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Research Article

Multicriteria Decision Analysis of Spectrum Management Frameworks for Futuristic Wireless Networks: The Context of Developing Countries

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National regulatory authorities (NRAs) in developing countries need an accelerated means to formulate technical regulations for the telecommunications sector. This will enable countries to gain maximum benefits from the rapid advances in technology. The existing regulation-making processes are time-consuming and do not cope with the emergence of global technological changes. This article presents an efficient and quicker approach to formulate regulatory framework to govern the wireless technologies that are based on the Dynamic Spectrum Access (DSA) technique. The approach utilises Multicriteria Decision Analysis (MCDA) tools. The article uses a case study to evaluate dominant Dynamic Spectrum Management (DSM) frameworks. Finally, a sustainable DSM framework that has potential to address the digital divide challenges in the context of developing countries is proposed.

1. Introduction

Spectrum is a precious limited resource required to build, maintain, and expand of the Information and Communications Technology (ICT) infrastructure of any nation [1, 2]. Good policy and regulations governing spectrum usage are key ingredients for the deployment of and coexistence of wireless technologies, applications, and services [3, 4]. The exponential increases of data traffic for wireless communications [5], coupled with inefficient legacy spectrum management frameworks and access techniques, are the causes of the looming scarcity of radio spectrum particularly below 3 GHz [6]. However, rapid technological advances such as Dynamic Spectrum Access (DSA) improve spectral utilisation efficiency and capacity through sharing and the use of small cells [7–11]. These efforts have been supported by leading National Regulatory Authorities (NRAs) by introducing flexible spectrum management frameworks such as the Television White Spaces (TVWS), Spectrum Access System (SAS), and the Licensed Shared Access (LSA) [12–17].

In contrast to the aforementioned progressive approaches and forward-looking decision-making taken by the leading NRAs, the opposite is true of many regulators in the developing economies. Despite allowing many technological pilots and trials to take place [18], regulators have so far not been able to reform and put in place the required technical regulations for enabling new wireless technologies. El-Moghazi et al. [19] argue that uncertainty in spectrum policy reforms in developing countries is due to various challenges such as political bureaucracy and lack of sustainable human capacity development.

It is worth noting that the uncertain atmosphere and the slow pace of regulatory decision-making process in the light of rapidly changing wireless communications technologies could cause the Original Equipment Manufacturers (OEMs) to abandon their plans to mass produce chip-sets for a particular technology. This could amount to the loss of opportunity in the creation of knowledge-based industries and, even more detrimental, cause delays in achieving broadband connectivity targets.

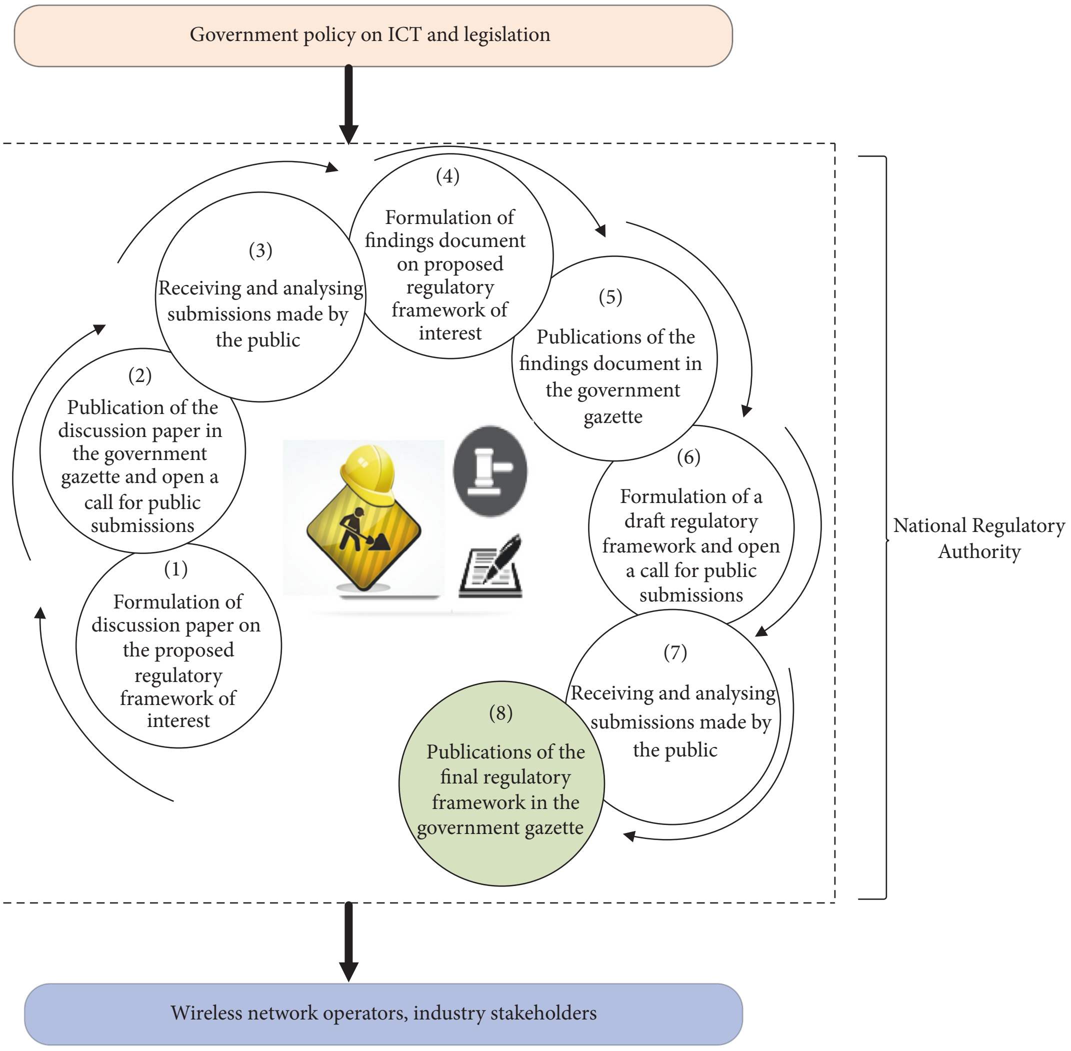


Figure 1: Bureaucratic approach followed by National Regulatory Authorities when formulating technical regulations.

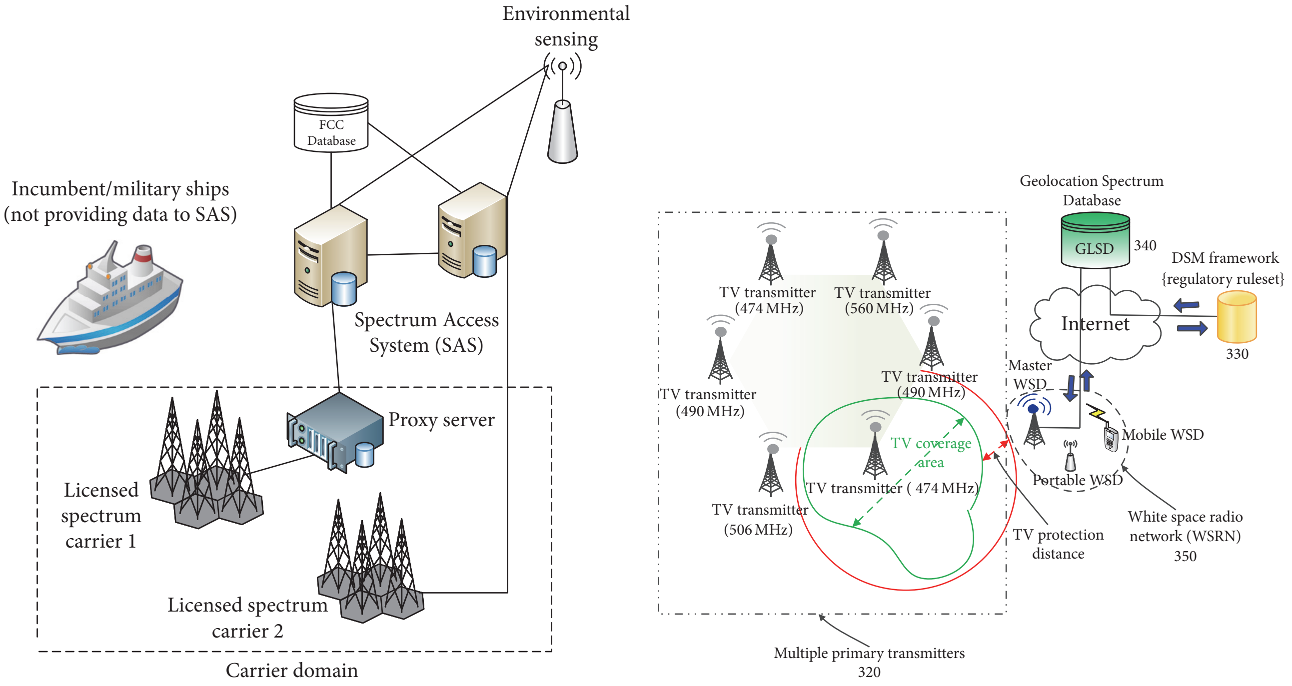
1.1. Regulatory Frameworks Formulation Process in Developing Countries. Typically, the technical regulatory framework formulation cycle is comprised of eight bureaucratic stages that can take more than two years to complete. The National Regulatory Authority (NRA) involves lengthy bureaucratic decision-making process that involves many different stakeholders. Even if such regulations do already exist elsewhere, the respective NRA would be required to publish in a gazette a public call for comments which contains several questions and suggestions relevant to the proposed technical regulation. A time frame would be set to receive comments from the public. Subsequently, a team of experts assembled by the regulator would be required to formulate a findings document after a lengthy process of reviewing all the received public comments. Next, the findings document has to be published in a government gazette, followed by formulation of the draft regulatory framework document. The draft document has to be published in a government gazette and an open call for comments from the public is made. Ultimately, after reviewing and analysing the received comments from the public, the final regulatory framework document is published in the government gazette and gets enforced as the governing regulations.

