Revisiting TVWS for Rural Broadband: Policy Insights from Nationwide Availability Analysis and ARA Field Validation

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***Abstract*—The TV White Space (TVWS) spectrum in the 470–608 MHz band offers significant potential for rural broadband, but it remains severely underutilized due to regulatory assumptions, limited traction from chipset and ecosystem developers, and fundamental limitations of database-driven spectrum management frameworks. Although the technology failed to mature during its initial rollout, the upcoming broadcast license renewals and 6G's renewed emphasis on "connecting the unconnected" create a timely opportunity to reassess TVWS spectrum policies and operational models. Here we present a national-scale assessment of TVWS availability across the United States, complemented by a field study using real-world measurements from the ARA wireless living lab in central Iowa. Our study indicates high availability of unused TVWS spectrum, for instance, with nearly 45 MHz of spectrum available nationwide on average and at least 6 Mhz available in 2779 i.e 90% of U.S. counties. However, traditional database-based spectrum management with conservative statistical channel models cannot fully utilize the available spectrum. For instance, through field measurements in the 560+ square miles area of the ARA wireless living lab, we observe that, even though there are 90 MHz of spectrum available, the database-based spectrum management system allowed only 18 MHz spectrum for high power wide-area coverage use. From a secondary user perspective, we analyze the impact of these policy mismatches on achievable coverage, throughput, and service reliability. The findings motivate the prioritization of TVWS spectrum for rural broadband and a transition toward closed-loop, data-driven TVWS spectrum management frameworks that can improve spectrum utilization while maintaining incumbent protection and enabling reliable and scalable rural broadband access.**

***Index Terms*—Spectrum Policy, TVWS, Dynamic Spectrum Sharing, Radio Environment Map, Data-Driven Governance, FCC, NTIA, RDZ.**

I. INTRODUCTION

The TV White Space (TVWS) spectrum in the 470–608 MHz band offers favorable propagation characteristics, including long-range coverage and strong penetration capabilities. These characteristics allow TVWS-based systems to cover large geographic areas with relatively modest infrastructure needs while meeting capacity demands for fixed wireless and agriculture applications [1]–[3]. Recognizing this potential, the Federal Communications Commission (FCC) authorized unlicensed secondary access to TVWS in the 2010s, establishing one of the earliest large-scale database-driven dynamic spectrum sharing frameworks [4].

Despite the technical promise and regulatory authorization for unlicensed secondary use since 2010, TVWS has seen limited deployment in rural areas of the United States and other parts of the world where it could be most beneficial [5]. Although early studies demonstrated feasibility and led to the establishment of technical standards such as IEEE 802.11af [6], actual rural deployments did not materialize due to limited traction from chipset makers and ecosystem developers, primarily due to the regulatory uncertainty, inherent challenges in spectrum availability, and a lack of interference protection for secondary users. Consequently, TVWS adoption remained limited and effectively ceased in the United Kingdom following the exit of the last TVWS database provider, leaving no active deployments [7]. Such a disconnect between technical capability and real-world adoption raises a critical question: *Do regulatory frameworks constitute a major barrier to TVWS utilization precisely where it could offer the greatest value?* This question is particularly time-sensitive given upcoming broadcast license renewals in the United States (2028–2031) [8] and the UK (2034) [9], as well as 6G's vision to *connect the unconnected*. Together, the aforementioned factors create a narrow policy window to reassess the TVWS spectrum policy and management framework before the spectrum is reassigned to alternative uses, including licensed auctions to mobile network operators.

Current TVWS management relies on geolocation databases that secondary users must query prior to transmission which enforces protection zones around TV broadcast towers using conservative channel models like Longley-Rice Irregular Terrain Model (ITM)) . However, this approach has design constraints that under-allocate the available spectrum to secondary users, especially in rural regions. The inefficiencies of the TVWS database systems are manifested in two most prominent ways i.e temporally: when the spectrum availability for SUs don't change while the broadcasters have a nightly sign-off period and spectrum sits idle yet inaccessible to SUs, and spatially where pre-computed protection contours with extra buffer zones are applied nationwide regardless of local terrain, actual receiver distribution, or measured RF conditions. As a result, rural counties with sparse television viewership receive the same protection zones as dense urban markets, despite vastly different interference risk profiles. Beyond primary user protection, the databases also fail to coordinate among secondary users themselves. When multiple secondary users share overlapping coverage areas, they compete for the same static channel list with no coordination mechanism, producing a tragedy of the commons that degrades service quality, raises deployment costs, and ultimately undermines the small ISPs and agricultural enterprises best positioned to serve rural connectivity needs.

In this paper, we present a comprehensive assessment of TVWS from the perspectives of spectrum availability and effective spectrum use. First, we analyze TVWS spectrum availability across all U.S. counties to quantify regional disparities, to understand how TVWS spectrum availability looks like in urban vs rural areas across different regions around the US. Second, we conduct a large-scale field study using the ARA wireless living lab [1] in central Iowa, covering more than 560 square miles. Using real-world measurements, we quantify the mismatch between database-reported spectrum availability and actual ground-truth conditions, finding that the database underestimates available spectrum by 69 MHz and that current availability.

