (LQ) density to compare the concentration of a given industry in a specific area to the concentration of that industry across the entire country. In this case, the highest concentration of manufacturing industries is centered around major Canadian cities such as Montreal, Ottawa and the greater Toronto area. The business count data, which also captures information from industry segments similar to those listed in Table 3, provides valuable insights to both regulators and database administrators about areas of high and low activity. Regulators can use this information to prioritise license applications for certain industries and encourage their growth in specific geographical areas. Administrators of database-assisted systems can also utilise this information to prioritise and monitor new entrants to the market and provide feedback to regulatory bodies on the impact of their decisions.

In the following section, two case studies are presented to highlight the potential benefits of using additional data sources to improve spectrum sharing.

TABLE 2. **Opportunities to evolve database-assisted sharing systems.**

Capability	Relevant Data	Opportunity
Predict Spatial/Temporal Spectrum Use (short term)	Network Traffic Types Areas of Business Activity	Re-use spectrum more dynamically and in a flexible manner meeting surges in spectrum demand
Predict Spatial/Temporal Spectrum Use (long term)	Technology Adoption Rates Network Configuration Historical Traffic Patterns Population Growth Industrial Locations Public Events Weather	Long term prediction yields opportunities to plan and release additional spectrum from the perspective of the regulator and allows database administrators to manage the spatial and temporal use of spectrum more effectively
Modify exclusion/ protection zones to account for local environment	Operational Margins (Incumbent) Network Traffic Types Equipment Specifications (Incumbent) Equipment Specifications (Lower Priority Users)	Tailor individual protection zones for incumbent services as a function of geography and the operational considerations of both incumbent and lower priority services sharing the spectrum
Enhance Interference Criteria	Operational Margins (Incumbent) Service Type (Incumbent) Service Type (Lower Priority Users) Equipment Specifications (Incumbent) Equipment Specifications (Lower Priority Users) Weather	Implement different interference criteria depending on the relevant data. This includes the services offered by both incumbent and lower priority users, their respective tolerance to interference, the operator equipment and operational signal margins that are being used

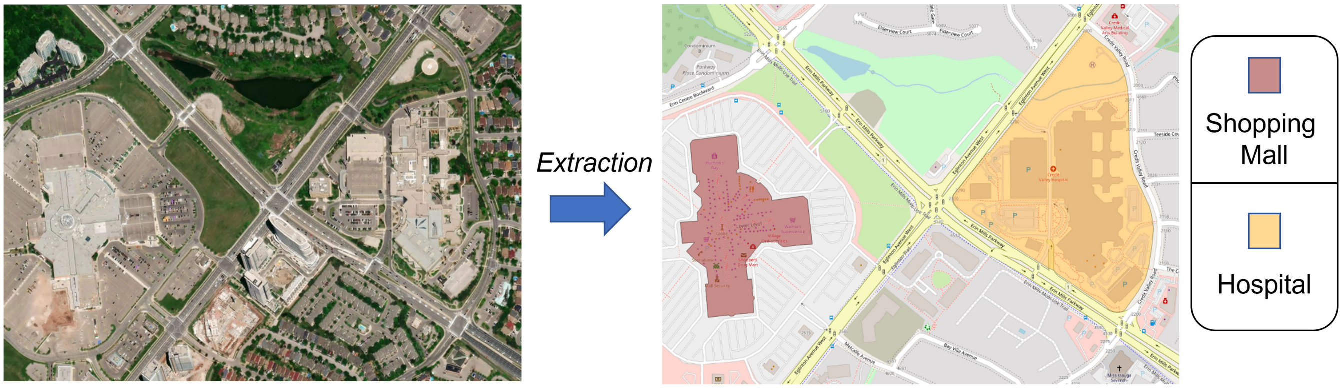

FIGURE 2. **Example data extraction using OpenAerialMap satellite imagery [21] and OpenStreetMap industrial data.**

IV. CASE STUDIES: SHARING WITH EARTH STATIONS IN MID-BAND

The case studies demonstrate, through simulation analysis, the benefits of incorporating supplementary data sources to enhance spectrum sharing, particularly for fixed satellite service (FSS) earth stations using mid-band spectrum in Canada. The studies focus on high demand areas in urban and suburban regions and employ various sources of data, including OpenStreetMap polygons to identify potential demand locations, technical specifications of RF equipment, operational margins and weather data. The first case study proposes an alternative interference protection criteria (IPC) metric for incumbent earth stations in the C-band, while the second study, in the K-band, proposes an IPC threshold that changes due to seasonal climate information.