Figure 1 depicts a typical bureaucratic regulation-making approach prevalent in developing countries.

This article utilises the case study of Dynamic Spectrum Management (DSM) frameworks for exploitation of the Television White Spaces (TVWS) to propose an efficient approach of formulating technical regulations for future wireless networks such as 5th generation (5G) networks [24]. This proposal is useful for NRAs in the developing countries particularly when such regulations exist elsewhere.

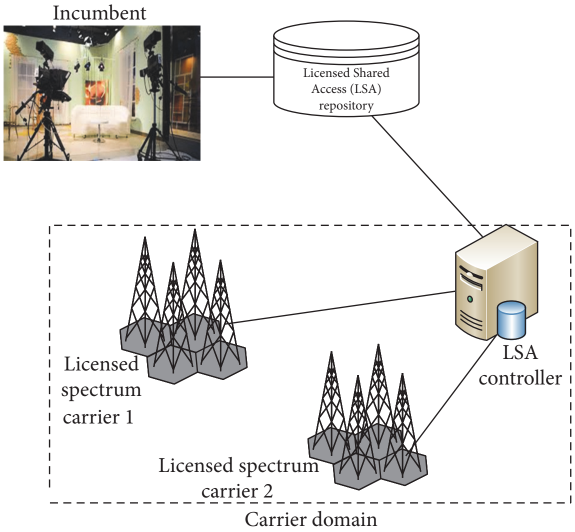
Figure 2 depicts complex future wireless network ecosystems. These highly dynamic systems are numerically illustrated as follows:

(i) Figure 2(a): the three tier dynamic spectrum sharing framework through the Spectrum Access System (SAS). The framework enables creation of broadband small cells networks by sharing spectrum in the Citizen Radio Band (i.e., 3.5 GHz) [16].



(a) The Spectrum Access System (SAS) model

(b) The TV White Spaces (TVWS) model



(c) The Licensed Shared Access (LSA) model

Figure 2: Illustration of heterogeneity of highly dynamic spectrum sharing frameworks for future wireless networks ecosystems.

(ii) Figure 2(b): the Television White Spaces (TVWS) spectrum sharing framework. Secondary users are allowed to dynamically share the locally unused broadcast spectrum and form affordable long-range broadband networks through the Geolocation Spectrum Database (GLSD) [15].

(iii) Figure 2(c): the authorised spectrum sharing framework in the licensed band/Licensed Shared Access (LSA). The holder of the spectrum license can temporarily dynamically share the portions of underutilised spectrum with the secondary user. This framework is enabled by the LSA repository and is preferred by Mobile Network Operators (MNOs) due to the guaranteed QoS [17].

1.2. Key Contributions. This article presents the following major contributions:

(1) An efficient approach for formulating spectrum management frameworks for future wireless communications technologies using Multicriteria Decision Analysis (MCDA).

(2) A proposed sustainable DSM framework for TVWS relevant to the context of developing countries.

The remainder of this article is arranged as follows: Section 2 reviews transdisciplinary analysis approaches of strategic objectives, while Section 3 presents categories of DSM frameworks. Section 4 highlights key technical parameters to consider. Section 5 presents DSM frameworks from leading NRAs and other nongovernmental entities. A case study is presented in Section 6. The interpretation of results is performed in Section 7, while Section 8 proposes a sustainable DSM framework. Section 9 concludes this article.

2. Transdisciplinary Analysis Approaches of Strategic Objectives

The best possible spectrum management policy framework should be the one that (i) allows optimal but sustainable utilisation of the natural resource (radio spectrum); (ii) accelerate bridging of the digital divide to reach underserved and low income communities, particularly those located in rural areas; and (iii) spurs innovation and creation of new knowledge-based industries. However, selecting a framework that fulfils these qualities is a complex decision-making problem that converges multiple conflicting, qualitative objectives from the policy and technoregulatory perspectives.

Researchers have used different approaches to select the best technoeconomic strategy in wireless communications. For example, the authors in [25] have developed a framework that utilises a Cost Benefit Analysis (CBA) to determine the best possible operator strategy for deployment of indoor and hotspot wireless network infrastructures in shared spectrum scenarios. More noteworthy, in [26, 27], a framework that utilises Multicriteria Decision Analysis (MCDA) approaches is presented as a means for modelling policies to enhance sustainable development growth. Key objectives of the framework are to enable decision-makers to develop better policies that would allow the sustainable extraction of natural resources and to enable current and future quality of life in society at large. The approach focuses on solving the environmental challenges caused by harmful emissions of Green House Gases (GHG).

Conceptually, a multiobjective decision problem can be formulated as maximisation, minimisation, or a combination of both functions [28]:

$$\text{Maximise } f(X) \left| \begin{array}{l} g(X) = 0 \\ h(X) \leq 0 \\ X \geq 0, \end{array} \right. \tag{1}$$

where X is a portfolio of decision variables, $f(X)$ is a portfolio of objective functions, $g(X)$ are equality constraints, and $h(X)$ are inequality constraints.

3. Categorisation of Dynamic Spectrum Management Frameworks

In this section we categorise DSM frameworks in the context of TVWS of which the GLSD technique is used for spectrum sharing and control. This categorisation is based on how frameworks are integrated into the National Regulatory Authority (NRA) spectrum management function.

3.1. Tight Coupling Spectrum Management Frameworks. The tight coupling (TC) approach requires the National Regulatory Authority to play a central conservative role in enforcing and coordinating key functional aspects of the DSM framework by employing a reference GLSD. This entails the provisioning of calculated baseline spatio- and spatioagnostic Operational Parameters (OPs) required to protect incumbent receivers to the secondary GLSDs that are operated by qualified private entities. The OPs could include, but are not limited to, the allowed White Space Device (WSD) transmitting power levels with respect to the operation of DTT and the allowed WSD power spectra densities with respect to the ad hoc operation of Programme-Making and Special Events (PMSE) and other low-power auxiliaries. Furthermore, the regulator provides a technical guideline including algorithm and the type of propagation model to be used by qualified GLSD operators in their implementation. Additionally, the regulator jointly coordinates the interference management function with the operators.

The chief advantages of tight coupling DSM framework are as follows:

(i) *Increased capability to enforce and monitor ruleset implementation*: the use of the regulator's *reference GLSD* to perform baseline calculations to determine TVWS availability and WSD transmit power limits improves optimal spectrum allocation and utilisation efficiency by all stakeholders. Specifically, this is attributable to the fact that private operators must strictly enforce the set-out regulatory limits calculated by the regulator in their GLSD implementation. Furthermore, the tight coupling framework allows more efficient monitoring of possible interference by WSD to incumbents as this function is collectively carried out with private GLSD operators. The framework gives the regulator the ability to switch off noncompliant secondary GLSDs.

(ii) *Better privacy of primary user data*: since baseline calculations are performed by the regulator's reference GLSD, there is no requirement to provide the primary user dataset to secondary GLSD operators.

Disadvantages of this approach are as follows:

(i) *Complexity*: the requirement to have a reference GLSD to perform baseline calculations to determine TVWS availability and the corresponding WSD transmit power limits translates to added investment and running costs on the overall framework implementation to the regulator. Additionally, this means that the regulator must possess expert personnel to run and maintain such a complex infrastructure. Such complexity and costs render this approach less feasible to regulators from the developing world who often are plagued by weak institutional capacity [19]. Figure 3 illustrates this further.