The rest of the paper is organized as follows: Section II reviews the current spectrum policy framework and recent developments in TVWS while Section III analyzes the availability of TVWS spectrum in all U.S. counties, highlighting opportunities and challenges. Section IV examines the impact of current FCC and NTIA spectrum-sharing regulations on secondary users. In Section V, we propose a spatiotemporal model-based spectrum allocation method to define dynamic protection zones within rural Radio Dynamic Zones, and evaluates the coverage metric using real-world measurement data from the ARA PAWR testbed. Section VI explores open research questions related to modeling and protocol design, emphasizing the benefits of spatiotemporal approaches based on spectrum sensing for dynamic spectrum management.

II. RELATED WORK

In what follows, we trace the evolution of TVWS spectrum policy in the United States, examining deployment failures and uncovering their root causes. We then review the existing spectrum sharing paradigms employed by U.S. spectrum enforcement agencies, before highlighting the dynamic spectrum sharing frameworks proposed in the literature. This progression underscores the limitations of existing approaches and motivates why measurement-enhanced, database-driven allocation represents the essential next step for designing future spectrum sharing frameworks tailored to rural TVWS deployments.

a) TVWS Policy Evolution and Deployment Reality: The FCC authorized the unlicensed secondary use of TVWS in 2008, establishing geo-location databases as the primary coordination mechanism [4], [10]. This initial framework established the foundational principle that white space devices (WSDs) would rely on geo-location databases and, by September 2010, the FCC finalized operational rules through a Memorandum Opinion and Order that removed mandatory sensing requirements and established technical specifications for both fixed and personal/portable devices. The rules defined three device classes: fixed devices operating with higher power (up to 4 watts EIRP), Mode I personal/portable devices obtaining channel lists from fixed devices, and Mode II personal/portable devices with integrated geolocation and database access capabilities (limited to 100 milliwatts EIRP) [4]. Database administrators were required to protect incumbent services including full-power and low-power television stations, wireless microphones, broadcast auxiliary services, and other authorized users through conservative propagation modeling using the Longley-Rice Irregular Terrain Model and additional buffer zones. Moreover, technical standardization was achieved with IEEE 802.11af [6], which defines international specifications for unlicensed white space devices operating under database control.

Despite global regulatory authorizations, standardization efforts, and favorable propagation characteristics, TVWS deployment remained limited, with fewer than 1,000 devices deployed in the U.S. by 2015 [11]. Deployments slowed primarily due to regulatory uncertainty stemming from the Spectrum Act of 2012 and the incentive auction process [12], which discouraged investment, delayed chipset development, and made ISPs reluctant to deploy TVWS networks amid shifting spectrum availability [11]. In response to the continued under-utilization of TVWS in rural areas, the FCC implemented targeted regulatory updates in 2020, increasing power limits and antenna heights for fixed devices in less congested regions, and introducing high-power, geo-fenced mobile white space devices. The FCC also expanded TVWS use to support narrow-band Internet of Things (IoT) applications. Despite these regulatory updates, rural deployment remains in the U.S. remains limited. The experience of the UK is particularly instructive: despite pioneering TVWS regulations, its framework effectively collapsed in 2024 following the exit of the last database provider, leaving no active networks [4], [7]. This outcome highlights systemic barriers that extend beyond regulatory authorization or technical feasibility, emphasizing the need for approaches that address these persistent challenges.

b) Spectrum Sharing Paradigms and Limitations: Information for spectrum sharing frameworks is obtained via four main mechanisms: database-driven systems (e.g., TVWS and CBRS), device-based spectrum sensing (cognitive radio), Listen-Before-Talk (LBT) protocols, and hybrid methods [13], [14]. Database-driven systems provide scalability, however most are open-loop and depend on static propagation models (e.g., Longley-Rice ITM for TVWS and CBRS), potentially over-protecting primary users and producing large errors [15], [16]. Pure spectrum sensing or cognitive radio methods rely on techniques such as energy detection, matched filtering, and cyclostationary feature detection [17]–[19]. However, they require sophisticated hardware at every secondary device, increasing both computational and hardware complexity, and are also susceptible to hidden terminal problems [20]–[22]. While they enable opportunistic spectrum access through carrier sensing, they provide no coordination among users and cannot detect primary users beyond the local sensing range. Recent machine learning architectures leverage the cognitive capabilities of receivers to perform binary occupancy detection, determining whether spectrum is in use, rather than continuous propagation prediction for dynamic protection zones, which would map the spatial interference landscape. [17], [23].

To address the above challenges, Radio Environment Maps (REMs) offer a promising solution by capturing a physics- and data-driven spatial interference distributions for spectrum-aware planning. Traditional methods, however, face tradeoffs: for example, the Longley-Rice ITM is computationally efficient but can be inaccurate in complex terrain with shadowing [15]. Kriging-based mapping approaches perform poorly under non-stationary interference conditions and require a dense sensor deployment [24], while deep learning methods lack physical consistency and require large amounts of training data [25]. Physics-Informed Neural Networks (PINNs), on the other hand, embed electromagnetic propagation laws into their loss functions [26], enabling accurate predictions from sparse data while maintaining the physical consistency crucial for regulatory credibility. For example, ReVeal [15] derives a second-order PDE governing RSSI spatial dynamics, achieving regulatory-grade accuracy.