Note, while the data sets and case studies are based in the Canadian context, the data-driven methods and principles can be applied to any national regulatory authority dealing with spectrum sharing challenges.

A. INTERFERENCE PROTECTION CRITERIA

For the simulation analysis, the IPC is used to define the level at which the aggregate interference from all secondary services reduces the performance of an incumbent priority user to an unacceptable level. The IPC value is typically system-specific depending on the protection requirements of

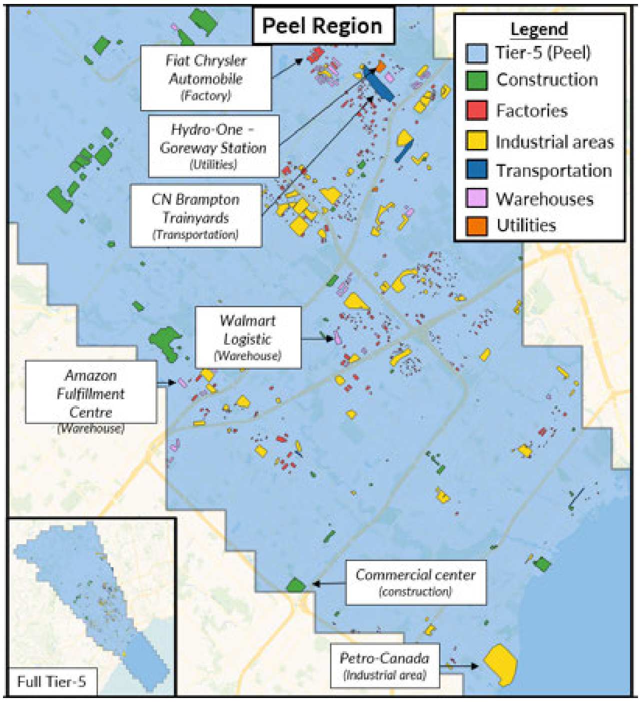

FIGURE 3. Extracted data for Peel, ON region of Canada.

TABLE 3. Example categories of geospatial data available from OpenStreetMaps.

Industry	Sub-category
Agriculture	Precision agriculture, vertical farming
Construction	Industrial worksites
Education	University, college campuses, schools
Energy	Power plants, oil and gas, wind farms
Entertainment	Sports stadiums, race tracks, casinos
Forestry	Harvesting areas, mill facilities
Government	Municipal, Federal buildings
Healthcare	Hospitals, healthcare centres
Hospitality	Convention and exhibition centres
Innovation Hubs	Research and development complexes
Manufacturing	Factories, automotive plants
Mining	Surface mines, underground
Ports & Transportation	Seaports, inland ports, airports, train stations
Retail	Shopping malls
Utilities	Water treatment plants, gas, electricity generation

the incumbent user, the operating conditions and the desired level of protection specified by the spectrum regulator. Two commonly used IPC metrics use threshold levels based on either the interference-to-noise ratio (I/N) or the carrier-to-interference-plus-noise ratio (C/(I+N)). For the former, the theoretical noise floor is used as a reference whereas the latter considers the receiver performance degradation subject to both desired (e.g., the satellite carrier signal level in our scenario) and undesired signals (interference and noise).

For the I/N IPC metric, commercially deployed systems typically use a single fixed value, irrespective of the operating conditions, equipment, or orientation of the earth station towards the satellite. For example, in the CBRS system a I/N $= -12$dB is used for every FSS receiver station. This ratio is equivalent to assuming a noise temperature of 142.8 Kelvin (K) resulting in a power measurement of -129dBm/MHz. In contrast, the AFC system uses an I/N of -6dB for license-exempt devices. However, it should be noted that this is not meant to measure the aggregate interference caused by multiple devices.

In terms of the data requirements, the IPC metric of I/N is relatively simple to calculate. The thermal noise is derived using the operator bandwidth reported in the regulatory database, combined with an estimate of the noise temperature. Whereas, the aggregate interference is determined at the output of the incumbent receiver chain and includes the effects of the antenna gain pattern, available through the ITU website [28]. Note, the use of a single I/N IPC metric results in a general over-estimation of the aggregate interference in the spectrum environment. The one-size-fits-all approach, doesn't allow for individual services or local factors to dictate an appropriate aggregate interference level mirroring the actual interaction between incumbent and secondary services.