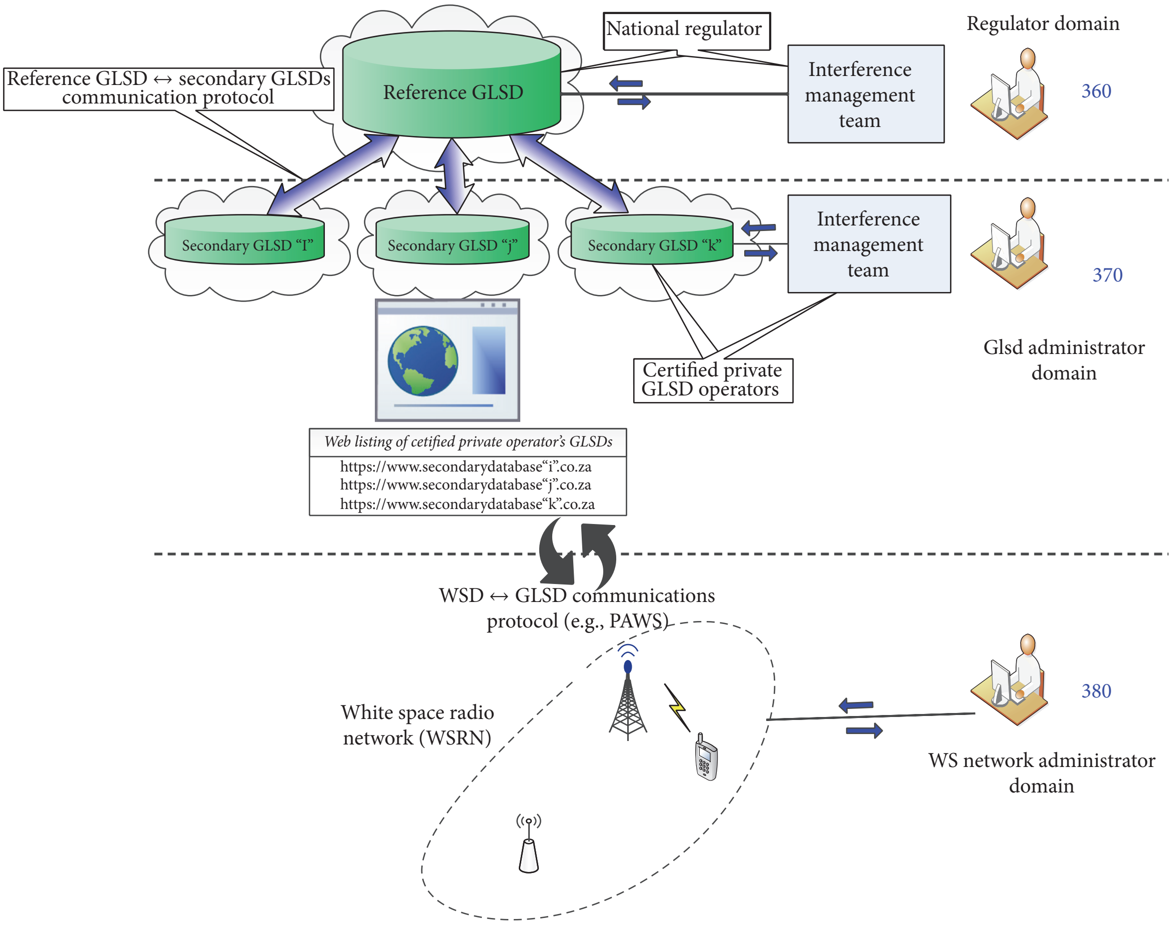


Figure 3: Functional architecture of tight coupling DSM framework using geolocation approach.

3.2. Loose Coupling Spectrum Management Frameworks. The loose coupling (LC) DSM framework approach does not require the National Regulatory Authority to operate a reference GLSD. However, the regulator furnishes private GLSD operators with raw technical information required to calculate the protection parameters of the incumbent receivers. These include, but are not limited to, the location of the incumbent transmitter, antenna height, transmitting power levels, pattern, and technical details of the type of the approved WSDs. Furthermore, the regulator provides technical guidelines including the algorithm and type of propagation model to be used by approved GLSD operators in their implementation. The regulator independently monitors possible interference that might be caused by the WSDs to the incumbent services. The loose coupling DSM framework has many advantages, chief among which are the following:

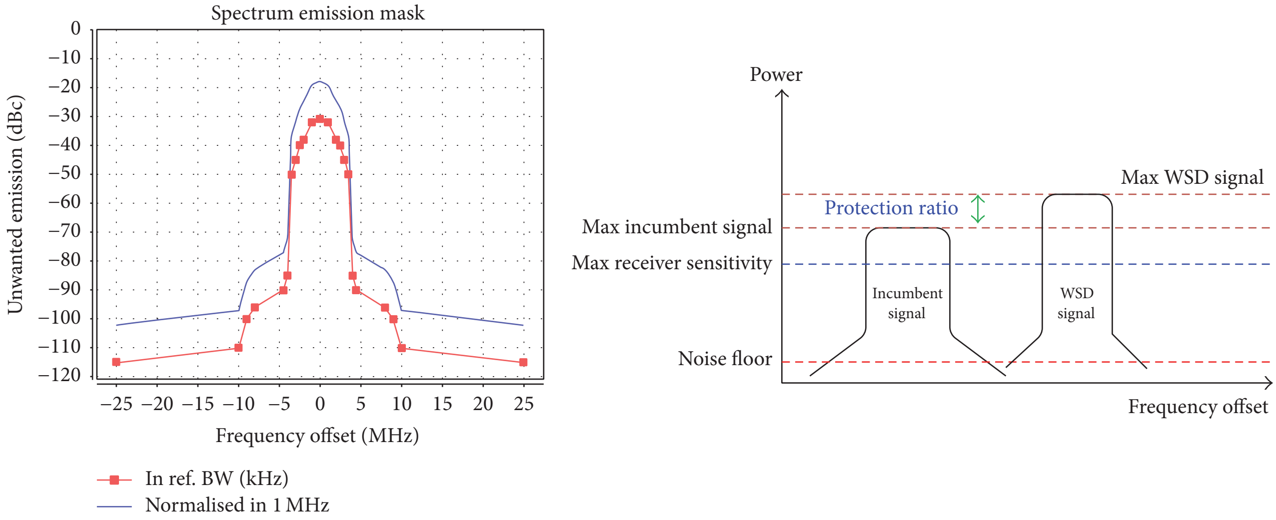
(i) *Simplicity*: once the regulator has provided the relevant technical information about incumbent networks and the framework guideline to the qualified private GLSD operators, there is no requirement for a regulator-controlled *reference GLSD* to perform baseline calculations for determining TVWS availability and corresponding WSD transmit power limits. As such, there is no ambiguity about how operators can implement the DSM framework. This lightly applied DSM policy enforcement is particularly suitable for deployment in the developing world environment, where weak government institutional-frameworks are prevalent coupled with a lack of institutional capacity.

The key disadvantage is as follows:

(i) *Reduced capability to enforce and monitor ruleset implementation*: the main drawback of this regime is reduced ability for the regulator to enforce and monitor the ruleset implementation. This is largely attributable to absence of a *reference GLSD*.

4. Key Technical Parameters to Consider in DSM Frameworks

4.1. WSD Spectral Emission Mask. Spectral emission masks are used to define the maximum permitted out-of-band (OOB) emissions for operation of secondary systems (such as WSDs) in the RF band of interest [29]. To ensure the protection of terrestrial broadcast TV receivers from potential harmful interference that might be generated by WSDs, spectrum regulators are required to prescribe WSD emission



(a) WSD spectral emission mask

(b) WSD-incumbent protection ratio

Figure 4: (a) Typical WSD spectral emission mask: key factors in determination of mask for a particular frequency band are the total emission power of a WSD in dBc and the reference bandwidth. In this example, the inner curve (also known as actual curve) is referenced at a given bandwidth of 50 kHz. The outer curve is normalised at a reference bandwidth of 1 MHz. This curve is used in the actual OOB calculation of WSDs as it provides a buffer offset from the (actual) inner curve. (b) Illustration of protection ratio (PR) between WSD transmit signal and incumbent received signal.

requirements with respect to cochannel and adjacent channels specifically for various channel bandwidths. Figure 4(a) depicts a typical WSD emission mask.

4.2. WSD-Primary System Protection Ratio. Protection ratios PRs are defined as the difference of primary system signal power and the secondary system at the primary system receiving antenna point of failure [30]. In contrast, blocking masks define the level at which a receiver rejects unwanted OOB emissions before the point of failure. Figure 4(b) depicts a WSD-primary system protection ratio.

4.3. Radio Propagation and Channel Model. Radio propagation and channel models are crucial components of the regulatory framework. They are used for performance evaluation of the behavioural patterns of complex wireless systems reflecting actual on-the-ground conditions [31]. Regulators are expected to prescribe preferred radio propagation model(s) for each reference planning geometry of spectrum sharing scenario.