c) Dynamic Spectrum Management Frameworks: Beyond technical prediction methods, operational frameworks for dynamic spectrum management have evolved significantly. CBRS (3.55–3.7 GHz) pioneered tiered dynamic sharing in the U.S., using Spectrum Access Systems (SAS) to coordinate three user tiers with Environmental Sensing Capability (ESC) for incumbent radar detection [27]. The success of BRS, with 400,403 devices deployed by 2024 and 67.5% coverage in rural areas [27] illustrates that database-driven allocation can scale effectively when paired with tiered coordination and real-time sensing of incumbents. More recently, Automated Frequency Coordination (AFC) systems, approved by the FCC in February 2024 manage the unlicensed 6 GHz spectrum using advanced propagation modeling [28]. However, both CBRS and AFC rely on deterministic propagation models rather than measurement feedback, inheriting the associated accuracy limitations.

Radio Dynamic Zones (RDZs) proposed by Zheleva et al. [29] conceptualized experimental platforms for spectrum coexistence with dynamic protection boundaries and monitoring systems. Operational implementations include PowDER-RDZ's OpenZMS prototype [30] and FlexRDZ's mobility management [31]. However, RDZ frameworks remain largely conceptual or limited to testbeds, lacking operational specifications for integration with FCC database certification processes, interference protection mechanisms aligned with current TVWS regulations, and clear regulatory pathways from experimental to operational deployment.

d) Unique Contributions of this Work: The evolution from static TVWS databases (2010) to dynamic CBRS SAS (2015) and advanced AFC systems (2024) [27], [28] highlights a clear trajectory toward increasingly sophisticated spectrum coordination mechanisms. However, all current frameworks share a critical limitation: they operate open-loop mode, lacking measurement feedback to validate propagation predictions or adapt protection zones to actual RF conditions. Such a limitation is especially problematic in rural TVWS contexts, where sparse primary user activity and conservative static protection result in substantial under-utilized spectrum.

Our work advances this trajectory by synthesizing insights from TVWS deployment failures, CBRS success factors, PINN-based propagation prediction, and RDZ conceptual frameworks into an operational measurement-enhanced system. We make three key contributions: (1) Empirical characterization through 90-day continuous measurements across 560 square miles quantifying temporal white spaces, spatial over-protection, and secondary coordination failures, revealing throughput degradation of 35–60%, (2) Regulatory-validated PINN prediction demonstrating models trained on 39 locations achieve Longley-Rice-comparable accuracy (RMSE $< 6\,\text{dB}$) while validating primary user protection through direct interference measurements at broadcast Grade B contours, demonstrating that PINNs can transition from a research technique to a deployable regulatory tool, and (3) Operational R-RDZ framework with concrete regulatory pathways compatible with FCC administrative structures.

By quantifying allocation inefficiencies and demonstrating a viable solution through measurement-driven dynamic allocation that maintains protection standards, we provide an evidence-based foundation for modernizing TVWS policy ahead of upcoming broadcast license renewals. Our technical and regulatory mechanisms are immediately actionable, offering a practical pathway from policy aspirations to operational deployment.

III. AVAILABILITY OF TVWS SPECTRUM ACROSS THE U.S.

In this section, we present a comprehensive geo-spatial analysis of TVWS spectrum availability across the United States. Using region-level availability estimates and practical capacity metrics, we provide a definitive assessment of TVWS spectrum viability for bridging the digital divide. Our analysis is based on data obtained from a commercial TVWS database provider and adheres to FCC Part 15 rules and regulations [32].

Fig. 1 illustrates the baseline spatial distribution of TVWS spectrum availability across the U.S., revealing a clear inverse relationship between secondary-user TVWS spectrum availability and regional population density. The national analysis shows that 89.4% of U.S. counties (2,779 of 3,108) have at least one available TVWS channel with an allowed transmit power of 42 dBm, with a national average of 7.37 channels per county. This confirms that TVWS represents a broadly available wireless resource, especially for rural connectivity.

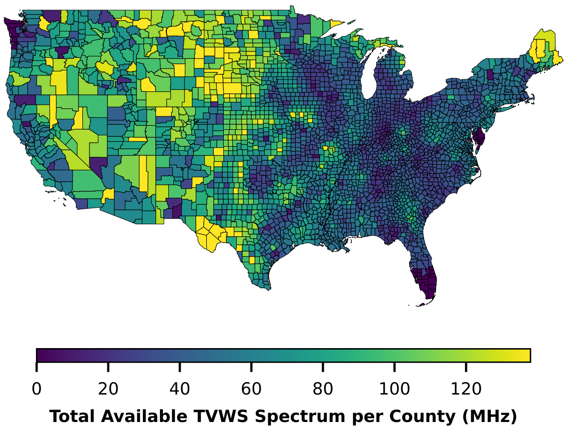


Fig. 1. Spatial distribution of TVWS spectrum availability across U.S.