Developing metrics that reflect the individual systems being used in different geographical areas requires additional steps and data. For example, the IPC metric of C/(I+N) can be used by performing a link budget analysis to estimate the carrier signal from the transmitting satellite to the earth station. A link budget analysis typically uses various data such as the locations of the satellite and earth station, the relative orientation and gain pattern of the transmit and receive antenna, the satellite transmit power and the receiver noise temperature. A suitable propagation model is also required to capture the link losses between the transmitter and receiver.

Since the C/(I+N) metric uses the wanted signal to determine the impact of aggregate interference, it is crucial to capture the operating margin or C/N objective required by the earth station operator to provide adequate service. For example, a link with an estimated C/N that is much greater than the C/N objective will tolerate much more aggregate interference than one that is marginally above the C/N objective.

B. LINK BUDGET CALCULATION

The power of the carrier signal, in dBm, received at the receiver earth station can be calculated as [29]:

$$C = P_{T_x} + G(\theta)_{T_x} - FSL - AL - RL + G(\theta')_{R_xES} \quad (1)$$

where

P_{T_x}: Transmitting satellite power (dBm)
$G(\theta)_{T_x}$: Satellite antenna gain (dBi) in the direction, θ, of the earth station
$G(\theta')_{R_xES}$: Receiving gain (dBi) of the earth station at angle θ'

and FSL is the free space loss (dB) derived as follows:

$$FSL = 20(\log f + \log d) + 32.45, \quad (2)$$

where f is the carrier frequency in MHz and d is the distance between an earth station and a geostationary satellite, in km,