4.4. Coexistence Calculation Methodology. The following are commonly used coexistence calculation methodologies (also known as *Algorithms*) utilised in geolocation based DSM frameworks [32]:

Notations used in Algorithms 1–3 are as follows:

D_c is signal coverage of incumbent station.

D_{prt} is the protected distance from the edge of incumbent coverage contour.

HAAT is height above average terrain of the antenna.

D_{prt}: adjc, coc is the protected zone from the cochannel and adjacent channel of the incumbent contours.

CINR is the carrier to interference noise ratio.

$\text{PR}_{\text{WSD-TV}}$ is the WSD-to-TV protection ratio.

E_u is the wanted field strength.

q is the location probability.

UHF is Ultra High Frequency.

VHF is Very High Frequency.

WSD is White Space Device.

4.4.1. Vectorised Approach. Typically, this is a Minimum Coupling Loss (MCL) based methodology that largely relies on rigid rules of separation distance vectors to each grade of terrestrial broadcast TV contour in order to determine the availability of TVWS channels [9, 21]. The separation distance vector calculations are performed using statistical curves of wanted and interference field strengths, respectively. Algorithm 1 describes key parts of the vectorised approach.

4.4.2. CNIR Threshold Approach. This is basically an enhanced MCL-based methodology; the approach compares the received signal power level within a small geographical area of interest against the minimum CINR threshold to determine if a channel is occupied [18, 33]. The process is repeated across all small areas. Algorithm 2 further describes the CNIR threshold approach.

4.4.3. Degradation of Location Probability Approach. This is a statistical approach that utilises a Monte Carlo (MC) simulations methodology to determine the degradation in

```
Require: Regulatory rules are followed
Ensure: list All data at hand
(1) procedure MCL
(2)   for each technology types of incumbent stations do
(3)     select appropriate propagation model to derive Incumbent station coverage $D_c$ per each contour grade in the
        geographical area of interest
(4)   for each class of WSD (transmit power, antenna-HAAT) do
(5)     select appropriate propagation model to perform calculation of protected distance $D_{\text{prt}}$ from the edge of each
        incumbent coverage contour grade
(6)     establish incumbent protected zone from adjacent and co-channels $D_{\text{prt}}$: adjc, coc as the sum of incumbent coverage
        and protection distances $D_c + D_{\text{prt}}$
(7)   for each test points of interest (WSD geo-location, HAAT and all channels in VHF/UHF) do
(8)     derive and analyse availability of TVWS for co-channel and adjacent channel
(9)     that is, a channel might be available if a WSD is located outside of $D_{\text{prt}}$: adjc, coc
```

Algorithm 1: Vectorised approach.

```
Require: Regulatory rules are followed
Ensure: list All data at hand
(1) procedure EMCL
(2)   for each technology types of incumbent stations do
(3)     select appropriate propagation model to derive the received signal power levels in all channels within a small
        geographical area of interest
(4)   for each channels per small area of interest do
(5)     compare the received signal strength against the minimum CINR threshold
(6)     that is, a channel is occupied if the received signal strength power level is above the minimum CINR threshold,
        otherwise a channel is available
(7)   for each free channels per small area of interest do
(8)     calculate and analyse maximum allowed WSD transmitting power levels based on the $\text{PR}_{\text{WSD-TV}}$ and adjacent channel
        selectivity threshold
```

Algorithm 2: CNIR threshold approach.

location probability of a DTT receiver in small geographical coverage areas (pixels). Any presence of a WSD interfering signal within a pixel reduces the location probability of an incumbent receiver, [34–36]. This degradation is subsequently used to calculate the availability of TV white space channels. Algorithm 3 describes the main parts of the degradation of location probability approach.

5. DSM Frameworks from Leading National Regulatory Authorities

The following sections discuss dominant TVWS-based DSM frameworks from leading NRAs across the world. Table 1 lists the building blocks of a DSM framework.

Table 1: DSM framework building blocks.

id	Component
i	Framework type
ii	GLSD certification
iii	WSD certification
iv	GLSD algorithm
v	WSD <=> GLSD communication protocol
vi	Spectrum sharing model
vii	Interference management protocol
viii	WSD maximum transmit power
ix	WSD categorisation
x	Number of GLSD providers

5.1. Federal Communications Commission TVWS Framework

5.1.1. Rationale. The TVWS framework by the Federal Communications Commission (FCC), the regulator of the USA, is meant to allow opportunistic access to the unused spectrum in the TV bands by unlicensed wireless devices in order to increase the availability of broadband services particularly in rural and underserved areas [12, 20]. This could be achieved while protecting television and other services that operate in the TV bands. TVWS spectrum has superior propagation characteristics that allow signals to reach farther and penetrate human made and natural structures. Moreover, the FCC believes that opportunistic exploitation of TVWS could potentially enable many other innovative applications such as real-time video streaming in home networks and the

```
Require: Regulatory rules are followed
Ensure: list All data at hand
(1) procedure LP
(2)   for each technology types of incumbent stations do
(3)     select appropriate propagation model and perform Monte-Carlo simulations to determine location probability per pixel
        before introduction of an interference signal (in the presence of system noise only)
(4)   for each and for each class of WSD do
(5)     select appropriate propagation model and perform Monte-Carlo simulations to determine location probability per pixel
        after introduction of an interference signal (in the presence of system noise only)
(6)   for each pixels do
(7)     determine maximum permitted degradation or change in location probability that is $\delta q = q_{\text{before}} - q_{\text{after}}$
(8)     therefore permitted change in location probability is set as $\delta q = E_u$ ($E_u$ is usable field strength of wanted signal required
        for achieving a desired signal quality)
(9)   for each test points of interest per channel do
(10)    calculate and analyse maximum allowed WSD transmitting power levels
```

Algorithm 3: Degradation of location probability approach.

deployment of sensors to monitor wide-area power and water grids.

5.1.2. The Regulatory Rules. Regulations governing the operation of unlicensed low-power, low-antenna height television band devices (TVBDs) commonly known as WSDs are defined under Title 47 in the Code of Federal Regulations (CFR), Part 15, Subpart H. The GLSD technical rules are outlined in [12, 20]. The TVWS networks are required to operate without causing harmful interference to receivers of incumbent networks and to accept interference to their receivers. This is achievable through the use of GLSDs to be operated by designated administrators.

(i) *Framework Type*. We categorise the approach as loose coupling (LC).

(ii) *Spectrum Assignment Model*. The framework utilises nonprioritised access, license-exempt spectrum assignment approach.

(iii) *Number of GLSD Operators*. The framework allows an unlimited number of GLSD administrators.

5.1.3. Roles of GLSDs. The framework requires certified GLSD administrators to utilise the prescribed algorithm to perform necessary calculations for protecting incumbent services. Moreover, the framework requires GLSDs to avail the list of unused TVWS channels and time validity to the interrogating Fixed or Mode II WSDs at any particular time and location. Additionally, the framework requires GLSDs to store up to date datasets containing incumbent and WSD technical information.

5.1.4. GLSD Algorithm. The framework prescribes an algorithmic guideline for performing the necessary calculation required to protect incumbent services. Fundamentally, the algorithm follows a vectorised approach by utilising the provided table of separation contour distances and their corresponding transmit power levels that WSDs could use in the vicinity of incumbent service areas. Coverage contour distances are calculated using the $F(50, 50)$ and $F(50, 90)$ statistical curves for analogue and digital TV broadcasting technologies, respectively. Separation contour distances are calculated using the $F(50, 10)$ statistical curves. Additionally, the separation contour distances of 1 km or less and antenna heights of less than 10 m are calculated using TM-91 method [37]. Separation contours for protecting different incumbent services are illustrated in Figure 5. Extract from the FCC calculated separation distance contours is illustrated in Table 2 [20].

Table 2: Extract of WSDs antenna height above average terrain (HAAT) versus required separation distance from the incumbents (analogue and digital TV) protected contours [20].

WSD ant HAAT (m)	Coch sep	Adj ch sep
Less than 3	4.3 km	0.4 km
3 less than 10	7.3 km	0.7 km
10 less than 30	11.1 km	1.2 km
200–250	31.2 km	2.4 km

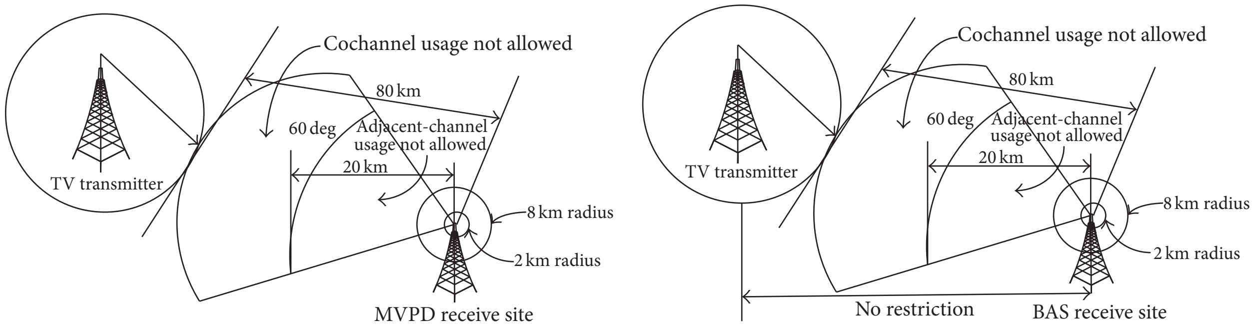
5.1.5. Certification of GLSD Administrators. Entities wishing to become a designated GLSD administrator are required to undergo a 45-day public trial as part of the qualification process. During the trial the candidate GLSD must demonstrate the capability to implement the framework rules to the satisfaction of FCC. Such capabilities include the following:

(i) Providing protection to all incumbents as required by the framework, including protecting primary services located in the border areas of neighbouring countries.

