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Database-Assisted Television White Space Technology: Challenges, Trends and Future Research Directions

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ABSTRACT Television white space (TVWS) technology is approaching the potential roll-out phase for commercial deployment, supported by recent pilot projects being conducted globally. Undeniably, TVWS technology is faced with daunting challenges that require attention. To enable an ecosystem in which TVWS technology can flourish, there is a need for a complete analysis of the challenges, trends and future research direction related to this technology. Database-assisted TVWS technology is market driven, geared toward the spectrum reuse paradigm, and faces fewer technical hurdles. Our goal in this paper is to present a tutorial review of the challenges related to database-assisted TVWS networks using the SLEPT (social, legal, economic, political, and technological) analysis framework. The SLEPT framework is a management model that is extensively used for quantitative analysis. A brief review of TVWS technology using the SLEPT model reveals that the technology has been socially accepted, legal challenges are evident in some countries, economic models are the way forward and are main focus of current research trends, TVWS technology cannot be implemented without political will emanating from spectrum reforms, and there are many coexistence-motivated technological issues confronting TVWS technology. In summary, this paper provides an up-to-date survey on TVWS and presents current trends and future research directions in the TVWS context.

INDEX TERMS TVWS, auction, self-coexistence, SLEPT, geolocation database.

I. INTRODUCTION

An important observation that can be drawn from successful global spectrum utilization campaigns is that the licensed portions of the broadcast spectrum are heavily under-utilized, leading to the notion of White Space. Moreover, when such White Space occurs in UHF bands assigned to TV channels, it is called Television White Space (TVWS) [1]. Thus, in essence, the licensed spectrum is not fully utilized for significant periods of time. Several excellent review papers on global spectrum measurement campaigns have been published [2], [3]. As the commercial consumption of wireless broadband services continues to grow [4], more of the spectrum will be needed to accommodate the additional capacity that will be required both now and in the future. The challenging question that is now being asked is ''where will the additional spectral bandwidth come from?'' In response to the need for additional bandwidth, many proposals have emerged. One of these proposals is to use the recently freed up regions of the TV spectrum, which would provide approximately extra 300 MHz of spectrum bandwidth [4].

Several spectrum regulators have put forth proposals for the unlicensed use of the free portions of the TV broadcast spectrum [5], [6]. A key requirement for such use of TV bands is that viewers of licensed broadcast television must be protected from harmful interference due to secondary spectrum usage. Despite the inherently good RF propagation attributes of TVWS, the technology is confronted with numerous technological challenges arising from such coexistence constraints, which require users to avoid causing interference to incumbent devices or among themselves i.e. self-coexistence. To address the implementation issues confronting TVWS technology, COGEU (COGnitive radio systems for efficient sharing of TV white spaces in EUropean context) has formulated the comprehensive framework illustrated in Figure 1.0. COGEU [7] is a collaborative project designed to exploit the transition from analogue to digital

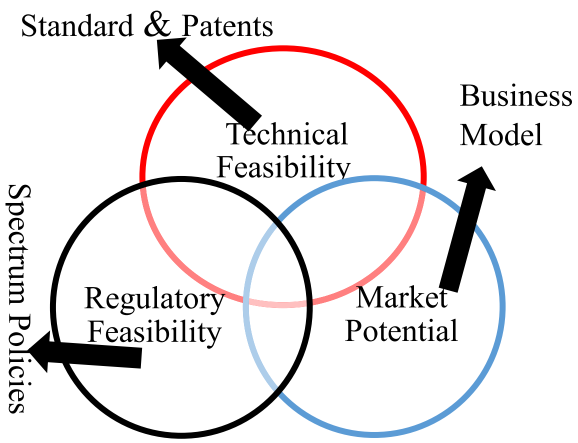

FIGURE 1. COGEU TVWS Framework (Source: [8]).

TV by developing cognitive radio systems that leverage the favourable propagation characteristics of TVWS through the introduction and promotion of real-time secondary spectrum trading.

The TVWS that is available across the globe varies significantly based on the policies of spectrum regulatory bodies, and this is the main limitation of the COGEU model as currently implemented. Hence, a framework is needed to fully comprehend the capabilities, opportunities and limitations of TVWS technology. In this paper, we adopt the widely used SLEPT (Social, Legal, Economic, Political and Technological) framework as a tool for analysing the current challenges and future research questions related to database-assisted TVWS technology. Motivated by recent TVWS pilot projects being conducted globally, this paper presents a consolidated view of TVWS technology and its challenges. To the best of our knowledge, the limitations of the COGEU framework leave a gap in the exploitation of this technology that gives rise to a need for a comprehensive survey on this topic using this approach. The contributions of the paper can be summarized as follows:

- A tutorial review of the challenges facing TVWS networks using the SLEPT analysis framework.
- A summary of the challenges faced by geolocation database technology from a practical perspective, based on inferences drawn from TVWS pilot projects in the United Kingdom and Singapore.
- A survey of current research trends in TVWS technology, focusing on recent developments (until 2015).

The remainder of the paper is organized as follows. A discussion of the various approaches to spectrum usage regulation and sources of TVWS are presented in Section 2. In Section 3, we present an overview of TVWS technology with a focus on database-assisted architecture and the practical challenges related to geolocation databases. In Section 4, we present a tutorial review of the challenges facing TVWS networks using the SLEPT analysis framework. Section 5 presents current and future research trends related to TVWS networks, and finally, Section 6 concludes our work.

II. SPECTRUM REGULATORY MODELS

The broadcast spectrum is an important wireless commodity, and over the years, spectrum regulatory bodies, which are government institutions mandated with the responsibility of defining and enforcing suitable spectrum etiquette, have formulated three spectrum usage rights models to reflect the needs and characteristics of the wireless environment. These three spectrum regulatory models, as illustrated in Figure 2 [9], are the command and control model, the exclusive-use model and the common-use model.

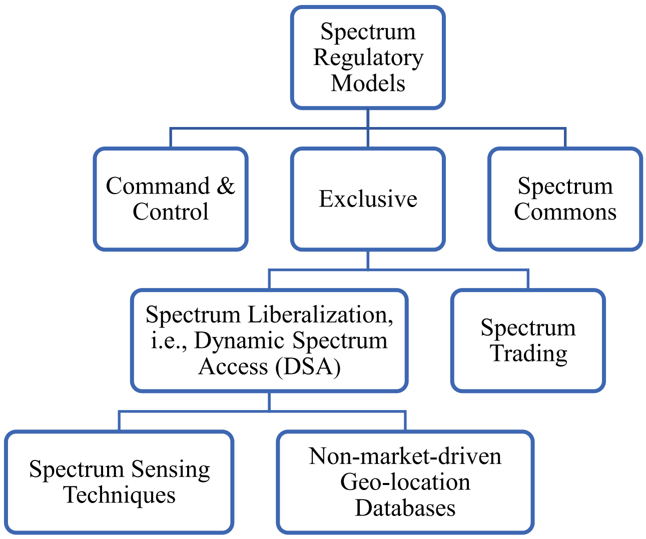

FIGURE 2. Spectrum regulatory models.

These three spectrum models, based on the definitions of the FCC and Ofcom, can be described as follows:

- The command and control approach to spectrum regulation is characterized by a rigid and restrictive approach in which spectrum use is tied to particular technologies and services. It is easy to implement and manage, and as a result, it is widely used by governmental agencies such as the military, paramilitary groups, and disaster control and emergency response teams.
- In an exclusive model, spectrum owners are empowered to temporarily lease their spectrum resources, through auctions or another market model, to third parties with minimal regulatory intervention [10]. This model also drives dynamic spectrum access (DSA) and dynamic spectrum sharing (DSS) techniques, which can be implemented using either spectrum sensing or geolocation database techniques.
- The Spectrum Commons concept grants equal spectrum usage rights to all unlicensed users. An implementation of this concept in practice can be seen in the ISM bands. These unlicensed bands have proven to serve as a remarkable vehicle for innovation. Unfortunately, unlicensed bands can be strangled by their own success,

TABLE 1. Spectrum management models below 3 GHz.

	Command and Control	Exclusive Market	Spectrum Commons
1995	95.8 %	0.0 %	4.2 %
2000	95.8 %	0.0 %	4.2 %
2005	68.8 %	27.1 %	4.2 %
2010	21.1 %	73.7 %	4.2 %

Source: [12], Spectrum Framework Review Statement (2005), P.36

since as more devices occupy these bands, intra-device interference increases [11].

The exclusive-use and command and control approaches represent licensed regimes. The existence of unlicensed bands regulated through the spectrum commons approach is primarily designed to encourage innovation through the avoidance of the potentially exorbitant fees associated with the purchase of licensed spectrum bands through auctions [9]. However, the licensed approach offers users protection against unwarranted interference and, hence, drives their QoS upwards. Whereas spectrum liberalization can be engineered based on the formulation of sophisticated protocols, network architectures and algorithms, spectrum trading has been introduced to provide an alternative route for easily and successfully implementation of DSA and DSS techniques. The use of spectrum trading schemes based on exclusive usage rights has been on the rise in recent years, as shown in Table 1.

A. SOURCES OF TVWS

A sustained interest in the secondary usage of the UHF bands that are traditionally reserved for broadcasting services has been spurred by the excellent propagation characteristics of UHF spectrum bands, a growing appetite for broadband services, and spectrum reforms driven by regulatory support [13]–[15]. Based on the authors' review of the literature, supported by the references presented in this manuscript, there are two parallel but similar schools of thought regarding the sources of TVWS, which can be classified as the conservative and non-conservative approaches.

B. CONSERVATIVE APPROACH

In the conservative approach to sources of TVWS, the public is presented with information in a concise format highlighting the most salient dividends of digital switchover (DSO), i.e., the vacated portions of the spectrum following the cessation of analogue TV broadcasts and the geographic interleaved spectrum. Two types of TVWS sources are identified: spectrum liberalization and spectrum trading [9]. Spectrum liberalization techniques are concerned with TVWS information acquisition techniques that rely on spectrum sensing and geolocation database techniques [8], [16]. The main aspects of the conservative approach can be summarized as follows and form the basis of this work.

