International Journal of Science and Research Archive

eISSN: 2582-8185

Cross Ref DOI: 10.30574/ijsra

Journal homepage: https://ijsra.net/

(Review Article)

Future spectrum allocation for mobile broadband and Internet of Things

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International Journal of Science and Research Archive, 2025, 14(01), 1848-1851

Publication history: Received on 19 December 2024; revised on 27 January 2025; accepted on 30 January 2025

Article DOI: https://doi.org/10.30574/ijsra.2025.14.1.0308

Abstract

The continuous growth of wireless communication technologies has heightened the demand for spectrum availability, underscoring the importance of dynamic spectrum access strategies. TV White Spaces and TV Gray Spaces represent underutilized spectrum opportunities within licensed TV bands. This paper provides a comprehensive review of advancements in TV White Spaces and TV Gray Spaces technologies, focusing on their applications in Internet of Things, low-power wide-area networks, smart grids, and rural broadband connectivity. The paper highlights state-of-the-art trends in cognitive radio systems, spectrum assessment methodologies, and regulatory frameworks across various regions. Challenges such as coexistence, interference, and spatial-temporal variability are analyzed. Finally, future trends, including integration with future technologies, advanced spectrum sharing, and energy-efficient network designs, are discussed to pave the way for scalable and sustainable spectrum management.

Keywords: 5G; 6G; Broadband; Gray Spaces; Spectrum; TV White Spaces

1. Introduction

With the rapid proliferation of IoT and wireless communication technologies, the demand for spectrum resources has surged. Traditional static spectrum allocation methods are unable to meet this demand, leading to the exploration of dynamic spectrum access (DSA) techniques. Cognitive radio technology enables opportunistic use of underutilized licensed bands, such as TV White Spaces (TVWS) and TV Gray Spaces (TVGS). These vacant or partially utilized spectrum bands offer significant potential for enhancing spectrum efficiency without interfering with primary users. This review synthesizes key advancements in TVWS/TVGS research, focusing on their technical, regulatory, and application dimensions [1]-[4].

Dynamic spectrum management has gained prominence, with studies showing that static allocation policies leave large portions of the spectrum underutilized. Advanced technologies like cognitive radios allow for dynamic access, enabling both licensed and unlicensed users to coexist. Research efforts such as the Palghar testbed in India demonstrate practical implementations of TVWS in rural broadband settings. Furthermore, international trials, such as those in South Africa and the United States, reveal TVWS's effectiveness in addressing spectrum scarcity challenges for IoT, broadband, and rural communication needs.

TVWS and TVGS TVWS refers to unoccupied frequency bands within the licensed TV spectrum, typically in the VHF and UHF ranges. These bands are identified using cognitive radio technologies and geolocation databases. TVGS, a relatively new concept, represents additional spectrum available indoors but not accessible outdoors due to signal attenuation [5]-[6]. These unique characteristics of TVGS make it particularly valuable for indoor IoT applications. The distinction between TVWS and TVGS is crucial for designing efficient spectrum-sharing models that account for propagation difference. A typical block diagram of TV White spaces is as shown in Figure 1.

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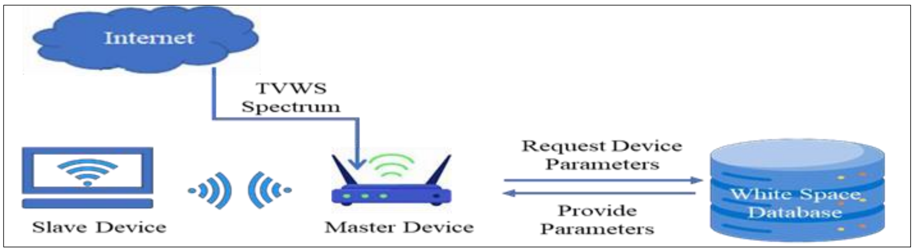

Figure 1 TVWS System Block Diagram

Several nations, including the United States and the United Kingdom, have set clear guidelines for the exploitation of TVWS for public and private communication networks. These frameworks emphasize the potential for TVWS to support large-scale deployments in urban, suburban, and rural settings.

Assessment and Utilization Advanced measurement techniques, including geolocation databases and spectrum sensing, have facilitated the identification and quantification of TVWS and TVGS. The Hata model for path loss and field measurements in diverse regions like the US, UK, and India underscore the variability in TVWS availability. For example, quantitative assessments in Pune, India, highlight the potential for using over 100 MHz of accessible spectrum in the 470-590 MHz band for cognitive radio networks.

Studies in developed regions, such as Europe and North America, utilize spectrum sharing mechanisms to maximize TVWS utility. For instance, cooperative sensing techniques have enabled real-time detection of white spaces, improving access for secondary users. Meanwhile, in developing nations, spectrum databases and affordable sensing technologies have demonstrated cost-effective approaches to bridging the digital divide.

Challenges in Implementation Key challenges include spatial and temporal variability, coexistence with primary users, and interference management. Effective utilization of TVWS requires robust spectrum-sharing protocols and improved propagation models that account for indoor and outdoor differences. Real-world trials have revealed that propagation barriers, such as building materials and interference from neighboring channels, significantly impact TVGS availability. Furthermore, ensuring coexistence with licensed users remains a critical regulatory and technical hurdle.