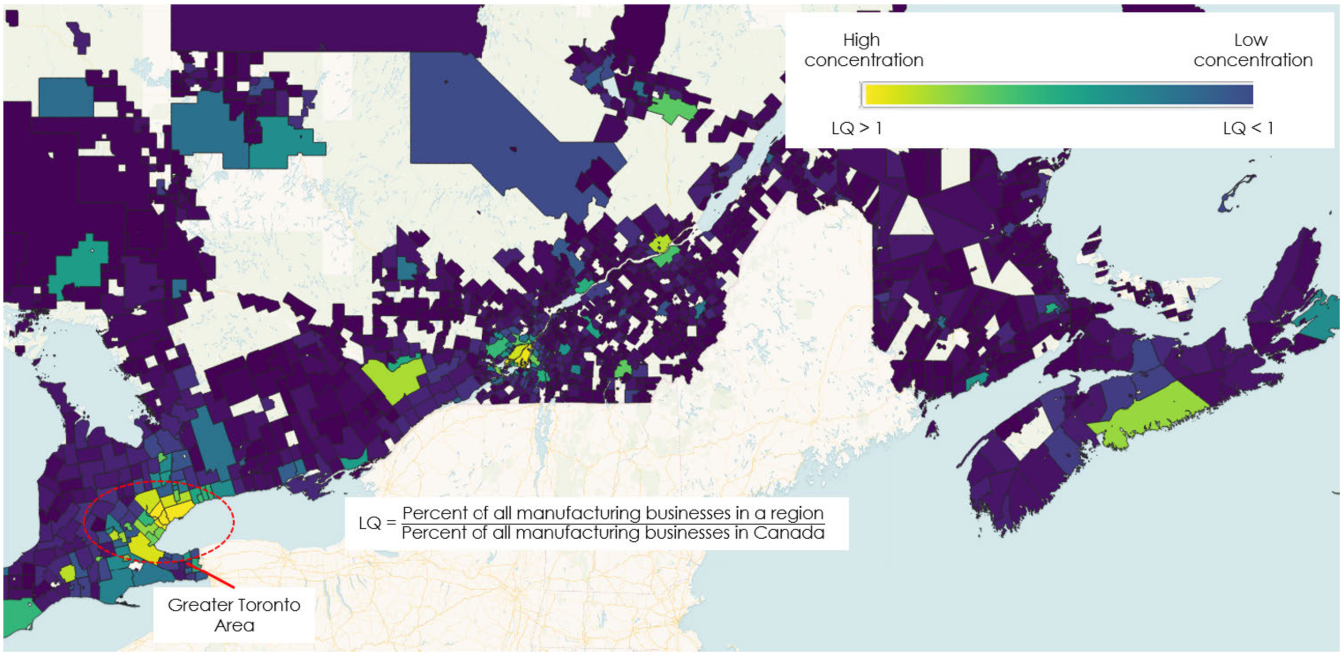

FIGURE 4. **Map showing the relative concentration of industry use in Eastern Canada, as a function of location quotient (LQ). Data taken from Statistics Canada "Canadian business counts, with employees."**

given by:

$$d = 42644\sqrt{1 - 0.2954\, cos(\psi)} \tag{3}$$

with $cos(\psi) = cos(\zeta).cos(\beta)$, where ζ is the latitude of the earth station and β is the difference in longitude between the geostationary satellite and the earth station. Furthermore, AL and RL in (1) represent attenuation due to absorption by atmospheric gases, as well as rain and other precipitations that affect the carrier. ITU Recommendation P.618 [30] provides detailed calculations of these losses as a function of frequency, elevation angle and long-term rain statistics at the location of the earth station. For our case studies, the losses are calculated using Centre National D'études Spatiales (CNES) Propa software [31] which implements ITU's recommendations.

From (1) a key source of data needed to avoid significant under- or over-estimation of the received carrier signal is the technical specifications for the actual satellite serving the earth station. This includes information on the beam coverage, antenna pattern and gain factor. Typically, not all of this information is available from the regulatory licensing database and must be determined from alternative sources. One such source of information is the ITU space network systems (SNS) database [32] which contains technical operating parameters such as transmit power, antenna gain, beam-width and operating frequencies, for both geostationary and non-geostationary satellites.

Once the received carrier signal has been estimated for both clear sky and with rain, and the information on the C/N objective has been extracted from the ITU SNS database, the interference margins for the satellite earth station can be determined. For example, a predicted C/N with clear sky of 20dB and a C/N objective of 10dB results in a C/N margin (clear sky) of 10dB. In other words, for the IPC metric of C/(I+N), the incumbent system can tolerate an increase of 10dB in the combined aggregate interference plus noise with respect to the carrier signal.

The following section describes the simulation approach and presents results using different data sets comparing I/N and C/(I+N) metrics where appropriate.

C. SIMULATION METHODOLOGY

The presented simulation results depict potential secondary transmitter locations using OpenStreetMap polygons associated with industrial areas, retail parks, shopping malls, and construction sites, as displayed in Fig. 3. The use of polygon data serves as a more realistic representation of possible sources of interference, in addition to providing an extra data source for the simulation scenario. This approach differs from the conventional method, which assumes a random distribution of potential secondary transmitters around the incumbent receiver, either homogeneously or population-weighted [33]. In this case, using the locations of the polygons is more representative of spectrum demand from specific vertical markets.

In the study, the transmission location for a secondary system with a single base station is selected as the centroid of the polygons. Parameters listed in Table 4 are utilised to simulate local broadband network coverage, following the methodology suggested by [22]. Additionally, it is assumed that the secondary systems operate on the same frequency, with the level of mutual interference between them determined by calculating the path loss between polygon centroids. For the simulation scenarios, the notation $I_{i,j}$ is

TABLE 4. Parameters for the secondary systems in the simulation environment.

Parameter	Value
Transmitter EIRP	24dBm
Bandwidth	10 MHz
Antenna Height	10m
Antenna Directionality	Omni
Antenna Gain	0dBi
Downlink Traffic	Fixed, 100%
Antenna Location	Outdoor

used to represent the terrestrial interference power from transmitter i to receiver j. Thus, the interference, in dBm, between two points is defined as:

$$I_{i,j} = P_i + G_i(\theta_i) - L_p(i,j) + G_j(\theta_j) \tag{4}$$

where the first two terms on the right represent the transmitted effective isotropic radiated power (EIRP) and

P_i: Power (dBm) from the i^{th} transmitter location
$G_i(\theta_i)$: Antenna gain (dBi) for the i^{th} transmitter at angle θ_i
$L_p(i,j)$: Path loss (dB) between the i^{th} transmitter and j^{th} receiver
$G_j(\theta_j)$: Antenna gain (dBi) for the j^{th} receiver at angle θ_j.