- Digital switchover: TVWS becomes available as a result of the removal of the much-needed buffer spaces in an analogue TV configuration. These buffer bands become redundant because digital terrestrial TV (DTT) is robust to interference by virtue of advanced signal processing algorithms embedded in the filter technology. This is considered a direct digital dividend of DSO [17].
- Spectrum leasing: In an exclusive spectrum model, TVWS can be made available by licensed spectrum owners, who possess the right to temporarily lease a portion of their currently unused spectrum bandwidth for a fee while retaining all of the legal and statutory rights associated with that wireless resource [18], [19].

C. NON-CONSERVATIVE APPROACH

The non-conservative approach involves presenting, in detail, all of the dividends that accrue from DSO [4], [20]. The elaboration of these dividends tends to highlight the merits of DSO and can be summarized as follows.

- Architectural reconfiguration: In the analogue TV transmission era, the minimum separation distance between two VHF TV channels was 97 km, and that for UHF channels was 240 km. By contrast, for DTT, the minimum separation is 245 km for the VHF band, and that for the UHF band is 224 km, depending on the zone [4]. Effectively, this means that within a given geographical enclave, certain DTT frequencies will not be allocated to avoid co-channel and adjacent TV interference.
- Low population density ratio: TVWS becomes available in areas in which the broadcast spectrum is not fully allocated to TV channels because fewer than the maximum possible number of channels are authorized because of a limited demand for broadcast services (typically because of a low population density). This latter observation conforms with the widely held notion that TVWS is more prevalent in rural and semi-rural areas [21]. Moreover, after DSO, channels 2-6 cannot support DTT because of their higher ambient noise, interference with FM radio and larger antenna size requirements [22].

III. DATABASE TECHNOLOGY

Initially, TVWS technology was designed to be driven by spectrum sensing algorithms. However, several field tests results from the spectrum sensing algorithms were unsatisfactory [23]. Consequently, spectrum regulatory bodies have, for now, mandated the use of only geolocation-assisted TVWS technology [24]. For a geolocation database to be deployed

TABLE 2. Summary of SLEPT indicators for database-assisted TVWS technology.

No	Component	Indicators	Performance Metrics
1	Social	TVWS project-centric needs. Non-commercialization approach.	Successful completion of TVWS pilot projects. Technical issues such as self-coexistence and heterogeneous coexistence are not emphasized.
2	Legal	SDR enablement. Legal certifications. TVWS parameters to be permitted.	Market driven. Regulation driven.
3	Economic	Real-time strategy-proof auction mechanism for the secondary spectrum market. Highly competitive secondary spectrum price.	Strategy-proof real-time spectrum trading. Complexity analysis.
4	Political	Spectrum regulation and policies. Enabling acts for dynamic spectrum access.	Spectrum measurement campaigns, pilot projects.
5	Technological	Incumbent coexistence. Self-coexistence. Heterogeneous coexistence.	The existence of TVWSDBs. Transmission power control mechanism. Dynamic spectrum sharing.

for TVWS availability estimation within a geographical enclave, three tuples are needed. These tuples are the location, time, and frequency dimensions (3D). Such a 3D model can be easily implemented using an F-curve propagation model [25]. The FCC defines the protected contour for ATSC tuners within the range of a TV tower as the contour representing regions in which the field strength is 41 dBu, as determined via the *F (50, 90)* propagation model using a 9 m high outdoor receiving antenna. The F (50, 90) specification simply means that at 50% of locations and for 90% of the time, the actual field strength is higher than 41 dBu with respect to the ATSC mode. Extrapolating from Section 2.1 of [26], the radius of protection is approximately 125 km.

TVWS propagation models can be classified into (i) statistical propagation models, comprising the ITU-R empirical models [27], and (ii) deterministic propagation models, consisting of the Longley-Rice model and the irregular terrain model (ITM) [28]. The Longley-Rice model encompasses a broad variety of factors, from terrain shapes to atmospheric diffraction. When various parameters are considered, such as the transmitting power of TVWS devices (TVWSDs), geolocation contours, channel bandwidths, the number of channels, and whether the conservative or non-conservative approach is used, different configurations of these parameters could yield different plots. Based on the 3D TVWS input model, we compare TVWS availability in Europe and the USA in Figure 3. For a detailed overview of the input data, we refer the reader to [29]. This graph was generated by extracting the data from [29, Table 2].

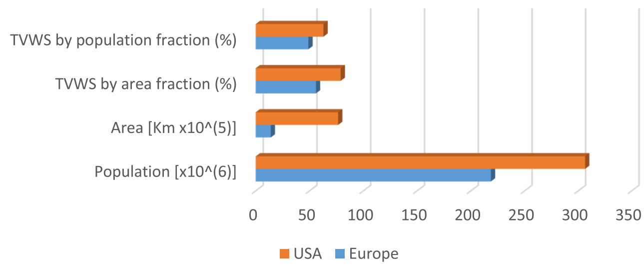

FIGURE 3. Comparison of TVWS availability between USA and Europe [29].

A. OPERATION OF GEOLOCATION-ASSISTED TVWS TECHNOLOGY

The consensus among spectrum regulators, standardization bodies and industrial organizations is that database-assisted TVWS technology guarantees the provision of an interference-free primary user regime. Under current database-assisted TVWS technology, TVWSDs consist of master and slave TVWSDs. A master TVWSD is able to communicate with and obtain operational parameters directly from a TVWS database (TVWSDB) operator simply because it is equipped with a location awareness capability, such as GPS. By contrast, a slave TVWSD can only access TVWS under the control of a master TVWSD. Figure 4 illustrates a typical example of the components and functions of a geolocation-assisted TVWS network, which can be summarized in terms of the six steps described below:

- *Step I* - A geolocation-assisted master TVWSD queries the spectrum regulatory body to acquire the list of official TVWSDB operators. This means TVWSDB operators that have gone through a qualification process, in which the spectrum regulatory body tests the TVWSDB operators to gain assurance that their databases are capable of operating in accordance with the specified operational terms and conditions before approval is issued.
- *Step II* - The spectrum regulator replies to the master TVWSD with the list of approved TVWSDB operators. The query result lists the currently qualified TVWSDB operators that have been tested and certified. Based on

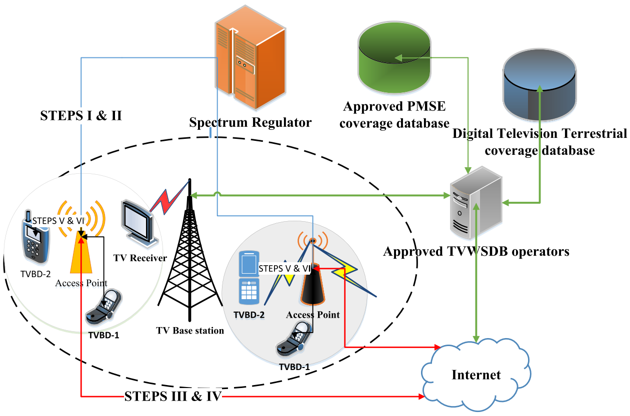

FIGURE 4. Database-assisted TVWS network architecture.

trials conducted by Ofcom [6], this list can dynamically reflect the currently compliance-certified TVWSDB operators.

- *Step III* - The master TVWSD subsequently queries the certified TVWSDB operators for available TVWS bands in its location by providing its operational parameters. These operational parameters include the antenna configuration in terms of the height above average terrain (HAAT), the maximum transmission power and the frequency range.
- *Step IV* - The TVWSDB operators respond to the queries issued by the TVWSD. However, to respond to such a query, a TVWSDB must perform the necessary calculations for the set of operational parameters corresponding to that particular TVWSD. The spectrum regulator must provide the TVWSDB operators with a database detailing the spectrum usage for DTT, licensed programme making and special events (PMSE) and wireless microphones. Then, the TVWSDB informs the TVWSD of what generic TVWS bands are available and what transmission power to use.
- *Step V* - A slave TVWSD queries the master TVWSD regarding what TVWS frequency and transmission parameters to use. The slave TVWSD must provide its unique device identifier. This can be considered as the slave TVWSD's MAC identity. The slave TVWSD can request TVWS operational parameters that are specific to it or can simply rely on generic parameters.
- *Step VI* - Upon receipt of the slave TVWSD's request, the master TVWSD broadcasts generic operational parameters to the slave device. The slave TVWSD must listen to the master device's broadcast before transmitting and must decode the generic operational parameter information. The slave device can decide whether to use the generic parameters or request specific operational parameters. Should the slave device request specific operational parameters, the master TVWSD would then relay this information to the TVWSDB, which would calculate the optimal specific operational parameters for that particular slave device.

B. PRACTICAL CHALLENGES IN EXPLOITING DATABASE-ASSISTED TVWS

Several TVWS pilot projects have been conducted in the United Kingdom (UK) and Singapore under the supervision of spectrum regulators utilizing a geolocation database scheme [6], [30]. The conducted studies were specifically designed to validate certain technical solutions for TVWS database analysis, which leverage propagation models for better efficiency and performance. The key function of the geolocation database is to ensure the protection of incumbent users. As discussed above, maps of TVWS spectral opportunities or radio environment maps (REM) are stored in the geolocation database. Geolocation datasets are generated via interference analysis utilizing an F-curve propagation model for TV signals [25], which subsequently leads to the design of incumbent radio coverage maps with mandatory regular updates upon the arrival of new information. Note that from a practical perspective, the deployment of a geolocation database scheme is markedly different in context and operation from the analytical tool described in [31]. To build on the success of recent TVWS technology pilot projects in the UK and Singapore, some of the notable challenges are as follows:

i). *Cross-national TVWSDB carrier harmonization:* A TVWS database is a cross-national technology that spans multiple regions and countries, where each region operates under a different regulatory regime. Based on the practical experience gained in the UK's Ofcom TVWS pilot, there is a need for a bicameral approach, in which geolocation databases are sub-divided into regional and national databases, each with a distinct operational jurisdiction and with interoperability enabled, thus enabling regional/global roaming for TVWS networks. This idea conforms with a COGEU policy paper [8].

ii). *A common interdatabase communication protocol is needed*: Because TVWS technology is market driven, different TVWSDB operators are allowed to enter and exit the market, facilitated by market competition. This implies that there will be several TVWSDB operators operating in a given region, each competing with one another in terms of broker fees, QoS and network coverage. The use of Spectrum Management Centres (SMCs), as proposed by Ofcom, can be adopted. During the TVWS pilot conducted in the UK, Ofcom approved eight TVWSDB operators [6]. Meanwhile, in its pilot, IDA Singapore approved five TVWSDB operators [30]. Therefore, there is a need for a common communication protocol for TVWSDB operators to facilitate the harmonization of TVWS information servers (TISs).