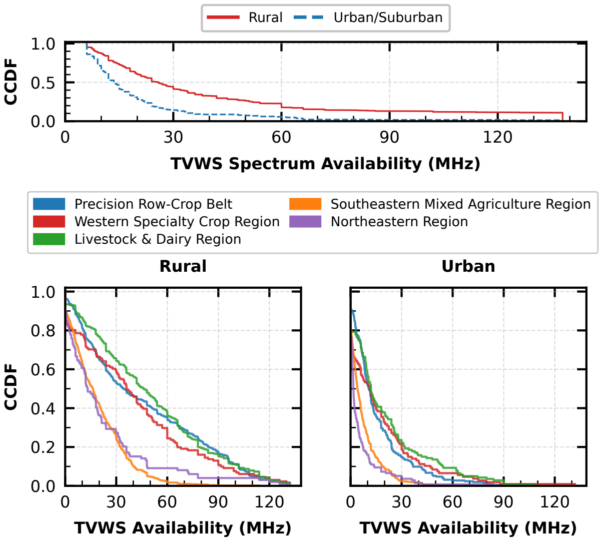


Fig. 2. Complementary CDF (CCDF) of TVWS spectrum availability (MHz) for rural and urban/suburban counties at the national level (top), and stratified by agricultural region for rural-only (bottom-left) and urban-only (bottom-right) counties

However, 329 counties (10.6%) qualify as *TVWS deserts*, defined as areas with no available TVWS channels in the 470–608 MHz band. These deserts are not randomly distributed; instead, they are concentrated in densely populated metropolitan regions along coastal areas and major urban corridors, as shown in Fig. 1.

Fig. 2 presents the CCDF of TVWS spectrum availability at national and regional levels. The top panel shows that on a national scale, rural counties exhibit substantially greater spectrum availability, with a median contiguous block of 26 MHz compared to only 14 MHz in urban/suburban counties. This disparity is consistent with the lower density of incumbent TV broadcasts in rural areas, leaving larger unoccupied segments in the UHF band.

The bottom panel of Fig. 2 divides the mainland US into five different regions centered on agricultural activity as

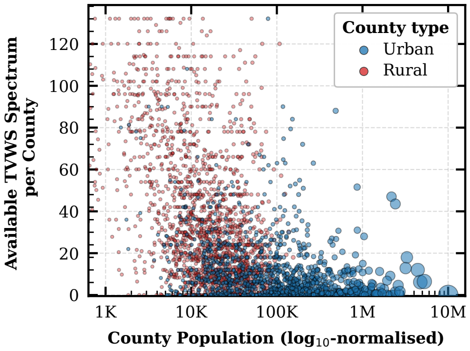


Fig. 3. Scatter distribution of TVWS spectrum availability per county as a function of county population

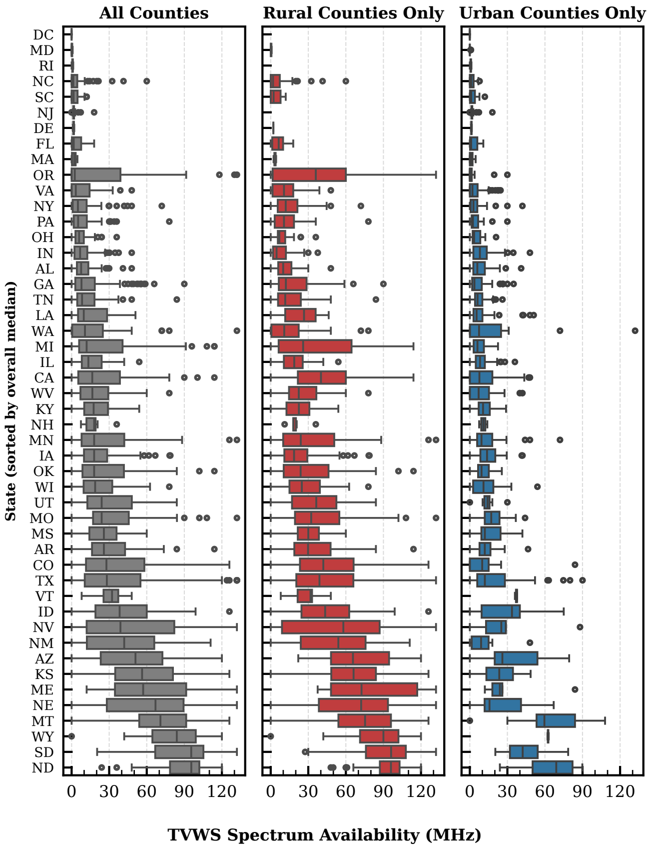


Fig. 4. State-level distribution of TVWS spectrum availability (MHz)