The aggregate interference between secondary and incumbent systems is given by assuming that there are N_a active secondary systems taken from a set of N_c locations of the data polygons, where $N_a \leq N_c$, and J incumbent systems. Using the notation $I_{i,j}^{mW} = 10^{I_{i,j}/10}$, the aggregate interference between a secondary transmitter and the incumbent receiver is calculated as:

$$I_{SI,j} = \sum_{i}^{N_a} I_{i,j}^{mW} \tag{5}$$

where $i = 1, 2, \ldots, N_a$ and $j = 1, 2, \ldots, J$. The aggregate interference between secondary systems is also calculated as follows:

$$I_{SS,n} = \sum_{i}^{N_a} I_{i,n}^{mW} \quad i \neq n, \tag{6}$$

where n ranges from 1 to N_a. Note, this equation calculates the sum of the interference between all active secondary systems, with the interference between a secondary system and itself excluded. Further the calculation of the point-to-point interference is greatly influenced by the propagation model being used in the simulation.

In a previous study [11], the impact of using different geospatial data sets of terrain and above ground clutter on the single IPC metric of I/N was analysed in a specific location using different propagation models. This paper builds upon those results by examining the additional IPC metric of C/(I+N) in two distinct spectrum bands and geographical areas, and utilising supplementary data sets to demonstrate the potential benefits.

For the simulation scenarios, the analysis uses Monte Carlo modeling where for each simulation trial the following steps are implemented:

1) Choose a candidate secondary location randomly from the set of N_c data polygons
2) Update the aggregate interference calculation, (5), from the candidate secondary location to the incumbent location
3) Update the aggregate interference calculation, (6), from the candidate secondary location to all other active secondary systems
4) Assign a channel to the candidate secondary location if the aggregate interference is below the interference threshold for both the incumbent and other secondary systems; otherwise remove the candidate location
5) Repeat steps 1-4 until either the interference threshold is exceeded or until all N_c of the possible candidate secondary locations are exhausted.

Although not a focus of this paper, the channel assignment methodology outlined in step 4 has a significant impact on both the distribution of the assigned secondary systems and their contribution to the interference environment. In the simulation results presented, channels are assigned on a first-come-first-served basis, based on the randomly selected secondary locations.

V. SIMULATION RESULTS

A. CASE STUDY 1 – ALTERNATIVE IPC METRIC

The first case study is centered around a C-band earth station in Montreal, Canada. The impact of the IPC choice is illustrated by running the simulations using two different interference protection criteria, an I/N of −6dB, and a C/(I+N) threshold which is derived for the specific earth station of interest.

Table 5 lists some of the parameters for the C-band earth station considered in this scenario where the operating C/N ratios under clear sky and rain were derived using the procedure detailed in section IV-B. Comparing this to the C/N objective of this link, C/N margins available for accommodating secondary transmitters were calculated for clear sky as well as rainy situations. Considering that the actual installation of the earth station might have other inefficiencies such as losses due to coupling, antenna pointing inaccuracy, and spurious environmental noise, without loss of generality, the available C/N margin is lowered by an additional 5dB. The exact value of this reduction can be fine-tuned on a case-by-case basis depending on the specifics of the installation. As can be noted from Table 5, the difference in available C/(I+N) margins for this earth station under clear sky and rain is only 0.5dB. Therefore, only results for the clear sky scenario are reported.

Fig. 5 and 6 show the complementary distribution function (CDF) of active secondary transmitters and aggregate I/N over different simulation runs, respectively. Aggregate interference results were generated using the ITU-R P.1812 [34] propagation model. The model incorporated High Resolution Digital Elevation Model (HRDEM) data [35] which includes

TABLE 5. Parameters of the earth station in case study 1.