iii). *No standardized validity period for database queries*: TVWSDs are expected to query TVWSDB operators within a stipulated period. Singapore mandated a six-hour query update period and a mobility corresponding to a 100-metre change in location. By contrast, Ofcom did not specify a period for query

FIGURE 5. **Timeline of TVWS adoption procedure.**

validity, although a global 50-metre location mobility for TVWS devices was adhered to. Considering Singapore's small land mass, six hours was deemed sufficient to ensure and enhance the protection of incumbent users. Note that a distance of 50 metres translates to a signal variation of 1 dB, and similarly, 100 metres corresponds to 2 dB [26].

iv). *Establishment of a framework for contracting, authenticating and qualifying prospective database operators*: Ofcom outlined three procedures for adopting a qualifying TVWSDB operator: self-declaration, off-line testing and simulated testing. In a self-declaration test, a TVWSDB operator visibly attests compliance with the stipulated guidelines by providing the necessary supporting evidence. An off-line test involves actual validation of the calculations to determine the operational parameters to ensure incumbent protection. A simulated test targets the capability to update the operational parameters upon receipt of new information [32]. IDA Singapore provided no details on how TVWSDB operators should be qualified.

v). *Lack of a standard procedure for framework testing*: The effective implementation of TVWSDB technology relies heavily on the adoption of a reliable TVWSDB pilot framework. Consequently, Ofcom advocated two approaches, namely, business process testing and end-to-end testing. Business process testing involves investigating the spectrum regulatory mechanisms and the processes for communicating with TVWSDB operators during a pilot project. This is designed to ensure quick setup capability and guarantee that these mechanisms meet the standards for technical and operational procedures. End-to-end testing offers a window of opportunity for analysing TVWSDs and TVWSDBs during live trial sessions and assessing compliance with the framework.

vi). *Query language and format*: No higher-level TVWSDB-compatible language has yet been defined. There are several extensible mark-up language formats available for TVWSDB coding. Consequently, several high-level language formats, such XML, HTML, PHP and Python, are currently in use across different operators. Hence, the adoption of one universal open-source scripting language capable of encouraging innovative ideas needs to be pursued.

IV. SLEPT ANALYSIS

It has been established that the desire for database-driven TVWS technology is market driven, based on the active research interest of many commercial vendors; see [6]. Hence, for a complete analysis of TVWS technology, a market model is required. In this paper, we adopt the widely used SLEPT (Social, Legal, Economic, Political and Technological) analysis framework. The SLEPT framework is a management model that is extensively applied in many areas [33]. Various management-based models have been deployed in the field of wireless communications in the past, e.g., minimum spanning tree models [34], knapsack problem models [35], and various relaxation and decomposition methods, including Lagrangian approaches [36]. Hence, management models are not likely to soon be abandoned in wireless communication. As a matter of fact, they are an integral part of wireless communication systems.

A. SOCIAL ENVIRONMENT

TVWS technology is increasingly being explored as a potential solution for last-mile connectivity. This is largely because of its favourable propagation and licence-exempt regime, as discussed above. Hence, an increasing number of regulatory bodies are showing an interest in TVWS technology. TVWS technology has the inherent capacity to improve lives in hard-to-reach areas and especially to provide rural connectivity. In pursuit of the benefits of TVWS technology, several social contexts have been exploited via TVWS pilot projects. Table 3 summarizes the highlights of recent TVWS pilot projects; the full details can be found in [37].

B. LEGAL ENVIRONMENT

For a radio licence to be granted, conformity testing for interference is mandatory. The government mandates that device manufacturers must make their radios available to the relevant authority to confirm that their devices will operate within the applicable technical laws. Upon the successful passage of the interference conformity test with respect to these technical laws, certification is granted and the device is permitted to be sold. The legal procedures vary depending on the type of radio involved. The procedure for the adoption of TVWS technology will naturally follow the pattern illustrated in Figure 5 [38].

Equipment law is a framework that assigns interference responsibilities to a particular entity in the case of the spurious emission of interference caused by bringing a device out of compliance. For instance, typical hardware modifications to a radio would involve changes in frequency bands, output power, filter elements and other RF features. This requires extensive engineering knowledge and hardware parts. By contrast, in the software-defined radio (SDR) context, in which TVWS technology operates, changes are controlled

TABLE 3. Overview of several TVWS pilot projects [37].

Continent	Country/Region	Projects	Highlights
Asia	Bhutan	Remote healthcare unit connections	Unlimited by terrain
	Philippines	Enhanced fishery activities, VSAT backhaul connections for disaster management	3-4 km transmission Cost-effective
	Japan	Disaster management communication	12.7 km transmission
	Taiwan	Ecosystem tourism (broadband)	3-10 km transmission
	Singapore	Indoor and outdoor applications, video surveillance, small cell backhaul	TCP/IP speeds of 20 Mbps @ 40 metres indoor NLOS
Africa	Mozambique	Support for online libraries and rural online schooling	Potential for free rural internet access
	Botswana	Telemedicine	Support for VoIP and Video over IP
	Namibia	Large-scale TVWS internet rollout	Targets a coverage area of 9,424 km^2
	Tanzania	Commercial feasibility of TVWS	Goal of providing access to over 74,000 students
	Kenya	Complimentary technology between TVWS and other licence-exempt bands at 13 GHz, 5 GHz, and 2.4 GHz	14 km PMP link, 2.5 EIRP @ 16 Mbs over 8 MHz TV bands
Europe	Britain	Diffusion of LTE into TVWS using the 802.11af standard, resulting in 45 Mbps in FDD mode (20 MHz each for uplink and downlink) via channel aggregation and 19 Mbps in TDD mode via the aggregation of 3 TV channels	3.7 km point-to-point link using 1 TV channel
	Scotland	Smart city project	TVWS sensors
North America	Seattle, Washington	Faster internet than existing technology	Focused on speed and coverage
	Washington County, Maine	TVWS transmission in challenging rural, semi-rural and urban terrain	NLOS PMP link of 5-8 km with a data rate of 10 Mbps
South America	Uruguay	Connectivity for rural schools	TVWS hardware technology diffusion
	Jamaica	High-speed internet connectivity	Broadband in a marine ecosystem

by ''downloads'' or modifications to existing parameters that require zero knowledge of the hardware configuration. Furthermore, this procedure is not only simpler but also cheaper to initiate. This approach implies a need for ''plug and play'' modules, as it is primarily concerned with software, firmware and user access restrictions. Hence, from the perspective of spectrum regulators, radios that can be easily modified without an extensive knowledge of hardware require special considerations.

The European Telecommunications Standards Institute (ETSI) has also expressed reservations regarding spurious interference emission [39]. Therefore, one question of interest is how to design unique SDR features so as to prevent spurious interference emission by ensuring device conformity with the law without sacrificing the flexibility and benefits associated with opportunistic access technology. In other words, question arise regarding who is permitted to modify such devices and under what circumstances such modification is permitted as well as what measures should be incorporated to preserve device integrity. In this subsection, we analyse the divergent approaches adopted by two notable spectrum regulators: the FCC in the U.S. and the Japanese spectrum regulator, the Ministry of Internal Affairs and Communications (MIC). The focus herein is the conservative approach to TVWS technology espoused by the Japanese spectrum regulator as compared with the FCC's market-driven approach.

1) THE APPROACH OF THE U.S. FCC

The U.S. FCC, as a market-driven spectrum regulator, strives to balance flexibility with the prevention of unwarranted interference emission in TVWS technology with an SDR kernel. This is undertaken through the adoption of a proactive stance on SDR, resulting in the vetting of related issues and the adjustment of rules favouring SDR technology [40]. These rules can be sub-divided into (i) the rules for the initial procedures for obtaining SDR certification, (ii) the rules for incorporating a strategy to avoid unauthorized modifications to SDR devices and (iii) requirements for security measures to prevent third-party modifications, with a focus on interference mitigation. In other words, any SDR that is open to modifications by any agent other than the manufacturer must be certified as an SDR device, and adequate security restrictions must be incorporated.

By adopting these rules, the FCC has been able to balance permitting innovation with preserving the integrity

TABLE 4. Differences between the legal paths to TVWS implementation as administered by the FCC and MIC.

Attribute	FCC	MIC
Market-based	Yes	No
Spectrum regime	Flexible	Rigid
Administrative public activity	Rulemaking initiated by the public	Rulemaking may not be initiated by the public
Negotiation regarding rulemaking	Extensive debates on rulemaking	Lack of unnecessary debates on rulemaking

of SDRs. In a bid to enhance technological innovation and improve flexibility, the FCC adopted two major approaches based on certain minimum technical and operational requirements [41]:

- *Pre-check technique specified in Part 15 for unlicensed device approval* [42]: This policy is intended as a legal substitute for formal device licensing. The document empowers the FCC to ensure that radio devices comply with the interference prevention rules before they are marketed, sold or even imported. Hence, with the authorization of appropriate policies and technical rules, the use and dissemination of equipment capable of causing interference can be prohibited. This offers the FCC some degree of freedom in adjusting the spectrum rules according to market demand.
- *Market-oriented spectrum allocation regime*: The FCC has demonstrated an unequivocal commitment to TVWS technology through the issuance of various notices of proposed rulemaking (NPRMs) that present rules for TVWS operations [24], [43]. For the protection of incumbent users, the FCC has mandated the use of a geolocation database technique that relies heavily on market forces. A geolocation database concerning real-time spectrum leasing is central to an interruptible spectrum market, and its role in secondary market design has also been discussed, along with its enforcement by authority [44]

2) THE APPROACH OF THE MINISTRY OF INTERNAL AFFAIRS AND COMMUNICATIONS (MIC) OF JAPAN

The approach to spectrum allocation and licensing adopted by the MIC of Japan can be characterized as keying into the international trends in spectrum activities as piloted by the ITU. This has largely driven the MIC to engage in extensive consultations with research committees concerning new technologies and the potential frequency spectrum to be allocated. In this way, the MIC is considered to take a more conservative attitude towards non-standardized wireless communication devices. The approach of the MIC can be summarized as follows [41]:

- *Lack of regulatory authority*: The MIC is not empowered to manage the authorization of equipment before it can be used in Japan. Instead, the MIC relies on extensive and costly field enforcement efforts employing highly sophisticated spectrum monitoring tools capable of delivering real-time reports [41].
- *Non-market-driven spectrum policies*: The spectrum allocation performed by the MIC is not driven by market demands, and consequently, non-licence-exempt regimes are widely implemented. This is evident in the TVWS licensing regime path administered by the MIC.