(ii) Proper application of the framework's algorithm in the calculations.

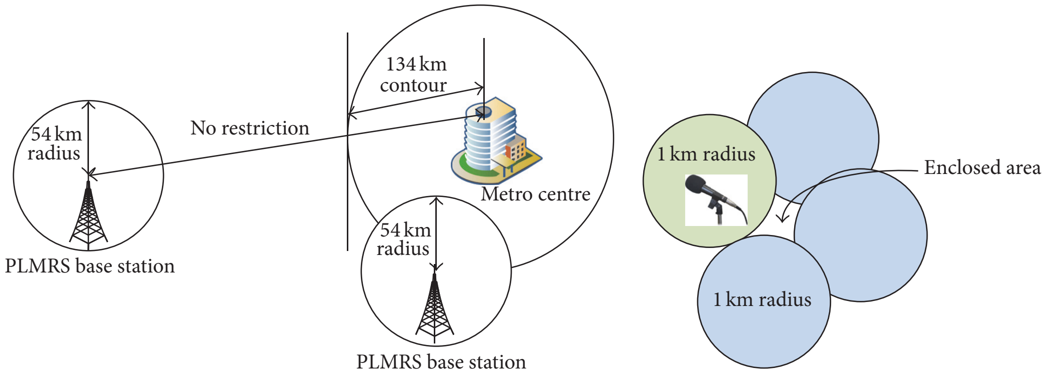
(iii) Extracting the necessary incumbent dataset and its corresponding updates from the regulators' central repository.

(iv) Providing adequate security and ensuring the integrity of the incumbent dataset.



(a) Multichannel Video Programming Distributor contours

(b) Broadcast Auxiliary Services contours



(c) Private Land Mobile Radio Services contours

(d) Programme-Making and Special Events contours

Figure 5: Illustration on application of various incumbent separation contours based on FCC algorithm [21].

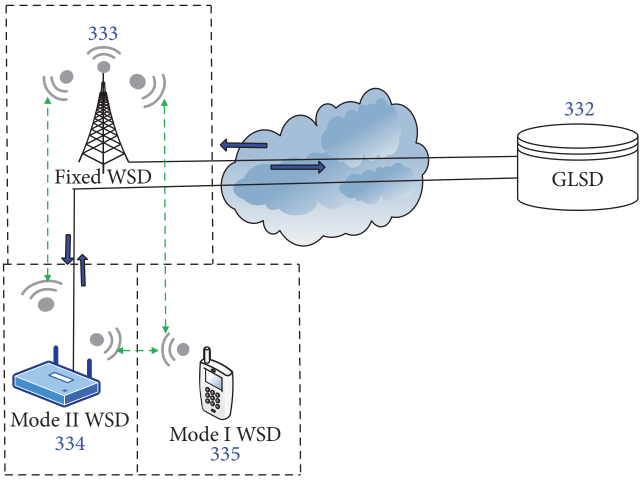


Figure 6: Categorisation of WSDs under the FCC TVWS framework.

5.1.6. WSD Categorisation. The FCC framework does not provide any distinction between manually configurable WSDs (M-CWSDs) and automatically configurable WSDs (A-CWSDs). Moreover, the framework allows operation of spectrum sensing WSDs. Categorisation of devices is further illustrated in Figure 6.

Description of Figure 6 is as follows:

(i) *333*. Fixed: this type of WSD must incorporate the following capabilities: (i) geolocation and (ii) access to allow the device to contact the GLSD and query for TVWS channels availability at its location.

(ii) *334*. Portable/personal Mode II: this type of WSD must incorporate similar capabilities as Fixed WSD (i) geolocation and (ii) access to allow the device to contact the GLSD and query for TVWS channels availability at its location.

(iii) *335*. Personal/portable Mode I: this type of WSD is not required to have geolocation or access to GLSD capabilities. Instead, the device is required to obtain a list of available TVWS channels and corresponding Operational Parameters from either Fixed or Mode II WSDs through an air interface.

5.1.7. Regulatory Power Limits and Protection Ratios. The maximum transmit EIRP for Fixed WSDs is limited at 30 dBm. However, such devices are allowed to utilise a 6 dBi antenna gain to make a maximum EIRP output of 36 dBm. Currently, Fixed WSDs are not allowed to operate adjacency of occupied TV channels. Portable and personal WSDs are capped at 20 dBm and 16 dBm, respectively, when

Table 3: Typical regulatory power limits for different categories of WSDs [20].

WSD catgr	Pwr lim	PSD lim	Adj ch lim
Fixed	30 dBm	12.6 dBm	−42.8 dBm
Portable	20 dBm	2.6 dBm	−52.8 dBm
Portable (adj ch)	16 dBm	−1.4 dBm	−56.8 dBm
Sensing	17 dBm	−0.4 dBm	−55.8 dBm

operating adjacency of occupied TV channel. The $PR_{\text{WSD-TV}}$ for cochannel is 23 dB and that of adjacent channel is −33 dB. The maximum allowed antenna height of Fixed WSDs is 30 m AGL or 250 m HAAT. The framework considers 14 dB front-to-back ratio (FBR) to compensate possible WSD antenna polarisation discrimination. Table 3 illustrates this further.

5.1.8. Certification of White Space Devices. Procedure for certification of WSDs is divided into the following two parts:

(i) Testing capability of WSD to correctly contact the designated GLSD and request for the available TVWS channels and corresponding Operational Parameters (OPs). Tests include, but are not limited to, (i) WSDs with direct connection to the Internet (base station); (ii) WSDs without direct connection to the Internet (CPEs); (iii) WSD operation within given geographical boundaries; (iv) WSD antenna height restrictions; (v) Unique identification of WSD; and (vi) ownership information of WSD.

(ii) Testing capability of WSD to correctly operate within given emission limits without causing interference to incumbents and other users of the band. Tests include, but are not limited to, (i) maximum conducting power output of WSD; (ii) power spectral density of WSD; (iii) adjacent channel power of WSD; (iv) radiated spurious emission beyond TV bands; and (v) AC power line conducted emission limits.

The above tests are performed by an accredited service provider recognised by the regulator. Models of WSDs that comply with the test specifications are certified and allowed to operate within the TVWS framework.

5.1.9. WSD <=> GLSD Communication Protocol and Security. Designated administrators are required to provide a layer of interaction between GLSDs and WSDs. However, the framework does not mention any specific communication protocol to be used. Moreover, such layer of interaction must enforce the following security measures:

(i) Prevention of unauthorised access to the system.

(ii) Maintaining integrity of client data to prevent manipulation, corruption, unauthorised input, and extraction.

5.1.10. Interference Management Protocol. The framework does not clearly define the primary responsibilities of the GLSD administrator within the interference management protocol.

5.2. Office of Communications TVWS Framework

5.2.1. Rationale. The Office of Communication (Ofcom), the regulator of the UK, took into consideration the following major justifications with regard to the operation of WSD in the UHF broadcast TV band (470 MHz–790 MHz) [38]:

(i) Improving utilisation efficiency of the RF spectrum.

(ii) Removing barriers to innovation.

(iii) Access to TVWS being a stepping stone for future opportunistic utilisation of other bands to meet the ever-increasing demand on spectra for data applications.

5.2.2. The Regulatory Rules. The operation of WSDs in the UK under Ofcom TVWS framework is governed by the wireless telegraphy (White Space Devices) (Exemption) regulations 2015 of December 2015 [13].