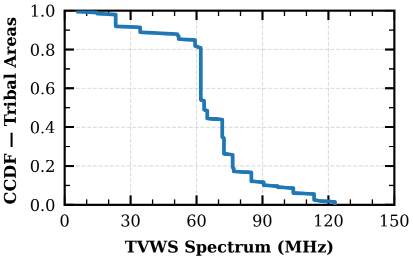


Fig. 5. Distribution of TVWS spectrum availability in tribal areas

TABLE I
AGRICULTURAL NETWORK REGIONS: USE CASES AND TVWS NETWORK REQUIREMENTS

Region	States	Agricultural Activities	Technology Needs	Network Requirements
Precision Row-Crop Belt	Iowa, Illinois, Indiana, Ohio, Nebraska, Kansas, Minnesota, South Dakota, North Dakota, Missouri	Corn, soybeans, wheat, large-scale mechanized farming	Precision agriculture, drone crop monitoring, soil sensing, automated tractors	Wide-area coverage (5–20 km), massive IoT sensors, moderate bandwidth, low-latency telemetry
Western Specialty Crop Region	California, Washington, Oregon, Idaho, Nevada, Arizona, Utah	Fruits, vegetables, vineyards, orchards, almonds, specialty crops	Smart irrigation, microclimate sensing, pest detection, agricultural robotics	High sensor density, higher bandwidth, low latency (<20 ms), localized coverage (1–5 km)
Livestock & Dairy Region	Montana, Wyoming, Colorado, New Mexico, Texas, Oklahoma	Cattle ranching, grazing lands, pasture management, feedlots	Livestock GPS tracking, drone herd monitoring, remote water/fence sensors	Ultra-wide coverage (20–100 km), sparse IoT
Southeastern Mixed Agriculture	Georgia, Arkansas, North Carolina, South Carolina, Alabama, Mississippi, Tennessee, Kentucky, Louisiana, Florida	Poultry, hog farming, cotton, peanuts, rice, mixed farming	Smart barns, livestock health monitoring, environmental sensors	Reliable indoor/outdoor connectivity, moderate bandwidth, coverage 2–10 km
Northeastern Mixed Agriculture & Specialty Crops	Virginia, West Virginia, Pennsylvania, Maryland, Delaware, New Jersey, New York, Vermont, New Hampshire, Maine, Massachusetts, Connecticut, Rhode Island	Dairy, poultry, horticulture, mixed small farms	Climate-controlled barns, crop sensors, robotics for high-value crops	Reliable connectivity, moderate bandwidth, localized coverage, low latency

TABLE II
REGIONAL DISTRIBUTION OF TVWS AVAILABILITY

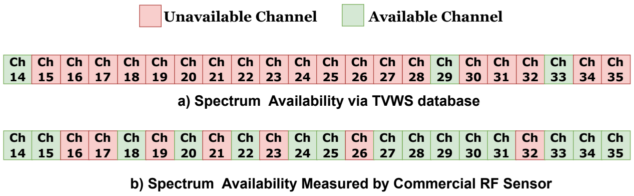
Regions	TVWS-Enabled Counties	Spectrum Availability Per County (MHz)		
		Median	P10	P90
National	2,787	44.22	6.90	101.88
Precision Row-Crop Belt	862	54.12	13.20	114.00
Western Specialty Crop Region	198	51.42	8.52	109.80
Livestock & Dairy Region	462	66.84	19.08	120.00
Southeastern Mixed Agriculture	922	26.82	4.38	54.00
Northeastern Region	200	24.54	3.30	60.00

defined by TABLE I with detailed statistics summarized in TABLE II. The Livestock & Dairy Region exhibits the highest median spectrum availability at 66.84 MHz per county, with a 10th percentile floor of 19.08 MHz, reflecting the consistently sparse broadcast environment across great-plains and Western range lands. The Precision Row-Crop Belt and Western Specialty Crop Region follow at 54.12 MHz and 51.42 MHz, respectively, both offering strong deployment potential across the majority of their respective counties. The Southeastern Mixed Agriculture and Northeastern regions present more constrained availability, with medians of 26.82 MHz and 24.54 MHz, respectively. The Northeast, however, looks particularly challenging with its 10th percentile counties showing only 3.30 MHz of available spectrum, indicating that a substantial fraction of Northeastern counties are near or at the TVWS desert threshold.

In both figures in the bottom panel of Fig. 2, the absolute spectrum availability values reduce across all regions in the urban case, showing that the rural-urban disparity is a structural nationwide phenomenon rather than a regionally isolated one. Fig. 3 further reinforces this by showing that rural counties consistently have higher TVWS spectrum availability across all population scales, while urban counties are clustered at higher populations with sharply constrained spectrum access.

Fig. 4 extends this rural-urban comparison to the state level, presenting horizontal box plots of spectrum availability for all counties in a state, along with rural-only, and urban-only subsets, sorted by overall state median. The rural-urban gap is most pronounced in the Precision Row-Crop Belt and Livestock & Dairy Region (e.g., North Dakota, South Dakota, Wyoming, Montana, and Nebraska) where rural counties achieve median availability exceeding 60 MHz while urban counties in the same state remain severely spectrum-constrained. At the opposite end, Northeastern and Southeastern states (e.g., Maryland, Rhode Island, New Jersey, and Delaware) show compressed distributions with medians near zero even in rural counties, reflecting the pervasive broadcast density of the Northeast corridor. Oregon presents a notable anomaly within the Western Specialty Crop Region, with rural availability comparable to Livestock and Dairy states, reflecting its sparse broadcast environment despite its agricultural classification.

Fig. 5 shows the availability analysis to tribal land areas, which represent some of the most persistently underserved communities in the United States. The CCDF reveals that a substantial fraction of tribal areas retain access to 60 MHz or more of TVWS spectrum, with the distribution skewed toward higher availability values relative to the national median. This suggests that TVWS is particularly well-positioned to address the broadband connectivity gap in tribal communities, where both spectrum availability and the absence of alternative



	Ch 14	Ch 15	Ch 16	Ch 17	Ch 18	Ch 19	Ch 20	Ch 21	Ch 22	Ch 23	Ch 24	Ch 25	Ch 26	Ch 27	Ch 28	Ch 29	Ch 30	Ch 31	Ch 32	Ch 33	Ch 34	Ch 35
a) Spectrum Availability via TVWS database	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟥	🟥	🟥	🟩	🟥	🟥
b) Spectrum Availability Measured by Commercial RF Sensor	🟩	🟩	🟥	🟥	🟩	🟥	🟩	🟥	🟩	🟥	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩

🟥 Unavailable Channel 🟩 Available Channel

Fig. 6. Comparison of spectrum availability assessment methods

infrastructure investment align favorably.