In Table 4, we present the differences between the legal paths to TVWS implementation as administered by the FCC and MIC.

C. ECONOMIC ENVIRONMENT

The exclusive spectrum usage model that leads to the TVWSDB approach has given rise to short-term spectrum trading, which thrives in TVWS networks. Historically, it is clear that TVWS network architectures, algorithms and protocols cannot be implemented without consideration of their techno-economic aspects [45]. As a result, database-assisted TVWS networks have received tremendous support from spectrum regulators, standards bodies and industry [46]. A database-assisted TVWS network consists of incumbent devices, database operators and TVWS network devices, as shown in Figure 6. Geolocation databases are seen as the way forward for the global adoption and implementation of TVWS technology. However, it is hampered by many technical and economic issues. Extensive efforts have been made towards alleviating the technical issues confronting TVWS technology, such as effective geolocation database design [31], the determination of accurate propagation models and terrain data [46], the design and implementation of multicell infrastructure-assisted TVWS networks [32] and TVWS network optimization [47]. These efforts have resulted in the practical deployment of TVWS technology, with the attendant emergence of TVWS geolocation vendors [48]. However, TVWS technology has not yet been fully implemented as a consequence of economic issues that must be addressed before massive rollout will be feasible.

Some of the unsolved economic issues that remain with regard to TVWS database networks are as follows:

- A lack of global standards, economic models and bidding language conventions across the heterogeneous platforms used by TVWS database providers and spectrum lessees and lessors.
- A lack of design specifications for currency and payment modules.
- A lack of specifications for TVWS duration models and contract enforcement modules for the application of secondary-user QoS constraints.

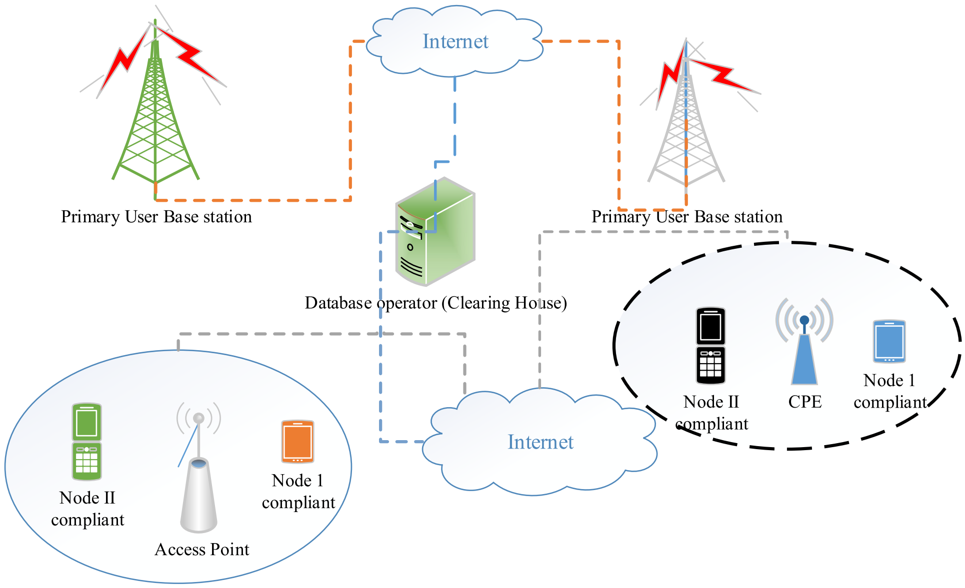

FIGURE 6. **TVWS economic framework.**

Currently, the various economic issues confronting TVWS databases have been approached by means of the auction/mechanism design and market models summarized in Figure 7.

1) AUCTION/MECHANISM DESIGN TYPES

Auction theories are a subset of economic models that have been applied in the field of wireless communication for the primary spectrum market across the globe [49], [50]. Auctions are perceived to be fair and efficient because they offer everyone an equal opportunity to analyse goods based on their private evaluations, and the goods are then traded to those who value them most highly. The auction process involves buyers/secondary users, who submit *bids,* and sellers/primary users, who submit *asks.* The *auctioneer/*database operator matches the *bids* with the *asks* at a *clearing price*. In a dynamic spectrum auction configuration, bidders may submit requests for multiple items in multiple channels based on their private and independent evaluations.

Auctions are classified according to various criteria. An auction can be an open cry auction or a sealed auction. In an open cry auction, the buyers and sellers publicly reveal their bids and asks. This is the most common auction mechanism, as it requires limited control of information, although this can lead to severe interference issues. When the bidding is continually ascending, the auction is classified as an English auction [49]. The distinguishing difference between Dutch and English auctions is that in the former, the bidding is descending rather than ascending [51]. In a sealed bid auction, the bid information is private and is revealed only to the auctioneer. In general, this preserves the belief of weaker bidders that they have a chance of winning the bid [52]. Furthermore, auctions can be either single-sided or double-sided. In the case of single-sided bidding, either the buyer or the seller submits only a single bid. In practice, this requires that all secondary users must submit their bids on a single sub-channel, either sequentially or concurrently [53]. Sequential bidding outperforms concurrent bidding. However, it incurs an excessive control message overhead on the MAC layer. When multiple spectrum sellers are participating in an auction, the auction is double-sided [54], [55]. The auctioneer simply computes the asks and bids from the primary and secondary users by executing a matching algorithm to clear the market. As an inadvertent consequence of this mechanism, cheaper spectrum prices are feasible.

Auctions can be either forward or reverse in nature. All of the auction types that have been described thus far are forward auctions because the buyers bid for goods from the sellers (buyer-side auction). This is in contrast to a reverse (seller-side) auction, in which the sellers initiate the transactions [56]. For instance, in an English auction, the winner is the seller who offers the lowest selling price, whereas in a Dutch auction, the bidder whose bid is first accepted is the winner. An auction can be classified as either static or dynamic. In a static auction mechanism, no strategy updating is possible based on new information. By contrast, a dynamic auction mechanism allows participants to provide incremental information about their preferences. In a wireless communication network that is characterized by time-varying radio quality, a dynamic auction mechanism provides ample opportunity for participants to update their strategies, through either reinforcement learning [57], [58], evolutionary game theory [59], Bayesian game theory [60] or a Bayesian non-parametric scheme based on Dirichlet processes [61]. In a combinatory auction, several heterogeneous goods are auctioned simultaneously, and bidders bid according to their needs.

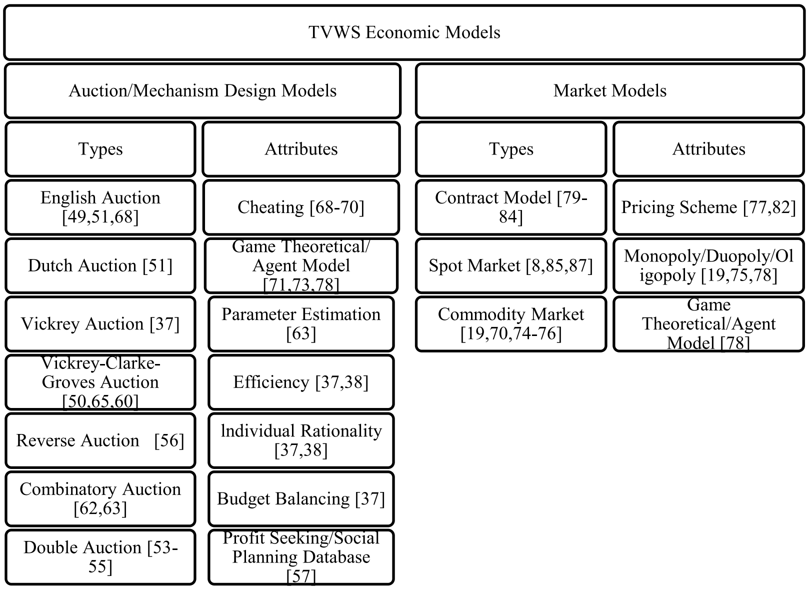

FIGURE 7. Taxonomy of TVWS economic issues.

A combinatory auction offers secondary users the opportunity to reflect on their unique QoS requirements and current market needs and to bid accordingly. Because OFDM technology is the underlying PHY layer modulation scheme, most primary users have the capacity, through a sub-channelization slot scheme, to implement a combinatory auction scheme. Of particular interest is the fact that a combinatory auction mechanism permits heterogeneous networks to coexist. For instance, ultra-wide band (UWB) signals are transmitted at a very low power across a wide bandwidth, whereas secondary users utilizing OFDM technology, which is generally considered to operate on a narrow bandwidth, may transit at the maximum permissible power using a narrower bandwidth. Several combinatory auctions have recently been analysed. Both [62] and [63] considered combinatory auctions that are uniquely suited to secondary users employing linear and quadratic programming techniques, with the latter specifically focused on auction truthfulness. Meanwhile, [64] designed a radio resource management framework exploiting combinatory auctions to consider a real-time TVWS auction scheme. Refer to [51] for a detailed tutorial on auction theory and to [52] for a discussion of the challenges involved in designing auction mechanisms.

2) AUCTION/MECHANISM DESIGN ATTRIBUTES

Database-assisted TVWS networks involve complex interactions between the primary users and the secondary users. An auction mechanism requires that the primary and secondary users must approach spectrum trading rationally, honestly, efficiently and in a strategy-proof manner and must be aware of budget balancing. It is evident from this characterization that the practical problem of spectrum trading is similar in context to scenarios encountered in real-world economics. Consequently, this problem can only be addressed using analytical tools developed for economics. The Vickrey-Clarke-Groves (VCG) auction mechanism is one in which the winner pays the second highest bid. It is widely regarded as being strategy-proof. As demonstrated in [50], however, the widely used VCG auction is not strategy-proof. It is susceptible to collisions, unfairness and truthfulness issues [65]. In the context of radio resource management, a general mechanism design framework for social utility maximization under linear constraints has recently been analysed [66].