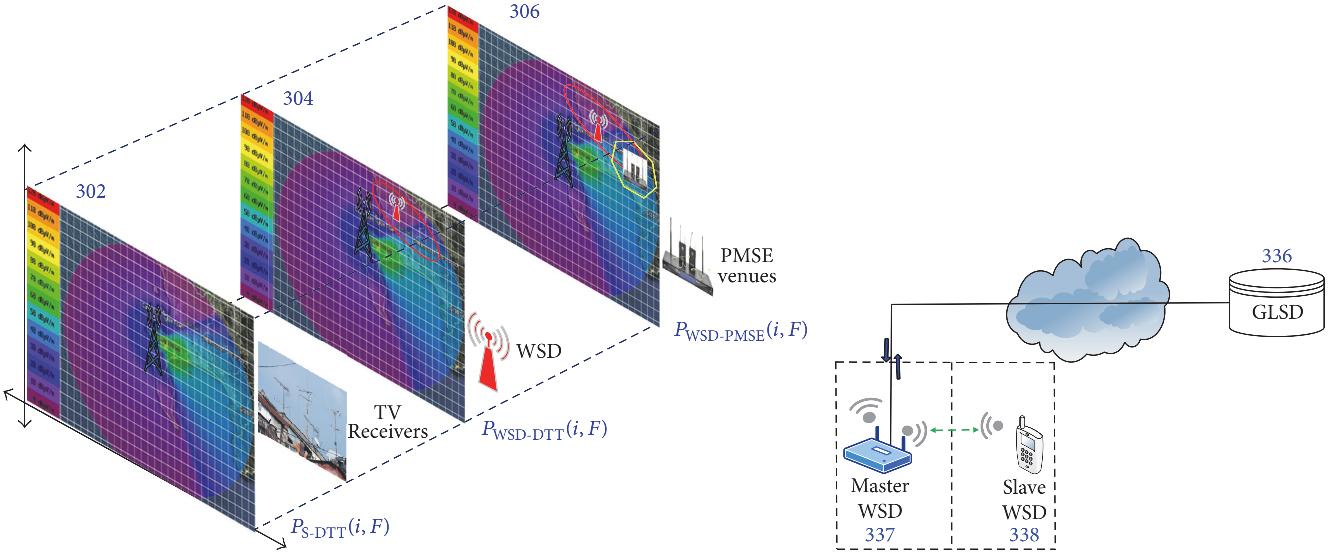
(i) *Framework Type*. The approach is categorised as tight coupling (TC).

(ii) *Spectrum Assignment Model*. The framework utilises the nonprioritised access, license-exempt spectrum assignment approach.

(iii) *Number of GLSD Administrators*. The framework allows multiple GLSD providers.

5.2.3. Roles of GLSDs. Unlike in the FCC approach where approved GLSD administrators are required to perform coexistence calculations with respect to protecting TV services and availability of TVWS channels, in the Ofcom framework such calculations are performed by the reference GLSD operated by Ofcom. Hence, the baseline TVWS availability dataset with corresponding power levels for each channel per pixel within the UK Ordinance Survey National Grid Reference (OS NGR) is generated and forwarded to secondary GLSDs operated by qualified providers. Secondary GLSDs in turn avail this information to master WSDs based on their query location. Moreover, qualified providers are required to perform coexistence calculations with respect to the protection of PMSEs, including incorporating periodic updates in the baseline dataset received from Ofcom.

5.2.4. GLSD Algorithm. The Ofcom framework utilises the degradation of location probability methodology Algorithm 3. In this approach, there are no separation contour distances to limit WSDs from operating close to primary services. That is, WSDs operations are allowed near TV receivers. Instead, a constraint is placed on the in-block EIRP of the WSDs as determined by the GLSD for each TVWS channel per pixel (typical size is 100 m × 100 m square) [36]. Additionally, PMSEs are protected at a pixel resolution of (10 m × 10 m square). The chief benefit of this algorithm is the provision allowing WSDs to operate at higher EIRPs in areas where there is strong primary service field strength. Key steps of the Ofcom approach are depicted in Figure 7.



(a) Ofcom TVWS calculation steps

(b) Ofcom WSD categorisation

Figure 7: (a) Illustration of Ofcom TVWS algorithm. (b) Illustration of the WSD ecosystem in the Ofcom TVWS framework.

The Ofcom calculation steps in Figure 7(a) are numerically explained in the following summary:

(i) *302*: Ofcom utilises the UK Planning Model (UKPM) to predict the nation-wide DTT received power $P_{\text{S-DTT}}(i, F)$ in dBm/8 MHz for each 100 m × 100 m square pixel. This results in the degradation of the location probability map with respect to DTT self-interference.

(ii) *304*: next, the WSD is introduced within DTT coverage area and calculations to determine availability of TVWS channels and corresponding maximum allowed WSD in-block power $P_{\text{WSD-DTT}}(i, F)$ in dBm/8 MHz per (100 m × 100 m) square pixel are performed. This results in a degradation of the location probability map with respect to WSD interference into DTT.

(iii) *306*: finally, the PMSE is introduced within a candidate DTT coverage area and calculations are performed to determine the maximum allowed WSD in-block power spectral density $P_{\text{PMSE-DTT}}(i, F)$ in dBm/100 kHz with respect to PMSE per channel in a resolution of (10 m × 10 m) pixel. This results in the degradation of the location probability map with respect to WSD interference into DTT and PMSE.

5.2.5. Certification of GLSD Providers. Under the Ofcom framework, entities wishing to become designated GLSD providers are required to undergo a rigorous qualification process which includes offline and online examinations by Ofcom's technical team. Candidate GLSD providers must demonstrate the capability to implement framework rules to the satisfaction of Ofcom. Such capabilities include the following:

(i) Correct implementation of the algorithms provided by Ofcom.

(ii) Correct implementation of the White Space Information Platform (WSIP) interface that allows Ofcom to monitor secondary GLSDs as per specifications prescribed by Ofcom.

(iii) Ability to retrieve and apply periodic updates from Ofcom within the required time-scales.

(iv) Ability to apply necessary changes to the algorithms within the prescribed time as required by Ofcom.

(v) Ability to communicate with master WSDs.

Subsequently, the qualified provider's GLSD is placed on the Ofcom discoverable web-list to be accessed by master WSDs.

5.2.6. Categories of WSD. The Ofcom TVWS framework draws a strict distinction between manually configurable WSDs (M-CWSDs) and automatically configurable WSDs (A-CWSDs). There is no provision for WSD capable of autonomous sensing. Figure 7(b) illustrates the device ecosystem in the Ofcom TVWS framework. The aforementioned WSD categorisation is numerically described as follows:

(i) *337*: the master WSD is allowed to contact the GLSD using an Internet connection and query for available TVWS channels and their corresponding Operational Parameters at its location.

(ii) *338*: the slave WSD is not allowed to query the GLSD. Instead, it is required to obtain list of available TVWS channels and their corresponding Operational Parameters from Master WSD via an air interface.

Additionally, both categories of WSDs are grouped into two types:

(i) *Type A*: this is a fixed WSD which may has an in-built, dedicated, or external antenna.

(ii) *Type B*: this is a mobile or nomadic WSD which has an in-built or a dedicated antenna.

5.2.7. Regulatory Power Limits and Protection Ratios. The EIRP outputs for the master WSD are between min −60 dBm and max +36 dBm/100 MHz and 16.97 dBm/100 kHz with respect to protection of DTT and PMSE respectively. The framework utilises a value of −999 to indicate a particular channel which is not available. The $\mathrm{PR}_{\mathrm{WSD\text{-}TV}}$ for cochannel is 17 dB plus 9 dB link margin. However, values for adjacent channels vary with respect to five different emission classes of WSDs based on Harmonised standard EN 301 598 developed by the European Telecommunications Standardisation Institute (ETSI) [39]. The framework prescribes six WSD antenna heights above ground level (AGL) (1.5 m, 5 m, 10 m, 15 m, 20 m, and 30 m). There is no consideration for compensation of possible WSD antenna polarisation discrimination.

5.2.8. Certification of WSD. The WSD certification procedure follows the directive 1999/5/EC on Radio Equipment and Telecommunications Terminal Equipment and the mutual recognition of their conformity (commonly known as RTTE directive). The Harmonised ETSI standard EN 301 598 is used by the Original Equipment Manufacturers (OEMs) to perform conformity tests of the RTTE directive [39].

5.2.9. WSD <=> GLSD Communication Protocol and Security. The framework expects the designated GLSD provider to provide a layer of interaction between GLSDs and WSDs. However, there is no prescription of any preferred communication protocol to be used. Moreover, such layer of interaction must enforce the following security measures:

(i) Prevention of unauthorised access to the system.

(ii) Maintenance of the integrity of client data to prevent manipulation, corruption, unauthorised input, and extraction.

5.2.10. Interference Management Protocol. The Ofcom TVWS framework places a tight, joint interference management function between Ofcom and the designated GLSD provider. This is largely made possible through a White Space Information Platform (WSIP) interface that allows interference management teams to automatically instruct master WSD to reduce or completely cease transmission. Additionally, Ofcom possesses the capability to remove a noncomplying GLSD from a device discoverable web-list.

5.3. DSM Frameworks Proposed by Other Regulators and Nongovernmental Entities. This section highlights TVWS frameworks proposed by other national regulators and nongovernmental entities. These frameworks have minor variations from the ones discussed above.