Together, Figs. 2, 3, 4, and 5 establish that TVWS is an inherently rural-centric resource, whose availability characteristics strongly favor low-density environments across all geographic regions and population scales.

IV. LIMITATIONS OF DATABASE-DRIVEN TVWS SPECTRUM SHARING FOR SECONDARY USERS

Although regulatory authorities have adopted database-driven approaches for TVWS spectrum access, most existing systems rely on statistical propagation models and lack feedback mechanisms to capture actual spectrum usage in a given geographic area. As a result, despite being conceptually well suited for enabling dynamic spectrum access, these database-driven solutions exhibit critical limitations that significantly constrain secondary user operations in real-world deployments.

As illustrated in the comparative analysis of Fig. 6, substantial discrepancies exist between database-reported TVWS availability and actual measured field conditions. To quantify this gap, we conducted simultaneous database queries and RF measurements at the Agronomy Farm base station of the ARA platform, representative of rural settings, with measurements collected at a height of 35 m. The TVWS database reported only three available channels in the UHF TVWS band (470–608 MHz), whereas Keysight N6841A RF sensor-based spectrum measurements indicated that approximately 15 channels were effectively available at the site. Channels were classified as available when the measured received signal strength fell below -110 dBm using a 1.5 kHz resolution bandwidth. This discrepancy arises from the conservative nature of database-driven allocation, which relies on worst-case propagation assumptions, static interference models, and overprotection from fixed buffer zones around primary user protection contours. Consequently, secondary users experience unnecessary operational constraints and are denied access to spectrum that empirical RF measurements demonstrate to be practically available.

To demonstrate the practical impact of database limitations on secondary user operations, we conducted comparative drive tests using the ARA TVWS mMIMO system at the Wilson Hall base station of ARA operating at 563 MHz with a 39 m antenna height. RF sensing confirmed that the target channel was unoccupied by primary users before transmission with background noise levels at -115 dBm. We compared two operational scenarios: (a) database-mandated power restrictions (16 dBm EIRP) and (b) the maximum FCC Part 15 permitted power (42 dBm EIRP) under the experimental license granted to the ARA platform. A mobile UE mounted on a truck collected throughput measurements at geo-referenced locations to generate empirical coverage maps as shown in Fig. 7.

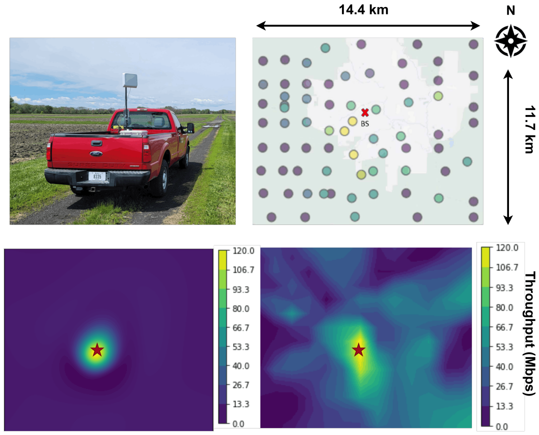
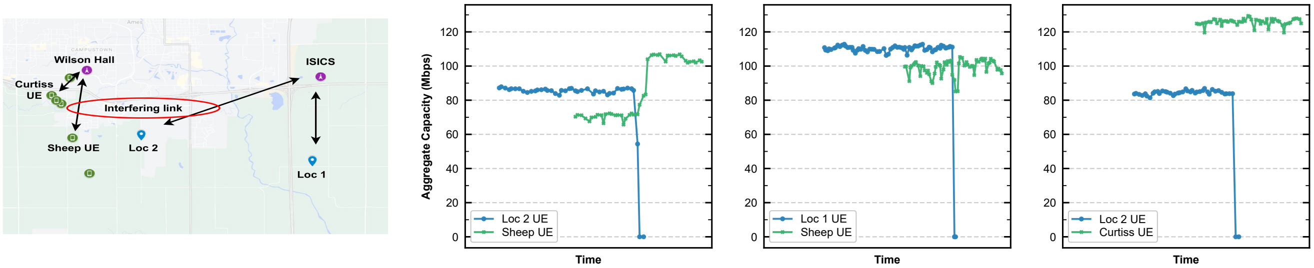


Fig. 7. Impact of low allowed power on coverage area

Under database-mandated 16 dBm EIRP restriction, the achievable coverage area was severely limited to approximately 2–3 km from the base station (Fig. 7, bottom left), despite RF measurements confirming the spectrum remained unoccupied with noise floors between -115 to -118 dBm. Operating at 42 dBm EIRP, the maximum allowed under FCC Part 15 for fixed TVWS devices, extended coverage to approximately 6–8 km radius achieving throughput close to 120 Mbps (Fig. 7, bottom right). The irregular coverage contours reflect real-world propagation effects that static database models cannot capture. This comparison quantifies the opportunity cost of overly conservative database approaches: over 26 dB power restriction on channels that are free leads to an order-of-magnitude reduction in coverage area, despite field measurements confirming the spectrum remained unoccupied with noise floors between -115 and -118 dBm. These results demonstrate that static database models significantly underutilize available spectrum and underscore the critical need for measurement-informed frameworks that dynamically adapt transmission parameters based on real propagation and interference conditions.