Mechanism design is a subfield of microeconomics [67] that can address challenges such as those highlighted in [65]. The ideal objective of an auction mechanism, when regarded as a game, is to analyse the dominant equilibrium strategy of the buyers and sellers. The dominant strategy is that which yields the best payoff, and the Nash Equilibrium (NE) is a common solution in auction games. It ensures that none of the players can unilaterally change his strategy because the other players' strategies are fixed. One may ask how an auction is fundamentally different from mechanism design. An auction is not cheat-proof and is not a type of mechanism design. Therefore, it is susceptible to cheating and manipulation. Several mechanism design approaches have been proposed with a focus on TVWS market models [66], [68]–[70]; however, a number of critical research gaps remain.

All of the aforementioned mechanism design approaches have considered a primary user spectrum market auction model in which the spectrum rights are leased for many years and spectrum transactions are conducted over many rounds [68]. Hence, the conclusion time for spectrum transactions is irrelevant. However, the secondary spectrum markets in which TVWS networks operate are characterized by short-term leases, which may have durations of minutes, hours, days, or months, depending on the contractual agreement [71]. If the spectrum leasing time is measured in hours or even minutes, the current auction mechanisms for spectrum price haggling are not suitable for the TVWS secondary spectrum model because they incur an unacceptable time delay.

Hence, there is a need to design an effective mechanism to reduce the TVWS spectrum transaction time based on the premise that a spectrum auction is a repetitive process. Moreover, secondary users are intelligent networks with memory, and they are capable of making informed decisions based on experience. Recent work on TVWS auction design has advocated the use of information trading [71] and a competitive game-theory-based auction mechanism [55]. It has been reported that an effective approach for enhancing truthfulness in mechanism design is through *incentives* or *taxation* [51]. Hence, there is a need for a model that incorporates all of the above approaches, resulting in a fast, competitive and truthful TVWS secondary market.

3) SECONDARY SPECTRUM MARKET MODELS

The secondary spectrum market allows incumbent users to temporarily lease their unused spectrum to secondary users. The goal of the secondary spectrum market is to drive spectrum utilization efficiency, as studies have shown that market forces enhance spectrum utilization efficiency [72]. Given the absence of widespread secondary spectrum markets in practice, the eventual modus operandi is not clear. Consequently, a study addressing this question has been performed using Transaction Cost Economics (TCE) through Agent-based Computational Economics (ACE) [73]. TCE seeks to understand the cost minimization approaches adopted by various organizations, whereas ACE provides an analytical tool for weighing the strengths and weaknesses of each organizational form under different scenarios.

4) SPECTRUM COMMODITY MARKET MODELS

This is the earliest and simplest approach adopted for treating the commoditized spectrum as a visible, tangible wireless resource, hence making it trivial to model spectrum trading and usage using conventional economic and wireless communication models. It is characterized by the use of a virtual currency model in which the virtual currency connotes real-world currency and transmission power simultaneously [19], [70], [74], [75]. Considering channel quality heterogeneity, a spectrum market model exploiting these unique characteristics has been analysed [19]. The key insight gained from the work is that there is a correlation between spectrum channel quality, centre frequency and signal propagation [74]. The modelling of a rural TVWS broadband spectrum market based on the Bertrand game model has also been proposed [76]. Different from the preceding work, the author considered the QoS for both primary and secondary users.

5) MONOPOLY/DUOPOLY/OLIGOPOLY MARKET MODELS

A monopoly is a market setting in which there is just one major dominant seller. Such a scenario often holds for electric power utility firms. When there are two sellers, a duopoly market is in place. When there are more than two sellers, the market is an oligopoly, and this scenario is regarded as being highly competitive. Concentrating on duopolistic spectrum leasing and pricing, a three-stage backward induction interaction model consisting of primary users, operators and secondary users has been analysed [19]. One may ask how fundamental is the importance of price and inventory competition in an oligopolistic TVWS market. Given the range of the importance, a study has been conducted on this topic [75]. It is a common goal of market models to understand the different forms of spectrum markets, including monopoly, incentive, and competitive markets, as well as demand and supply and practical implementation in the spectrum market context. Consequently, this topic has been analysed in [77]. From the tutorial perspective, an overview of spectrum markets based on business modelling for TVWS networks was presented in [78].

6) CONTRACT SPECTRUM MARKET MODELS

A TVWS secondary spectrum market is modelled after the contract theory model, which provides insight into contractual agreements in the presence of an asymmetrical information-exploiting incentive mechanism [79]. From a practical perspective, Ofcom proposed that upon the occurrence of a change in a contract, contract change notes should be issued to TVWS networks. Contract models are often the optimal tool in a limited-information environment, e.g., with a distribution of entity valuations. Envisaging the possibility of a secondary spectrum market, a contract-based spectrum sharing mechanism has been proposed [80]. Utilizing the contract theory principle, a monopolistic TVWS secondary spectrum contract system has been designed [81]. That paper is consistent with the notion that the satisfaction of secondary users will be enhanced by designing a quality-price contract model driven by incentives.

In a similar vein, a contract-aligned TVWS secondary market consisting of a reservation and service plan scheme under complete and incomplete secondary user information has been analysed [82]. Extending the domain of contract-based TVWS secondary markets, cooperative spectrum sharing between the primary users and the secondary users has been studied from a relay perspective [83]. Borrowing from the principle of the newsvendor model in the field of operations management, a contract model aimed at curbing the overflow during periods of high spectral resource need has been formulated [84]. The model is cast as a non-cooperative theoretical game between two primary users.

7) CONTRACT SPOT MARKET MODELS

Contract spot market models are designed to incorporate a real-time secondary spectrum market (RTSSM) into the radio resource management (RRM) of TV networks. The overall RTSSM architecture comprises two core subsystems: (i) a Spectrum Broker, which is responsible for coordinating TVWS access and administrating the economics of radio-spectrum exploitation, and (ii) a number of TVWS networks. By making use of real spectrum data concerning the TVWS availability in the Munich area, a fragmentation score, and a spectrum utilization score, such an RTSSM has been designed using a backward tracking configuration [85]. A hybrid form of a spot market that exploits the inherent properties of contract and auction mechanisms, referred to as ContrAuction, has also been proposed [86]. To promote a trans-national TVWS spectrum market in Europe, COGEU proposed and designed a reference spot market model [8]. The layered structure of an RTSSM consists of the local resource managers (LRMs), the spectrum managers (SMs) and the Spectrum Broker (SB) [87].

D. POLITICAL ENVIRONMENT

TVWS technology is entrenched in a spectrum paradigm based on the reallocation of the broadcast spectrum for telecommunication use. Likely, several issues hinged on spectrum politics are expected to arise, as spectrum resources for wireless communication are undeniably scarce. Based on this presumption, many regulatory bodies whose responsibilities are to draft spectrum management policies have adopted various institutional frameworks to address the issue of optimal spectrum utility. TVWS regulatory topics are focused on agile adaptive radios that use cognitive processing schemes. As illustration, we present examples of the policies of a few selected spectrum regulatory bodies around the globe to expound on the political provisions for and practical aspects of spectrum management.

1) UNITED STATES OF AMERICA

Spectrum management in the United States (U.S.) is the core responsibility of the Federal Communications Commission (FCC) and the National Telecommunications and Information Administration (NTIA). Whereas the FCC is more aligned with the U.S. Congress, the NTIA is closer to the office of the U.S. President, although both agencies are inextricably linked. Through the FCC, the United States has been the vanguard of spectrum liberalization based on its laissez-faire economic policies. This implies that market forces driven by industry play a pivotal role in the U.S. The Spectrum Policy Task Force (SPTF) was inaugurated under the jurisdiction of the FCC in June 2002 to recommend innovative spectrum policies. Moreover, in November of 2002, the SPTF advocated several policies, as highlighted below [5]:

(i) Spectrum management should rely less on a regulatory framework and align more with the flexibility to respond to market forces, and this should be achieved by incorporating flexible models that are more responsive to rapid changes in the market.

(ii) The single regulatory regime for all spectrum bands needs to be discontinued. Nonetheless, licensed users should have exclusive spectrum usage rights, whereas unlicensed spectrum (i.e., Industrial, Scientific and Medical) bands should be open to a variety of wireless devices, with none having exclusive rights.

(iii) Three spectrum usage rights models, namely, the exclusive-use model, the Spectrum Commons model and the command and control model, were advocated. These recommendations should be implemented for both already allocated and newly allocated spectrum bands.

Furthermore, any changes made by the FCC must protect the rights of spectrum owners, and new entrants must not cause harmful interference to licensed users. This policy statement forms the cornerstone of TVWS technology, in which TVWSDs are mandated to protect incumbent TV broadcasts. The FCC has defined the TVWS regulatory framework by defining the technical and operational guidelines for TVWS in the Second Memorandum Opinion and Order, FCC 10-174 [24]. Consequently, TVWS in the U.S. has developed into a mature technology.

2) CANADA

Industry Canada is the ministry that oversees Canadian spectrum management. The Canadian Radio-television and Telecommunications Commission (CRTC) is the regulatory authority for telecommunication and broadcasting. The CRTC does not issue or manage spectrum rights; rather, spectrum licences issued by Industry Canada must be registered by the CRTC. The Canadian approach to TVWS is based on a Radio Standard Specification issued by Industry Canada (RSS-196, Issue I), "Point-to-Multipoint Broadband Equipment Operating in the Bands 512-608 MHz and 614-698 MHz for Rural Remote Broadband Systems (RRBS) (TV Channels 21 to 51)" [88]. Moreover, specific technical requirements (SRSP-300.512, Issue 1), "Technical Requirements for Remote Rural Broadband Systems (RRBS) Operating in the Bands 512-608 MHz and 614-698 MHz (TV Channels 21 to 51)" [89], were formulated to standardize RRBS based on TVWS technology. Although the policies of Canada and the United States are similar to each other, significant differences exist. They differ in many respects, but they have common features. The common and divergent features of these regimes are outlined below [90]:

(i) Industry Canada TVWS is based on a licence-based system, allowing high transmission power over a long distance with the following specifications for customer-premises equipment (CPE): $\leq$ 1 W/6 MHz, PSD ≤ -7 dBW/100 kHz). Meanwhile, the transmission power limit for a base station is $\leq$ 125 W/6 MHz, PSD $\leq$ 14 dBW/100 kHz.

(ii) TVWS spectrum licence issuance is on a First Come, First Served (FCFS) basis. The Industry Canada spectrum policy takes a moderate approach, with a more cautious and more controlled realization compared with the U.S. laissez-faire economic approach.