(i) *Industry Canada (IC) TVWS Framework [14]*. The IC framework largely harmonises with that of the FCC. However, there are minor variations related to the protection of Remote Rural Broadband System (RRBS) stations that were historically licensed to provide broadband services in rural areas utilising the unused TV channels. In this regard, RRBS is a unique case since it is found only in Canada.

(ii) *Info-Communications Development Authority (iDA) of Singapore TVWS Framework [40]*. In principle, the proposed TVWS framework of the iDA is technically identical to that of the FCC with the following key variations: (i) the iDA proposes the use of the Okumura HATA radio propagation model in the coexistence calculations; and (ii) the iDA considers the designation of two High Priority Channels (HPCs) per GLSD administrator to be made exclusively available to users wishing pay for a prioritised TVWS service.

(iii) *DSA Alliance TVWS Framework [41]*. The DSA alliance proposes the use of Algorithm 2 (i.e., the CNIR threshold). Additionally, the framework considers a maximum EIRP limit of 10 W for Fixed WSD. Further, the proposal considers the use of point-to-point Longley-Rice radio propagation model in the calculations.

6. Case Study: Evaluation of DSM Frameworks

We evaluate Dynamic Spectrum Management (DSM) policy frameworks by utilising the Multicriteria Decision Analysis (MCDA) approach, [28, 42, 43]. The MCDA is an umbrella term for approaches and techniques used for solving or evaluating complex multistakeholder decision-making problems with multicriteria or multiobjectives and could potentially include qualitative or quantitative aspects. The evaluation approach of DSM frameworks includes the following key steps:

(i) Identifying the problem to be addressed.

(ii) Identifying the alternatives.

(iii) Identifying the criteria.

(iv) Scoring the alternatives in relation to the criteria.

(v) Weighing the scores according to the weighs assigned to the criteria.

(vi) Evaluating the alternatives.

(vii) Ranking the alternatives and making a recommendation.

In this evaluation we utilise the Preference Ranking Organisation Method for the Enrichment Evaluation (PROMETHEE) technique [44]. PROMETHEE method is chosen because it allows decision-makers to evaluate incompatible alternatives.

6.1. Identifying Criteria. The DSM framework building blocks listed in Table 1 were identified as evaluation criteria.

Table 4: System model and input parameters for evaluation of FCC and Ofcom DSM frameworks.

Criteria	W_k	$f(X)$	Obj	$W_{k\text{FCC}}$	$W_{k\text{Ofcom}}$
Frmwk type	2.2	Min	Reglt	2	1
GLSD cert	1	Min	Reglt	2	3
WSD cert	1.4	Min	Regult	3	1
GLSD algo	2.6	Min	Techn	3	2
Protocol	3.2	Max	Techn	4	2
Share model	2	Max	Polcy	2	2
RFI magmnt	1	Min	Reglt	3	2
WSD pwr	1.8	Max	Reglt	2	2
WSD catg	3.2	Min	Reglt	2	3
GLSD admin	6.2	Max	Polcy	1	1
Opex	2.4	Min	Econ	2	4

6.1.1. Weighting of Criteria. We asked a group of 25 respondents that included Small and Medium Enterprises (SMEs) ICT entrepreneurs, senior telecommunications engineers, and policy experts to provide weights (1 to 7) on each of the listed criterion with 1 being the highest weight and 7 the lowest. The average weights are used in this evaluation. The criteria normalisation is obtained as follows:

$$\sum_{k=1}^{n} W_k = 1, \tag{2}$$

where W_k is the criteria weight.

6.2. Identifying Objectives. This evaluation utilises multiple objectives across different disciplines, including regulatory, policy, technical, and socioeconomic. We align each criterion with the relevant objective.

6.3. Weighting of Alternatives. Based on the in-depth description of each alternative (i.e., the FCC and Ofcom DSM frameworks in Sections 5.1 and 5.2, resp.), we rated the two frameworks (alternatives) (1 to 7) against the criteria in order to obtain their respective weights.

A complete list of inputs for evaluation model is provided in Table 4, for which the mathematical function could be to minimise or maximise the various options.

Consider an evaluation scenario where there are criteria with variable C_k with preference function F_k and assigned weights W_k. We derive the pairwise preference comparison function for x over y as follows:

$$\pi(x, y) = \sum_{k=1}^{n} W_k F_k(x, y), \tag{3}$$

where π is the preference index.

7. Interpretation of Evaluation Results

7.1. Preference Comparison. The comparison is conducted among preference functions characterised by their flow types, namely, (i) the entering flow, (ii) the leaving flow, and (iii) the net flow [44].

The entering flow which is used to measure the weakness of action y relative to other actions, this is given by

$$\Phi^{-}(y) = \frac{1}{n-1}\sum_{k=1}^{n} \pi(y, x), \tag{4}$$

where $\Phi^{-}(y)$ is the entering preference index.

Similarly the leaving flow which is used to measure the strength of action x is given by

$$\Phi^{+}(x) = \frac{1}{n-1}\sum_{k=1}^{n} \pi(x, y), \tag{5}$$

where $\Phi^{+}(x)$ is the leaving preference index.

The net flow is determined as the balance of the between the entering flow and the leaving flow as follows:

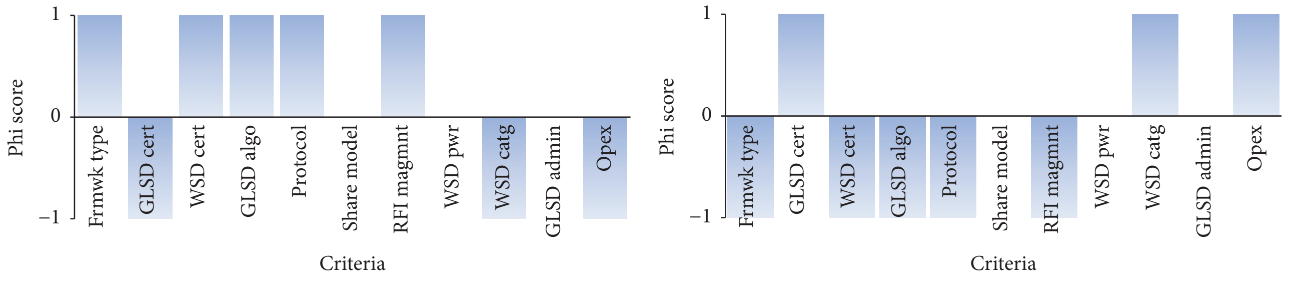
$$\Phi(x) = \frac{1}{n-1}\sum_{k=1}^{n} \left(\pi(x, y) - \pi(y, x)\right). \tag{6}$$

Hence, the equilibrium of (4) and (5) can be put into a compact form as follows:

$$= \Phi^{+}(x) - \Phi^{-}(x). \tag{7}$$

Figure 8 displays a comparison between the FCC and Ofcom DSM frameworks based on the criteria set out in Table 4. A positive preference flow value translates to a strongly preferred option, while negative flow value suggests a weaker preferred option. The results in Figure 8(a) suggest that the Ofcom DSM framework performs better than the FCC DSM framework in five criteria, namely, (i) the DSM Framework type; (ii) the WSD certification; (iii) the coexistence algorithm; (iv) the WSD-GLSD protocol; and (v) the interference management protocol.