Under current regulations, secondary users receive no interference protection from other users operating in overlapping coverage areas. As a result, multiple secondary users may simultaneously operate in an uncoordinated fashion with the same list of available channels, regardless of their relative distance and power limits imposed on either of the secondary users. This mutual co-channel interference can lead to significant performance degradation when multiple SUs operate close to each other and coverage zones overlap. To quantify this effect, we deployed two ARA TVWS mMIMO base stations, one at Wilson Hall and another at the ISICS facility, operating simultaneously on the same database-reported available channels (563 MHz channel at 42 dBm EIRP) under our FCC



(a) (b) (c) (d)

Fig. 8. Co-channel interference caused by uncoordinated SUs

experimental license, as illustrated in Fig. 8. We conducted interference measurements by positioning mobile UEs at various locations and monitoring throughput degradation when both base stations transmitted simultaneously versus individually. Fig. 8b illustrates the interference scenario at Location 2 (Sheep Farm UE) and a nearby remote UE. Initially, the Sheep Farm UE maintains a stable connection to its serving base station, i.e., Wilson Hall, at approximately 85 Mbps. However, when the interfering link between the remote UE at Location 2 and the ISICS base station was disabled, the throughput of the Sheep Farm UE improved and the aggregate throughput becomes approximately 105 Mbps which was close to 70 Mbps. Similarly, Fig. 8c and Fig. 8d depicts scenarios where UE pairs were positioned outside each other's interference zones. In such cases, disabling one link produced no measurable throughput improvement in the other UE's throughput, confirming that interference effects are spatially dependent and diminish beyond critical separation distances between secondary users. These results demonstrate that measurement-informed approaches can safely allow secondary users to operate at higher power levels than conservative database limits permit when the spectrum is genuinely unoccupied. At the same time, coordination mechanisms are essential to prevent destructive interference among secondary users sharing the same channels. This underscores the need for dynamic spectrum management frameworks that integrate real-time sensing with inter-operator coordination protocols, enabling maximal spectrum efficiency while maintaining reliable connectivity.

V. TOWARDS DATA-DRIVEN SPECTRUM GOVERNANCE MODEL

Empirical evidence from Section IV highlights three fundamental limitations of database-driven TVWS systems: (1) static protection contours around primary users despite dynamic primary user activity, (2) spatial over-protection due to uniform buffer zones that ignore local terrain and RF conditions, and (3) lack of coordination among secondary users with overlapping coverage areas. Addressing these limitations while maintaining incumbent protection requires a shift from a *spectrum permission* model (i.e. asking *Is this channel vacant for secondary usage?*) to a *spectrum risk management model* (i.e. asking *Can this transmission safely coexist here and now?*). Achieving this transition necessitates closing the feedback loop between regulatory policy and real-world spectrum conditions. This section outlines the principles and implementation pathways for measurement-informed governance capable of unlocking TVWS potential while maintaining incumbent protection, especially during the critical policy window before broadcast license renewals (2028–2031).

A. System Architecture Overview

Fig. 9 illustrates our proposed architecture, which extends the current FCC TVWS database system. The framework consists of four operational layers.

a) Distributed Sensing Infrastructure: Sparse RF sensors (e.g., fixed spectrum monitors at cellular towers, agricultural IoT gateways, or secondary user devices) continuously measure received signal strength (RSSI) across TVWS channels. Unlike traditional approaches that require dense sensor deployments, modern spatial interpolation techniques can achieve regulatory-grade accuracy from sparse measurements, even in irregular terrain and non-uniform sampling conditions.

b) Radio Environment Map (REM) Generation: Collected measurements are fed into spatial interpolation models to generate high-fidelity REMs that depict the spatial distribution of signal strength or interference across geographic areas. To balance the computational complexity and the cost of RF sensors, REM generation techniques must deliver high-accuracy while requiring only a sparse sensor deployment. Approaches include Physics-Informed Neural Networks (PINNs), as demonstrated by ReVeal [15], along with advanced terrain-aware Kriging [24], hybrid ray-tracing calibrated with measurements [33], and deterministic models are validated against ground truth. The key requirement is regulatory-grade accuracy, typically RMSE superior to current ITM models, while maintaining computational efficiency for real-time updates.

c) Spectrum Awareness Manager (SAM): SAM serves as a coordination engine, leveraging REMs information, which capture current spatial RF conditions from the current transmitters in the region, and database information to make dynamic allocation decisions. Unlike purely database-driven systems that rely on static protection contours, the SAM computes location-specific, time-aware interference risk based on measured propagation conditions.

d) Spectrum Warehouse and Commercial SAS (Spectrum Access Systems): The Spectrum Warehouse (Fig. 9) serves as the central repository for database that stores the spectrum usage data collected from REMs generated by the Modeling