(iii) Spectrum allocation is based on a "Use" approach, rather than a "User" approach. In essence, a spectrum band is first assigned specifically for the purpose of radio transmission before chunks of that spectrum band are allocated to competing networks.

(iv) In the context of TVWS, the RRBS specifications are for fixed wireless internet service access only, with no support for portable or nomadic topologies, in contrast to the FCC approach, which supports nomadic network topologies.
(v) Spectrum interference management is implemented by grouping compatible radio services to utilize similar spectrum bands and thus to reduce the probability of inter-standard interference. Nevertheless, Industry Canada promotes cooperation and coordination among adjacent users in adjacent service areas.

3) AUSTRALIA

The implementation of Australian spectrum reform was assigned to four specific Australian government entities: the Australian Communications and Media Authority (ACMA); the Department of Communications, Information and the Arts (DCITA); the Australian Competition and Consumer Commission (ACCC); and the Minister of Communications, IT and the Arts. The statutory responsibilities of spectrum regulation and the issuance and renewal of spectrum licences are administered by the ACMA. The Australian RC Act is heavily dependent on the ITU regulations for allocating blocks of the spectrum based on different technologies, such as fixed, mobile, radio-navigation and broadcasting. The landscape of Australia spectrum reforms is significantly influenced by three categories of spectrum licensing regimes for radio communications, namely, apparatus licensing, spectrum licensing and class licensing. These regimes are synonyms for the widely used command and control, exclusive-use, and common-use models of spectrum regulation as implemented by other spectrum regulatory bodies. Hence, the Australian spectrum environment can be summarized as follows [79]:

(i) *Apparatus licensing*: This is often referred to as a device-centric approach to spectrum management, focused on the allocation of spectrum blocks to specific types of transmitter configurations, receiver configurations or both. This can be seen as a more lenient approach to spectrum management in which tight technical requirements concerning transmission sites, power, and equipment standards are enforceable. It is argued that this approach is efficient because spectrum licences are allocated based on a tight frequency planning process, thereby reducing harmful interference. Furthermore, based on this tight interference control, the need for guard bands is greatly reduced. However, this approach is not flexible, as licensees are not permitted to develop or deploy services and technology at need.
(ii) *Spectrum licensing*: This is a space-centric approach to spectrum management in which spectrum licences are allocated by auction for a minimum of 15 years. Blocks of the electromagnetic spectrum are traded as standard trading units (STUs). In contrast to the apparatus licensing scheme, spectrum licensing is market driven, and licences are issued prior to price-induced allocation. There are many attractive design attributes of spectrum licensing. It confers on the licensee the right to deploy the licensed spectrum for any radio-communication services, hence ensuring service neutrality and service flexibility.
(iii) *Class licensing*: This is a non-prescriptive technology-centric licensing scheme in which all spectrum users compete in an open and shared spectrum access scheme. Spectrum users are not guaranteed exclusive usage rights. Interference management is left to the discretion of individual devices through either avoidance or mitigation. Most devices are operated under frequency hopping and CSMA/CA schemes, which are robust against inter- and intranetwork interference.

There is a high level of uncertainty regarding the deployment of TVWS technology in Australia. This is based on the fact that there is no reported policy direction in regards to a technical and legal framework supporting TVWS technology. Several factors might be responsible for this situation, such as (i) the highly commercialized spectrum topology, in which the commercial/private sector holds 59% of the total allocated spectrum, and (ii) the fact that since the issuance of the Australian Radio Communications Act (RC Act 1992), there has never been a major policy effort to review the existing spectrum regimes. Based on our limited study so far, there are no reports of any spectrum measurement campaign being conducted in Australia. Quite often, spectrum measurement campaigns are a prelude to the formulation of TVWS technology policy.

4) NEW ZEALAND

The underpinnings of the New Zealand spectrum regulatory framework are provided by the New Zealand Radiocommunications Act (RCA, 1989). The Act empowered the Ministry of Economic Development (MED) to play a pivotal role in New Zealand spectrum management and policy development, with the Cabinet and Commerce Commission playing supporting roles. The New Zealand spectrum is managed using three spectrum licensing schemes: (1) the spectrum management rights regime (MRR), which is similar to exclusive usage rights; (2) the radio licence regime (RLR), previously known as apparatus licensing; and (3) a general user licence regime, similar in context to Spectrum Commons usage rights. TVWS technology is actively supported in New Zealand based on the established technical and operational framework, as highlighted below [91]:

(i.) *Interim licence regime*: TVWS technology is only permitted to operate in the 510-606 MHz UHF bands, with a maximum of four (4) contiguous or non-contiguous channels with a 1 dB threshold degradation method [91]. There is no security over TVWS licence tenure, as it is subject to revocation as technology changes or as complaints from incumbent users arise.
(ii.) *Interference management scheme*: Prior to deployment, TVWSDs must be shown to conform to either FCC

CFR Title 47, Part 15, Subpart H - Television Band Devices 15.701 – 15.717, or ETSI EN 301 598 V1.1.1 'White Space Devices (WSD); Wireless Access Systems operating in the 470 MHz to 790 MHz TV broadcast band'. The TVWS database approach is not mandatory. Hence, the TVWS framework has not yet been fully defined.

(iii.) *Maximum EIRP transmission power*: The radio spectrum management specifications state that the maximum EIRP for TVWS CPE is 10 dBW/8 MHz. This is remarkably different from the transmission power limits adopted by the FCC and Ofcom, which are the leading spectrum regulatory bodies worldwide.

5) SINGAPORE

Singapore is regarded as one of the leading testbed nations for TVWS innovations and deployment in South East Asia. The regulatory framework for TVWS in Singapore is administered by the Info-communications Development Authority of Singapore (IDA), under the Info-communications Development of Singapore Act (Cap. 137A), the Telecommunication Act (Cap. 323), and the Postal Service Act (Cap. 237A). At the forefront of TVWS technology, several TVWS pilot projects have been conducted in designated TVWS testbed areas called CRAVE (Cognitive Radio Venue) zones. Singapore is roughly estimated to have 180 MHz of interleaved spectrum available for TVWS between the 174 - 230 MHz and 470-806 MHz bands. The Singaporean approach to TVWS is entirely based on practical deployment, and hence, it has the attributes of mature TVWS technology highlighted below [90]:

(i) Spectrum-regulatory-body- or private-entity-funded spectrum measurement campaigns are conducted to understand spectrum utilization trends and adopt policy statements to enable dynamic spectrum sharing.

(ii) A licence-exempt regime for TVWS technology is implemented to drive an innovative paradigm in dynamic spectrum access. This licence-exempt scheme will facilitate widespread use and technology innovation, as was the case for WLAN technology operating in the ISM bands. Nonetheless, device registration is mandatory, and minimum technical requirements are specified for a device to be permitted to transmit in these bands.

(iii) Specific frequency bands must be designated for TVWS technology, as is the norm in frequency spectrum assignment regimes. This is similar in context to apparatus licensing as practiced by some regulatory bodies.

(iv) Connection orientation to a geolocation database is mandatory, and an efficient geolocation database is expected to manage fewer queries per transaction instance. The instances of queries issued by TVWS devices to geolocation databases should be explicitly defined.

6) UNITED KINGDOM

In 2007, the Office of Communication (Ofcom), which is the regulatory body responsible for spectrum regulation and management in the United Kingdom, issued a policy paper titled "Digital Dividend Review", in which the body defined its stance on TVWS technology [92]. The enabling Act establishing Ofcom, based on which it regulates dynamic spectrum access schemes, is Section 3(1) of the Communications Act 2003 (or simply the Communications Act). The Communications Act empowers Ofcom to (i) further the interests of British citizens in matters of communication and (ii) to further the interests of consumers in relevant markets by promoting competition. This mandate can be summarized as requiring Ofcom to promote efficient management and economic use of the spectrum. It has been reported that dynamic spectrum access to TVWS is allowed on a licence-exempt basis over the interleaved spectrum in UHF TV bands as long as there is a low probability of harmful interference to existing DTT and PMSE operations.

Ofcom adopted the same criteria earlier mandated by the FCC, although notable differences exist, as highlighted in Table 1 of [16]. These notable differences between the Ofcom and FCC policies can be traced back to the differences in the TV channelization schemes in the two countries: the FCC has adopted a 6 MHz channelization scheme, in contrast to the 8 MHz format that is widely used in Europe. Furthermore, the two regulatory bodies have differing opinions on channel evacuation time, with the FCC proposing 2 seconds and Ofcom adopting a more conservative requirement of 1 second.

7) CHARACTERISTICS OF MATURE TVWS-FRIENDLY REGULATORY BODIES

TVWS technology is a burgeoning spectrum optimization scheme capable of improving spectrum utilization efficiency. As different regulatory bodies align their regulations towards dynamic spectrum access, certain commonalities are apparent. Among all TVWS-friendly regulatory bodies, dynamic spectrum access usage relies only on an overlay mechanism. An overlay mechanism is a dynamic spectrum access scheme in which TVWSDs ensure that their target band is free of incumbent operations. In other words, for a TVWSD to utilize a specific frequency band, there should be no incumbent receiver in its vicinity operating on the same frequency channel. We present the detailed attributes of several mature TVWS-friendly regulatory bodies for comparison based on the spectrum regulators selected as examples above.

E. TECHNOLOGICAL ENVIRONMENT

TVWS technology has not been widely adopted, largely because of several practical implementation issues that need to be addressed. Allowing TVWS technology to operate in the vacant spectrum between TV channels requires a detailed understanding of the numerous relevant constraints to enable the crafting of solutions for TVWS technology.

TABLE 5. Features of mature TVWS-Friendly spectrum regulators.