2. Applications of TVGS and TVGS

IoT and LPWAN Technologies TVWS supports IoT applications through its superior propagation characteristics, enabling long-range, low-power communication. Integration with LPWAN technologies, such as LoRa, enhances connectivity for smart agriculture, logistics, and asset tracking. Additionally, TVWS's resilience to interference makes it ideal for dense urban IoT deployments. Studies highlight the effectiveness of TVWS in enabling low-power, wide-area networks for applications like environmental monitoring and industrial IoT [7]-[10].

Specific case studies, such as those in Singapore, demonstrate how TVWS-based LPWANs facilitate urban sensor networks, enabling real-time data collection and analysis for smart city applications. For agricultural IoT, trials in rural India and Africa showcase TVWS's capability to connect remote monitoring devices efficiently, ensuring timely data transmission and operational reliability.

Rural Broadband Connectivity TVWS provides cost-effective broadband solutions for underserved rural areas. Trials and deployments in India and Africa demonstrate the potential of TVWS for bridging the digital divide by offering long-range coverage with minimal infrastructure. The AirJaldi initiative in India, using TVWS for rural broadband access, underscores the importance of regulatory support and low-cost deployment strategies [11]. Meanwhile, in the US, initiatives under the Microsoft Airband program have proven TVWS's scalability in expanding internet access to remote communities.

Smart Grids and Metering Smart grids leverage TVWS for middle-mile connectivity between control centers and smart meters. The resilience of TVWS to interference and its energy efficiency make it suitable for managing utilities in smart cities. For instance, TVWS-based communication networks have been employed in South Africa to monitor energy consumption in real-time, minimizing transmission losses and outages. Moreover, integration with renewable energy sources demonstrates TVWS's potential in supporting decentralized power systems and microgrid frameworks.

Indoor Localization and Multimedia Applications The superior penetration capabilities of TVWS enable applications in indoor localization and multimedia streaming. Techniques like RSSI-based fingerprinting have shown improved accuracy in indoor environments compared to traditional Wi-Fi. TVWS is being explored for healthcare and retail scenarios, enhancing real-time tracking and multimedia streaming reliability in high-density environments. Furthermore, hybrid systems combining TVGS and existing Wi-Fi infrastructure offer improved user experiences in smart buildings and entertainment hubs.

3. Technologies and standards for TVWS

Cognitive Radio Systems Cognitive radio systems play a pivotal role in identifying and managing TVWS through spectrum sensing, geolocation databases, and dynamic access protocols. Hybrid approaches combining sensing and database methods improve spectrum utilization. Integration of AI-driven dynamic spectrum access systems promises enhanced adaptability and spectrum efficiency. AI-enabled cognitive radios have further streamlined decision-making processes, allowing real-time adjustments to spectrum allocation based on user demand and environmental factors.

Regulatory Frameworks Countries like the US, UK, and Singapore have established TVWS regulations, with geolocation database-driven access being the most common method. India has initiated experimental licenses, highlighting the growing interest in developing nations. Notably, the FCC's hybrid licensing model allows for both licensed and unlicensed use, facilitating flexible deployment strategies [12]-[16].

Standards Development Standards such as IEEE 802.22 and 802.11af facilitate the deployment of TVWS for wireless regional area networks (WRANs) and Wi-Fi-like connectivity. Emerging standards aim to address coexistence and interference challenges in heterogeneous environments. ETSI's guidelines and IETF's PAWS protocol further enhance interoperability and spectrum sharing. Additionally, international collaborations, such as those spearheaded by the Dynamic Spectrum Alliance, have accelerated the development of harmonized frameworks for global adoption.

4. Future directions and trends

Integration with 5G and Beyond TVWS holds promise for augmenting 5G networks by providing additional spectrum for backhaul and IoT applications. Enhanced spectrum-sharing mechanisms and interoperability with 5G technologies are key research areas. Examples include deploying TVWS for rural 5G base stations and integrating it with edge computing frameworks.

Advanced Spectrum Management Future advancements include the development of three-dimensional propagation models that consider antenna height and building structures. These models can improve the accuracy of spectrum availability predictions for Indoor and outdoor environments. AI-driven spectrum management systems are also gaining traction. Energy-Efficient Networks Energy efficiency remains a critical focus, particularly for IoT applications [16], [17], [18]. Innovations in low-power communication protocols and spectrum sensing will enhance the sustainability of TVWS networks. Techniques such as duty cycling and energy-aware routing are being explored to optimize performance. Exploration of TVGS Further research into TVGS is essential to harness its potential for indoor applications. Analytical models and experimental validations are needed to understand the impact of building materials and interference patterns on TVGS availability

5. Conclusion

TV White Spaces and TV Gray Spaces represent transformative opportunities for optimizing spectrum utilization in wireless communication. By addressing challenges related to coexistence, interference, and standardization, TVWS/TVGS can support the growing spectrum demands of IoT, LPWAN, and smart city applications. Future research should emphasize seamless integration with emerging technologies like 5G and energy-efficient designs to realize the full potential of TVWS/TVGS in achieving scalable and sustainable spectrum management.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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