Parameter	Value
Center Frequency	3925.6 MHz
Noise Temperature (Clear Sky)	100 K
Noise Temperature (Rain)	107 K
C/N Objective	10 dB
C/N (Clear Sky)	18.4 dB
C/N (Rain)	17.9 dB
C/N Margin (Clear Sky)	8.4 dB
C/N Margin (Rain)	7.9 dB

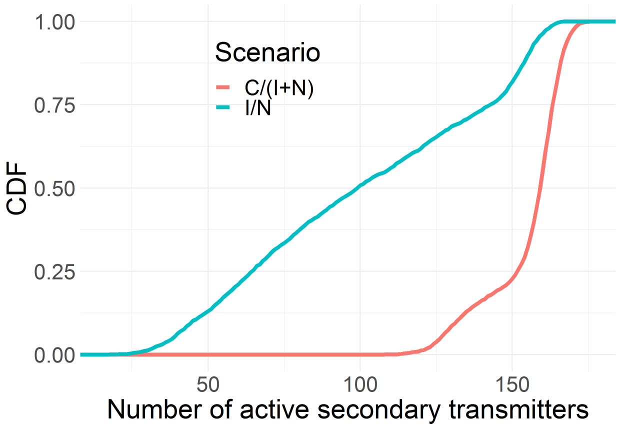

FIGURE 5. Case Study 1: Distribution of the number of active secondary transmitters over various simulation runs.

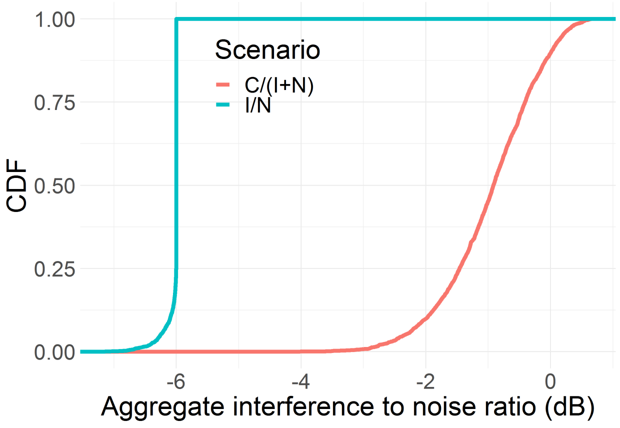

FIGURE 6. Case Study 1: Distribution of the aggregate I/N over various simulation runs.

both terrain and above ground clutter, applicable to the band. In order to have a meaningful comparison between the two IPC metrics, the same exclusion zone is imposed to both scenarios. In other words, the locations of candidate secondary transmitters that individually exceed an I/N of −6dB are excluded from the analysis.

As shown in Fig. 5 and 6, imposing a one-size-fits-all I/N threshold of −6dB unnecessarily impedes the introduction of additional active secondary transmitters while the C/(I+N) threshold allows improved sharing of the spectrum while still protecting the incumbent earth station. Specifically from Fig. 5, the alternative IPC metric enabled by leveraging additional data sources results in a 60% increase in the median number of secondary transmitters that can share the spectrum with the incumbent (160 transmitters for C/(I+N) vs. 100 for I/N). The potential benefits of using a data-driven approach tailored to the specific sharing scenario are reinforced by considering the CDF of aggregate interference to noise ratio in Fig. 6. In this case, the aggregate interference environment quickly exceeds the conventional I/N threshold, whereas using C/(I+N) results in a more moderate rise in the aggregate interference.

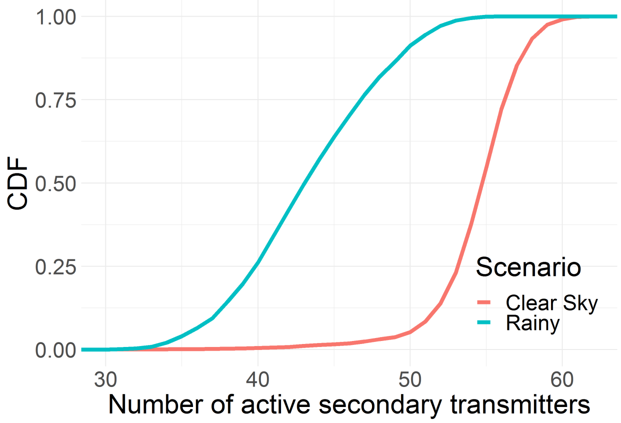

FIGURE 7. Case Study 2: Distribution of the number of active secondary transmitters over various simulation runs.