Attribute / Country	Spectrum Regulator	Spectrum Measurement Campaigns	TVWS Licence-exempt	TVWS Defined Frequencies	TVWS Pilot Projects
USA	Yes	Yes	Yes	Yes	Yes
Canada	Yes	Yes	No	Yes	No
Australia	Yes	No	No	No	No
New Zealand	Yes	Yes	No	Yes	No
UK	Yes	Yes	Yes	Yes	Yes
Singapore	Yes	Yes	Yes	Yes	Yes

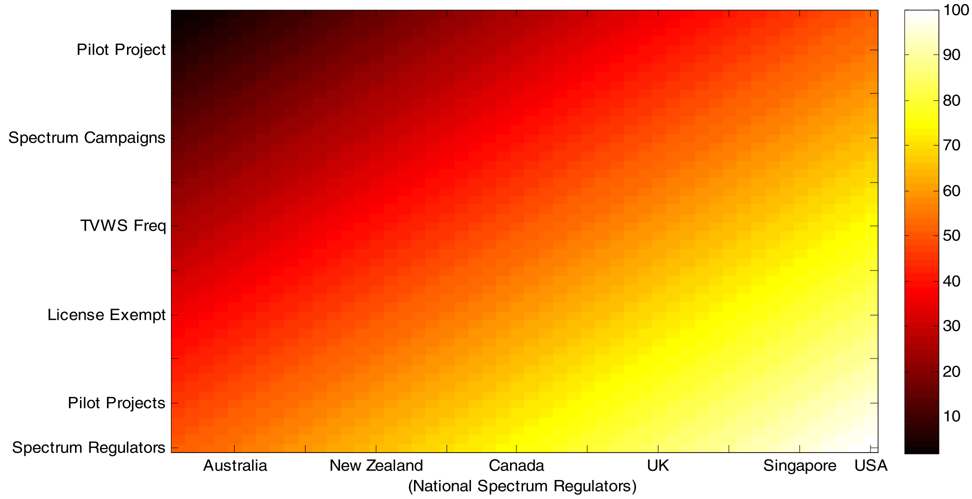

FIGURE 8. Heat map of the characteristics of a few selected TVWS-aligned spectrum regulators.

This section summarizes the many potential technological challenges adversely affecting the adoption of TVWS technology, as presented in Figure 9. The technological issues affecting TVWS technology can be broadly classified into macro and micro challenges. The macro technological challenges are defined as industry-based, whereas the micro challenges are related to wireless standards.

1) THE MACRO CHALLENGES

The macro issues concern the two major players responsible for the hardware design of TVWS devices. Differences arise as a result of the nominal TV bandwidth channelization, as the FCC and ETRI have adopted 6 MHz and 8 MHz channel bandwidths, respectively.

2) THE FEDERAL COMMUNICATIONS COMMISSION (FCC)

The U.S. spectrum regulator has made several clarifications regarding power limits, power spectral density and antenna rules for devices operating in the licence-exempt TVWS spectrum. The specified configuration is based on a 6 MHz channel bandwidth, with the maximal output signal power (∼4 W EIRP) for fixed devices with geolocational capabilities, whereas Mode II portable devices (equipped with geolocational capabilities) and Mode I portable devices (without geolocational capabilities) are to operate at 100 mW [24], thus resulting in a master-slave configuration. Notable industrial players that have adopted these specifications include Carlson RuralConnect and Adaptrum [6].

3) THE EUROPEAN TELECOMMUNICATIONS STANDARDS INSTITUTE (ETSI)

The ETSI has formulated a harmonized standard that serves as a common standard for TVWS devices across Europe and in other countries using an 8 MHz nominal bandwidth. The standard is similar to the FCC specifications but differs in a variety of ways [39]. For instance, the FCC measures the out-of-band emission (OOBE) using a 6 MHz nominal bandwidth, whereas the ETSI uses 8 MHz, thus resulting in different values for the spectral mask requirements. According to the information available to the author, several industrial players are currently operating based on the ETSI standard, such as 6 Harmonics [93] and NICT [94].

4) THE MICRO CHALLENGES

Dynamic spectrum access was designed to make new areas of the frequency spectrum available to wireless devices. Several collocated secondary users and primary users are envisioned to transmit using TVWS, as shown in Figure 6. Each network operating in TVWS bands has unique operational parameters and must adhere to regulatory requirements. Heterogeneity and coexistence are not novel issues in wireless communication and, hence, are not unique to TVWS technology. However, the combination of an opportunistic spectrum access scheme with the stringent requirement of non-interference to incumbents poses unique and subtle challenges. The objective of this section is to provide an

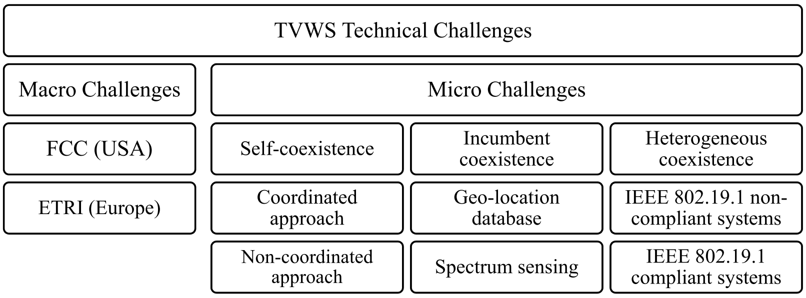

FIGURE 9. **TVWS Technological challenges.**

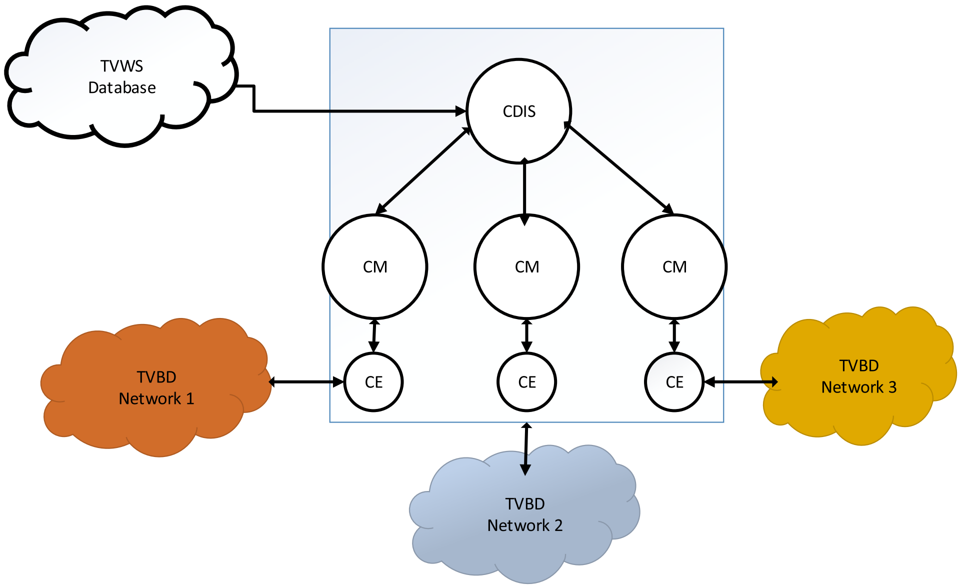

FIGURE 10. **IEEE 802.19.1 enabled centralized heterogeneous coexistence architecture.**

overview of the micro issues facing TVWS networks and to describe the various approaches that have been proposed to address these issues.

5) HETEROGENEOUS COEXISTENCE

Heterogeneous coexistence refers to the design of methods to avoid inter-channel interference among network devices sharing TVWS operating bands. Heterogeneity arises because of varying transmission powers, e.g., IEEE fixed devices are empowered to transmit at 4 W and have a reception sensitivity as low as −97 dBm. The 802.11af standard specifies transmission at 100 mW and a reception sensitivity of −64 dBm [95]. Distinct MAC strategies are also employed. IEEE 802.22 is a scheduling network standard based on TDMA MAC uplinks, whereas IEEE 802.11af is based on the non-scheduling format of CSMA/CA MAC. The two standards have different bandwidth configurations. IEEE 802.22 is based on a 6 MHz channelization scheme with the possibility of contiguous and non-contiguous three-carrier channel aggregation. IEEE 802.11af is based on a 5 MHz channelization scheme with extensible channel aggregation. Thus far, two conventional approaches have been adopted to protect secondary users from interference, based on either IEEE 802.19.1 compliant or IEEE 802.19.1 non-compliant networks. The IEEE standards agency has demonstrated commitment towards heterogeneous-coexistence-based TVWS utilization through the formulation of the IEEE 802.19.1 standard [96], which is equipped with the core functional modules to implement this functionality, as shown in Figure 10. An IEEE 802.19.1 enabled centralized heterogeneous coexistence architecture consists of the following components:

(i) The *Coexistence Discovery and Information Server* (CDIS) is assigned the responsibility of providing coexistence-related information to the coexistence managers and multi-radio access interfaces between coexistence managers.

(ii) The *Coexistence Manager* (CM) can be literally described as the intelligent unit of IEEE 802.19.1 compliant systems. Hence, a coexistence manager holds the responsibilities of discovering other coexistence managers and making critical coexistence decisions to facilitate coexistence solutions between TVWS networks.

(iii) The *Coexistence Enabler* (CE) is the in-between module responsible for information communication between the coexistence manager and the TVBD network.

TABLE 6. Findings regarding selected heterogeneous TVWS techniques.

Reference	Comments	Approach
[1]	Advocated the use of distributed coexistence beacon exchange among TVWS devices. Formation of cluster head equipment (CHE) that admits and coordinates cluster members. This approach leads to energy-saving techniques and can promote coordination.	IEEE 802.19.1
[97]	Decomposition of the TVWS coexistence framework into three components: coexistence enablers (CEs), coexistence management servers (CMSs), and a coexistence database (CD). Proposed a decision-making algorithm for new device/network discovery, thereby reducing device start-up time.	IEEE 802.19.1
[98]	Proposed the use of a multi-objective combinatorial optimization approach. Incorporation of machine learning for decision-making in TVWS coexistence. The proposed algorithm outperforms existing algorithms in terms of a fairness index and the percentage of demand served.	IEEE 802.19.1
[99]	Proposition of a novel joint power and channel allocation algorithm. The spectral needs of TVWS are decomposed into power and bandwidth problems.	Non-IEEE 802.19.1
[100]	A two-stage coexistence management framework and the use of an interference graph were introduced. The use of graph theory facilitates inter-network coexistence through the adoption of interference avoidance techniques in OFDM networks.	Non-IEEE 802.19.1
[101]	Designed a framework for coexistence between 802.11 af and 802.22. Proposed the use of a CPE sensing antenna to transmit a busy tone at a power of 100 mW with a known pattern	Non-IEEE 802.19.1
[102]	Proposed a coexistence gap technique called listen before talk (LBT), enabling coexistence between LTE and TVWS devices.	Non-IEEE 802.19.1
[103]	Interdisciplinary approach to TVWS coexistence via the incorporation of	Non-IEEE

We summarize some of the proposed TVWS coexistence techniques in Table 6.