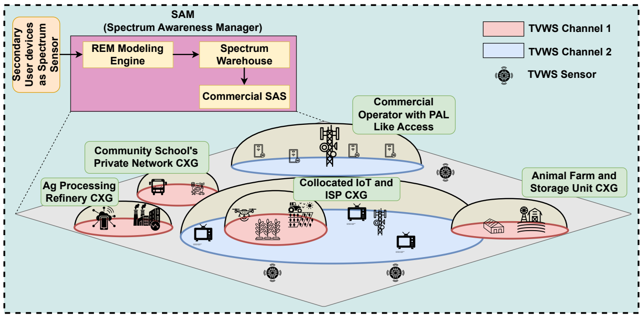


Fig. 9. Multi-slice spectrum sharing system architecture with real-time sensing and management

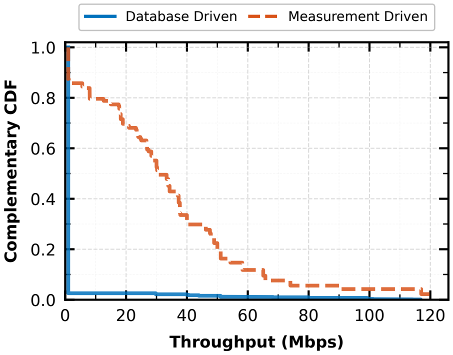


Fig. 10. Comparison of Database Driven and Spatio-Temporal Model Driven Spectrum Sharing Approaches

Engine. The primary purpose of the spectrum warehouse is to identify the spatio-temporal white spaces available for potential use and to interface with commercial database providers, ensuring compliance with regulatory frameworks approved by the governing authorities.

B. Results from the Real-World Testbed

To evaluate the effectiveness of spectrum-sharing solutions based on the spatial spectrum occupancy models, we collected 39 spatial samples of spectrum occupancy and RSSI across a 516 square mile area surrounding the ARA testbed using the Keysight Fieldfox N9963B as well as the Keysight RF Sensors N6841A. These measurements were used to train a Physics-Informed Neural Network (PINN) spatial model, achieving an RMSE of 1.3 dBm. Details of the PINN architecture are available in our prior work [15], [16]. REMs generated from the PINN model were then used to select available frequency channels within the ARA-RDZ to ensure maximum coverage using the Skylark TVWS mMIMO system. Fig. 10 compares the achieved throughput across the region using database-driven spectrum access versus data-driven, spatio-temporal model-driven spectrum sharing. The CCDF clearly demonstrates that spatio-temporal model-driven spectrum sharing achieves coverage over a significantly larger area compared to database-driven methods.

VI. POLICY RECOMMENDATIONS

Transitioning to dynamic and interference-aware spectrum governance requires coordinated regulatory evolution, industry engagement, and consideration of deployment economics. In light of impending broadcast license renewals and potential spectrum re-allocations, we propose a set of policy recommendations aimed at enabling measurement-informed, data-driven TVWS deployment while ensuring incumbent protection.

a) Formal Recognition in National Spectrum Strategy: The FCC and NTIA may consider recognizing the 470–608 MHz TVWS band as a strategic resource for rural broadband within the National Spectrum Strategy and the National Broadband Plan. Such recognition could help prioritize its preservation and proactive management alongside licensed mobile and mid-band spectrum. To support this effort, establishing an inter-agency task force involving the FCC, NTIA, USDA, and the Department of Commerce could be explored. This task force could develop a coordinated national roadmap for TVWS deployment and encourage participation from both terrestrial and non-terrestrial service providers. A coordinated approach of this nature has the potential to reduce operational costs, accelerate deployment timelines, and enhance the availability of reliable and affordable broadband in rural and remote communities, contributing to efforts to narrow the digital divide.

b) Regulatory Framework Modernization: The FCC should modernize Part 15 regulations to transition from a conservative, static model to a dynamic, risk-informed spectrum allocation framework. The current reliance on pre-computed, fixed protection contours is overly restrictive and fails to reflect actual, localized spectrum activity and dynamic usage patterns. To address this, the regulatory framework must integrate real-time or near-real-time spectrum sensing data, moving away from slow, assumption-based management. Future rules should explicitly support adaptive, data-driven access mechanisms that leverage advanced machine learning and deep learning techniques. These methods can incorporate live measurements, quantify interference uncertainty, and enable more efficient and trustworthy spectrum sharing, while maintaining robust protection for incumbent users.

VII. CONCLUSION

TV White Space spectrum offers substantial potential for bridging the rural broadband gap, yet it remains largely underutilized due to outdated, conservative database-driven policies. Our analysis demonstrates that while significant amount of TVWS spectrum is nominally available under current database frameworks, the open-loop nature of these systems creates a large gap between spectrum that is physically available and that which secondary users are permitted to access. To close this gap, we advocate a transition to closed-loop, data-driven, and risk-informed spectrum governance. This entails implementing dynamic protection zones based on real-time measurements, integrating sensing into spectrum management systems, and coordinated secondary user operations. Modernizing the regulatory framework ahead of upcoming broadcast license renewals is critical to unlock the full potential of TVWS, providing reliable, scalable, and equitable connectivity to underserved rural communities.

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