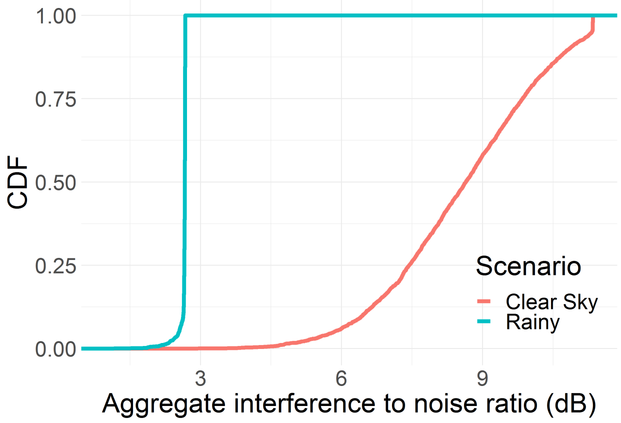

FIGURE 8. Case Study 2: Distribution of the aggregate I/N over various simulation runs.

B. CASE STUDY 2 – ADJUST IPC

Static interference protection criteria typically have to be based on worst-case assumptions. In this section, some potential benefits of having a spectrum sharing system that can adjust its IPC threshold based on current or forecast (as opposed to historical) data are demonstrated. More specifically, the impact of rain on the C/(I+N) IPC metric highlights the potential gains that can be realised by taking current or forecast weather data into account as opposed to long-term weather statistics. To this end, this case study is based on a Ku-band earth station in Calgary, Canada. The choice of Ku-band is driven by the fact that losses

TABLE 6. Parameters of the earth station in case study 2.

Parameter	Value
Center Frequency	12.45 GHz
Noise Temperature (Clear Sky)	290 K
Noise Temperature (Rain)	485.5 K
C/N Objective	10 dB
C/N (Clear Sky)	31.6 dB
C/N (Rain)	24.6 dB
C/N Margin (Clear Sky)	21.6 dB
C/N Margin (Rain)	14.6 dB

due to precipitation increase at higher frequencies, thereby increasing its relative importance in link budget calculations.

Table 6 lists some of the parameters for the earth station considered in this scenario. As before, the operating C/N ratios under clear sky and rain are derived according to section IV-B. Similarly to case study 1, not all of the available C/N margin calculated in Table 6 is used allowing for various other losses and inefficiencies.

Fig. 7 and 8 show the CDF of active secondary transmitters and aggregate I/N over different simulation runs, respectively. For the Ku-band, the terrestrial aggregate interference results are determined using the irregular terrain model [36] incorporating terrain data in the form of CDEM (Canadian Digital Elevation Model) [37]. Fig. 7 shows that allowing the system to operate with a modified C/(I+N) threshold under clear sky situation, instead of using a static threshold derived based on historical precipitation patterns, results in a 25% improvement in median number of active secondary transmitters (55 vs. 44 transmitters). In practice, the actual C/N margin for the incumbent would fall somewhere in between the two curves, depending on the precipitation levels specific to their location. Fig. 8 further illustrates how using a static threshold derived from historical rain data unnecessarily prevents secondary transmitters from sharing the spectrum under the clear sky situation. The results reinforce the case for a data-driven approach capable of calculating the IPC thresholds dynamically based on up-to-date, accurate data sources.

The case studies have showcased potential benefits in employing database-assisted spectrum sharing for scenarios involving fixed incumbent and fixed secondary systems. These methods hold applicability to similar scenarios in other bands and geographical locations, albeit reliant on obtaining relevant data from both existing services and secondary users. From a broader perspective, the integration of diverse data sources for management and coordination of spectrum sharing can significantly enhance its utilisation. For instance, incorporating additional data on network traffic from both incumbents and secondary systems allows for adjustments in measuring aggregate interference, enabling scalability of the number of new spectrum users permitted in a specific area based on the temporal spectrum usage patterns. Note, the latter would benefit from simulation studies incorporating higher layers of the communications protocol suite, modeling from the network to the application layers.

It is also worth highlighting that in both case study examples, the admission of active secondary systems into the environment is influenced by various factors. These factors include the location, propagation path between transmitters and receivers, antenna heights, orientations between systems, available operating margin for incumbent users and interference amongst secondary systems. Consequently, offering definitive guidance on the number of potential secondary systems that can be accommodated in a specific scenario proves to be a complex endeavour and should be determined on a case-by-case basis.

While the case studies have demonstrated some potential benefits, there are still several challenges that need to be addressed during the implementation and management of such systems. The next section will discuss some of the main challenges that future licensing systems need to overcome.