6) IEEE 802.22 SELF-COEXISTENCE

Co-channel self-coexistence in the IEEE 802.22 standard is a challenging problem. It concerns achieving the optimal performance of collocated networks while ensuring that each of these networks does not cause network degradation. The primary focus of self-coexistence is the reduction of the inter-cell interference coordination (ICIC) problem. Since TVWS networks are licence-exempt, many network operators will be operating on TVWS bands where there is no centrally controlled entity to address ICIC issues arising from multiple unlicensed networks coexisting in the same spectrum channel. To facilitate self-coexistence, two notable approaches have been adopted: the IEEE 802.22 centralized self-coexistence mechanism [104] and a non-centralized (distributed) approach based on non-cooperative game theory. The IEEE 802.22 inter-BS coexistence mechanism consists of four stages: spectrum etiquette, interference-free scheduling, Dynamic Resource Renting and Offering (DRRO), and Adaptive On-Demand Channel Contention (AODCC). Below, we summarize selected works on self-coexistence in TVWS networks.

V. RESEARCH CHALLENGES, TRENDS AND FUTURE WORK

Based on the various successes recorded during various TVWS pilot projects throughout the world, it can be confidently stated that a massive TVWS roll-out is on the horizon. Nevertheless, several challenges still remain to be addressed. In this subsection, we present some of the research challenges, trends and future work currently gaining research attention.

A. ECONOMIC MODEL RESEARCH CHALLENGES

Recent TVWS pilot projects have relied on geolocation databases. This implies that for the near future, TVWS technology will rely on market-driven geolocation databases. Desired improvements to geolocation-database-driven TVWS technology will be achieved by considering conventional market-driven issues, as discussed below.

1) DESIGN FOR UNIVERSAL PUNISHMENT FOR THE TVWS ECOSYSTEM

The central purpose of IEEE 802.19 is to serve as a TVWS resource allocator using a centralized architecture, as a distributed architecture is not feasible. However, it is possible that some nodes will cheat, thereby endangering the overall TVWS throughput capacity by causing unabated interference and degrading the QoS in the TVWS ecosystem. Therefore, there is a need to ensure a strategy-proof mechanism. Until recently, cheating in geolocation-database-driven networks has been treated in isolation, with a primary focus on SUs [114], [115]. Another dimension that has been neglected is the PU cheating dimension. Several studies have investigated the adverse effects of PU activities [116]–[118]. Consequently, there is a need to include a PU-side strategy-proof mechanism in the TVWS ecosystem.

2) INFORMATION-REUSE-ASSISTED REAL-TIME SECONDARY SPECTRUM MARKET MODEL

The secondary spectrum market is characterized as a spot market with high liquidity. Despite the highly prescriptive nature of the proposed RTSSM, there has not yet been any

TABLE 7. Highlights of selected TVWS self-coexistence techniques.

Reference	Comments	Approach
[105]	On-demand spectrum contention (ODSC) MAC protocol based on efficient and effective inter-base station communication. Based on contention, the winner with the lowest number wins the channel.	Centralized 802.22
[106]	Self-coexistence windows (SCWs) based on a coexistence beacon protocol (CBP) with underlying on-demand frame contention (ODFC) protocol synchronization. This approach is specific to the IEEE 802.22 standard and has been adopted	Centralized 802.22
[107]	Investigated inter-base station self-coexistence based on game theory. The proposed model has been shown to out-perform greedy and random algorithms.	Distributed architecture
[108]	The author investigated self-coexistence as an optimization problem using game theory	Distributed architecture
[109]	Non-cooperative theory based on a cost minimization approach.	Distributed architecture
[110]	The use of fuzzy logic was proposed based on the high flexibility and low complexity of coexistence in a multi-CRN environment.	Distributed architecture
[111]	A traffic-aware protocol for self-coexistence based on previous channel knowledge in a fixed channel assignment strategy.	Centralized 802.22
[112]	Decomposed the self-coexistence problem into transmission power control and channel assignment and solved this problem using non-cooperative game theory	Distributed architecture
[113]	Proposed the use of a learning mechanism and non-cooperative game theory to solve the resource allocation problem.	Distributed architecture

effort to exploit an information reuse approach through a parametrization technique [63]. Information trade has been applied in the context of QoS-limited networks for SUs [71]. In contrast to the PU spectrum market, which is active once every several years, the RTSSM is expected to exhibit high liquidity, considering the stipulated geolocation database refresh rate and the contract market model. This can be mitigated by modelling the RTSSM as a parametrized stochastic problem in which the reuse of previous spectrum trading information can be implemented [119].

3) FRAMEWORK FOR ADMISSION CONTROL IN A DATABASE-ASSISTED RTSSM

It has been widely agreed that the way forward is to adopt a licence-exempt scheme to encourage innovation in TVWS technology. This business model can be categorized as a social-planning database (such as those managed by non-profit organizations, e.g., government departments). In this scenario, the database manager's objective is to maximize the total network profit, i.e., the aggregate profit of secondary operators and the database manager. Hence, there is a need to design an admission control policy. Reference [120] has proposed the use of a distributed architecture for this purpose, whereas [30] proposed the use of the Spectrum Commons approach and a high-priority-channel model structure.

B. TECHNICAL RESEARCH CHALLENGES

Most of the technical issues confronting TVWS, such as those of incumbent coexistence, heterogeneous coexistence and self-coexistence, have been widely discussed and reported. However, there are some concerns that remain to be addressed, as highlighted below.

1) OFDM PHY LAYER PAPR

OFDM is the modulation scheme for TVWS networks. OFDM is known to perform poorly in terms of the peak-to-average power ratio (PAPR) [121]. The complexity of the problem is magnified when the high rejection filter requirements for power in adjacent bands are considered. There is a need to analyse different OFDM PAPR reduction techniques based on computational complexity, bandwidth expansion, spectral spillage and performance. Several PAPR mitigation techniques have been proposed [121]. In particular, a cognitive-radio-specific design proposal has been suggested [16]. The author of [16] proposed the use of the filter bank multicarrier communication (FBMC) technique, as it achieves both adjacent coexistence and spectrum pooling.

2) DISCOUNTED PRICE BASED ON SOFT FREQUENCY REUSE FOR SELF-COEXISTENCE

TVWS networks pay fees to PUs to temporarily use their currently unused spectrum bands. These ''fees'' carry a dual meaning of the actual payments paid by the TVWS networks to the PUs and a reduction in transmission power [65]. Soft Frequency Reuse is a smart technique that is widely applied to accommodate multiple networks transmitting on a given channel without causing interference or performance degradation [122]. By adopting a market efficiency approach [123], several TVWS networks can be aligned to use the same frequency via scheduling based on an appropriate transmission power control mechanism. This leads to lower spectrum prices for the TVWS networks and more profit for the Pus, as more TVWS networks can be accommodated in the same frequency channels.

3) ACCURATE PROPAGATION MODEL

The propagation model plays a crucial role in wireless communication and, as such, is always of considerable interest. Besides being generally important, it plays a crucial role in model accuracy, and several empirical models have been proposed for this reason [124]. Based on the experience gained in Singapore and other published works, some of the widely used propagation models for TVWS technology include the free-space path loss model [125], the Hata Okumura path loss model (''Hata'') [124], the Longley-Rice path loss model [126] and the ITU-R P.1411-6 model [127]. The computer-based implementation of the Longley model is the Irregular Terrain Methodology (ITM) [128]. The choice of a specific model is driven by several factors that must be jointly considered. For instance, [14] utilized the ITM model based on a unique case scenario. The Singaporean experience indicated a preference towards adopting the Longley-Rice and ITU-R P.1411-6 path loss models.

C. RECENT RESEARCH TRENDS

Although most current TVWS research is focused on RTSSM design, other TVWS-related topics are also being increasingly studied. In this section, we briefly highlight some of the current topics being addressed with regard to TVWS technology.

1) INTERNET OF THINGS (IoT)

Internet of Things (IoT) technology is expected to flourish under the TVWS framework, simply because of the favourable propagation characteristics of TVWS technology. The lower frequencies at which TVWS technology operates are desirable in remote and rural areas with less infrastructure. Moreover, shorter-range transmissions are well suited for penetrating through many floors and walls with minimal signal degradation. Hence, this technology is well suited for home and office applications. To exploit these beneficial characteristics of TVWS, several papers have been published on TVWS IoT machine-to-machine communications [129], [130].

2) BIG DATA/SMALL DATA ANALYTICS (IoT)

With the use of geolocation databases and the need for regular updates regarding the available TVWS channels, it is evident that big/small data analytics will be important optimization tools. In addition to being extremely efficient, these tools will be highly advantageous for the RTSSM models that are currently being advocated. TVWS technology embodies the five V's of big data analytics: volume, velocity, variety, viability and veracity [131], [132].

3) 5G-LTE IN TVWS TECHNOLOGY

The evolution towards 5G mobile networks is being driven by the need to facilitate the coexistence of many wireless devices with increased device and service complexity as well as the requirement of ubiquitous access to mobile services. TVWS technology can thus be exploited to gain access to the additional necessary spectrum bandwidth. Many proposals for the design and deployment of LTE in TVWS technology have been published, including [133], [134].

VI. CONCLUSIONS

The use of database-driven techniques has systematically mitigated the problem of incumbent coexistence in TVWS network technology. Based on the SLEPT framework, the following observations were made in this study. Socially, TVWS technology has been accepted, based on numerous successful pilot projects that have been conducted globally. Legally, Japan has adopted a more conservative approach compared with the U.S. FCC, which espouses a market-driven approach. Economically, there is a need to design a real-time secondary spectrum market model that is strategy-proof and affordable. The design of TVWS licence fees is also another area that requires urgent attention. In addition, TVWS utilization has some political undertones. A great deal of political will is required before TVWS technology can be implemented, as numerous countries have yet to declare their stances in regards to TVWS technology, e.g., Malaysia.. Technologically, database-assisted TVWS technology cannot be implemented without due consideration for issues related to both self-coexistence and heterogeneous coexistence.

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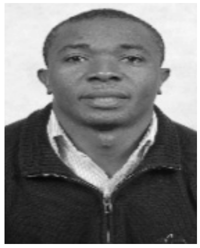

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