VI. CHALLENGES

Future database sharing systems face three main challenges including: the regulatory implications of sharing systems, their suitability for different spectrum bands with diverse incumbent services and limitations in available data.

A. REGULATORY IMPLICATIONS

Regulators encounter numerous challenges when implementing database-assisted spectrum sharing systems. They must ensure transparency in their decision-making processes to safeguard the interests of all stakeholders. Additionally, they must promote efficient spectrum usage while balancing regulation with promoting shared spectrum usage. Overly restrictive regulations may create artificial barriers to entry and stifle innovation, which must be avoided.

Moreover, regulators must establish procedures that protect sensitive information while allowing the database to be used for spectrum sharing. This requires careful consideration of data privacy and security issues, along with measures to prevent unauthorised access and misuse of data.

Additionally, from a spectrum management perspective, regulators need to collaborate closely with database administrators to enforce compliance with established rules and regulations for spectrum usage. This includes identifying and resolving cases of interference, monitoring compliance with spectrum policies and promoting equitable and efficient spectrum sharing among all users. Furthermore, the regulatory approach needs to be flexible and adaptable to allow for a case-by-case analysis of new spectrum requests in various geographic areas with different incumbent services.

Finally, as more regulatory processes become automated with increasing reliance on data and decision-making algorithms, the mindset of both regulators and stakeholders must adapt to embrace more risk in management decisions. To manage this risk, spectrum sandboxes may be employed where novel spectrum policies can be tested and validated before more widespread use is approved.

B. APPLICABILITY TO OTHER BANDS

Challenges remain when applying these systems to different spectrum bands with diverse incumbent or priority systems. One such challenge is coordinating between different incumbent systems, each with their own priority levels and requirements. Another challenge is handling different bands of spectrum with unique characteristics such as frequency ranges, propagation characteristics and interference profiles. Additionally, systems must ensure fairness and equitable access to the spectrum, especially for users with different priority levels or incumbent status. As more users and devices access the radio spectrum, it becomes more likely that interference will occur, resulting in complex scenarios that the database must handle by managing a wide range of interactions. Lastly, ensuring compatibility between different sharing systems with varying requirements and technical specifications can pose a challenge.

C. DATA LIMITATIONS

The quality and accuracy of data plays a critical role in the decision-making processes for database-assisted systems. In particular, the methods used to collect, analyse and make decisions are all determined by factors such as the completeness of the data, its consistency, reliability and its potential to introduce bias into the EMC analysis and decisions to share the spectrum.

For example, inaccurate or incomplete data can lead to incorrect allocations of spectrum, resulting in interference between users and degraded performance. Moreover, as database-assisted systems evolve, becoming more reliant on real-time data to allocate spectrum dynamically, the underlying data must be updated frequently to reflect changes in spectrum availability and usage.

Another factor that can impact the quality and accuracy of data is the sample size. In general, larger sample sizes are more representative, however, the available sample size is highly dependent on the source of data. For instance, a small sample of the types of network traffic expected in a given area may be insufficient to predict the temporal spectrum use. This would increase the risk of interference from secondary systems. Similarly, collecting large samples from many spectrum sensors can result in increased costs, complexity and storage of the subsequent data. This results in privacy and security concerns.

One method to overcome some of the challenges with data limitations is through developing more robust and resilient algorithms and processes to collect, analyse and use the data and handle conflicting information from different sources.

VII. CONCLUSION

As database-assisted spectrum sharing systems continue to advance, they will increasingly rely on location-specific data to inform spectrum allocation decisions. This approach, compared to more restrictive global assumptions, has the potential to improve spectrum use. In the example case studies, the simulation results indicate that leveraging specific receiver satellite data and local weather data improves the spectrum usage by 60% and 25% respectively when compared to more conventional interference metrics. Following this, it is reasoned that including more scenario-specific data into the decision making processes will facilitate more dynamic allocation decisions and promote innovation. However, as the volume and variety of data used in these systems grows, significant challenges arise, including diverging stakeholder interests, ensuring the accuracy and reliability of data, managing conflicting information, and protecting sensitive information. Despite these challenges, the benefits of evolving database-assisted spectrum sharing systems can be realised as the quality and accuracy of data improve, and the use of these systems becomes more widespread.

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