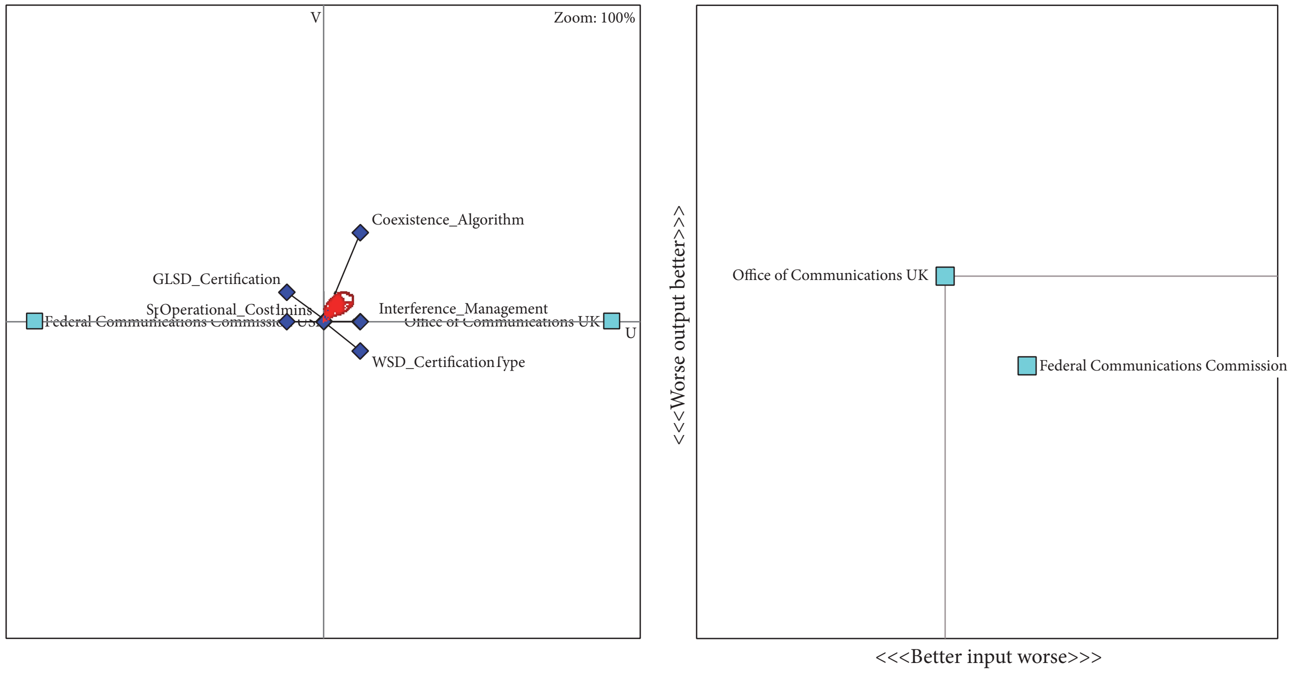
However, the Ofcom DSM framework performed poorly in the following criteria: (i) the GLSD certification; (ii) the WSD categories; and (iii) the operational cost. Moreover, the results in Figure 8(b) suggest that the FCC DSM framework performs better in the following three criteria: (i) the GLSD certification; (ii) the WSD categories; and (iii) the operational cost. The FCC framework performed poorly in the following criteria: (i) the DSM framework type; (ii) the WSD certification; (iii) the coexistence algorithm; (iv) the WSD-GLSD protocol; and (v) the interference management protocol.



(a)

(b)

Figure 8: (a) The overall evaluation of the Ofcom DSM framework: the resulting Φ score of 0.1407 is an indication of how well the preferred framework compared to the FCC approach. (b) The overall evaluation of the FCC DSM framework: the resulting Φ score of −0.1407 suggests that the framework is weakly preferred compared to the Ofcom approach.



(a) GAIA sensitivity

(b) Preference efficiency

Figure 9: (a) Sensitivity analysis suggests that the decision-makers were highly influenced by the coexistence algorithm, the interference management protocol, and the WSD certification criteria in the Ofcom DSM framework. This is confirmed by the position of the so-called *decision-makers' brain* which firmly lies on the upper part of the decision axis in the Ofcom side. (b) The preference efficiency diagram confirms that Ofcom DSM framework dominates the FCC one as it is located on the higher side of the diagram towards the *better* direction.

7.2. Sensitivity Analysis. Figure 9 presents a sensitivity analysis with respect to weights during the decision-making process.

Generally speaking, the results in Figure 9(a) suggest that the decision in favour of the Ofcom framework is *stable* since the ellipse *decision-makers' brain* lies entirely on one side of the decision plane, that is, the Ofcom side. Hence, the results suggest that this decision largely gravitates around the following criteria that are close to each other: coexistence algorithm and interference management. Figure 9(b) further confirms the efficiency of the decision made as the Ofcom DSM framework clearly appears to be positioned on the upper side over the FCC DSM framework.

Figure 10 depicts a typical interference management protocol for the DSM framework. The protocol details eight key steps that must be observed by stakeholders in order to mitigate any potential interference to the primary network caused by the secondary network.

8. A Proposed Sustainable DSM Framework

8.1. Definition of a Sustainable DSM Framework

Sustainable DSM Framework. We define a sustainable DSM framework as one that promotes efficient utilisation of the RF spectrum to achieve socioeconomic development objectives

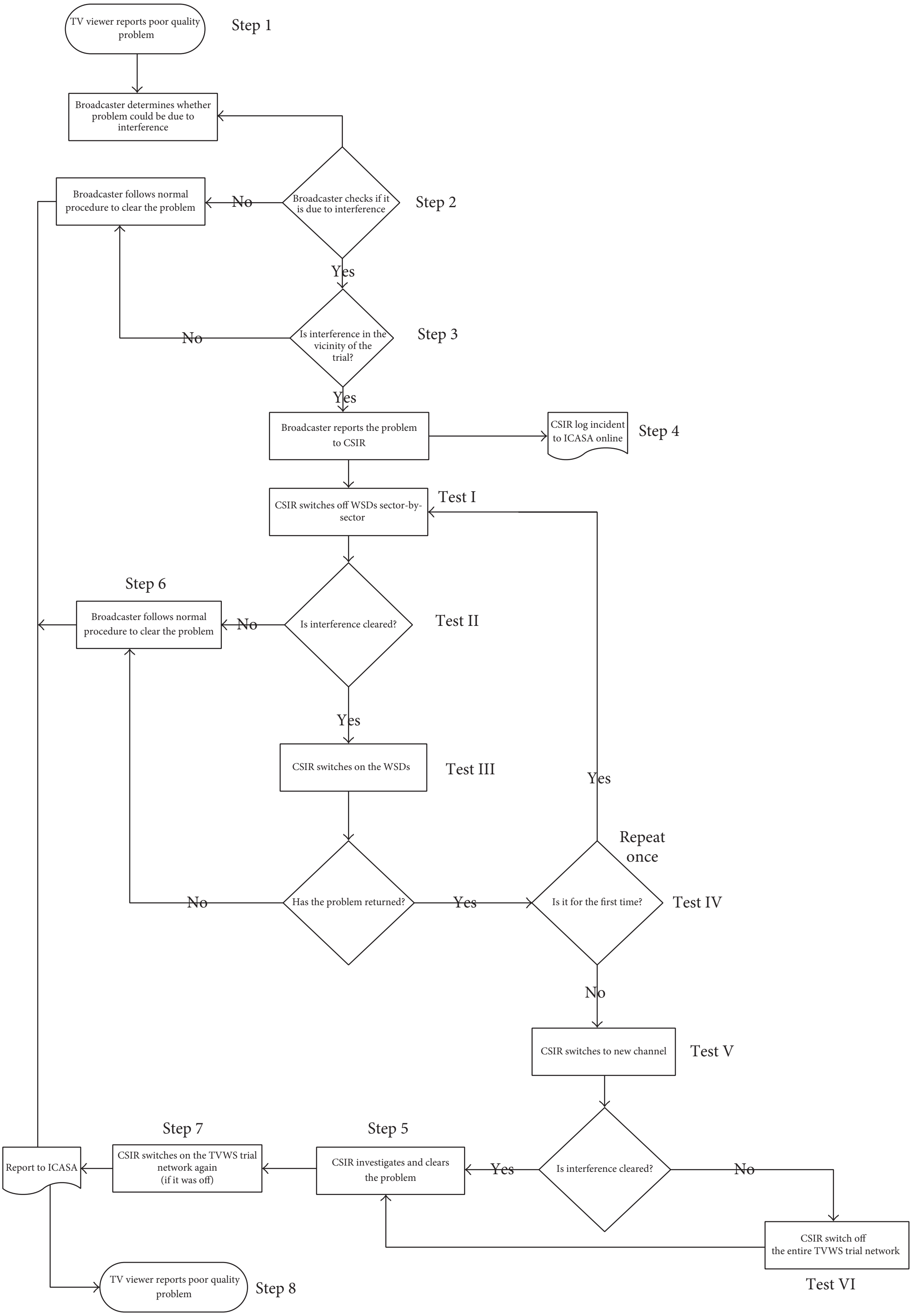


Figure 10: Typical interference management protocol flow diagram used in TVWS trials in South Africa [22]. These trials were meant to assist the Independent Communications Authority of South Africa (ICASA) to establish the viability of DSA technologies and to formulate relevant technical regulations for South Africa [23].

in resource constrained environments relevant to the context of developing countries.

8.2. Sustainable DSM Framework Proposition. We finally propose a sustainable DSM framework relevant to the context of developing countries by (i) introducing new features that are not found in either of the evaluated frameworks and (ii) borrowing salient features from the two evaluated DSM frameworks (i.e., FCC and Ofcom):

(i) *DSM Framework Type*. We propose the tight-coupled framework approach used by Ofcom to empower the national regulator with a firm control of the process.

(ii) *Spectrum Sharing Model*. We prefer the lightly managed license-exempt approach used by both the Ofcom and FCC. Notably, Stucke [45] proposed a four-level spectrum assignment regime that would include time-dependant spectrum usage fee. However, we argue that this approach is not suitable for promoting new entrants and growth of SMEs, as these often fall into the previously disadvantaged population in developing countries.

(iii) *WSD Certification*. We prefer the approach used by Ofcom based on ETSI European Harmonised standard since Africa belongs to the same ITU region 1.

(iv) *GLSD Certification*. We prefer the simpler approach used by the FCC.

(v) *Interference Management Protocol*. We propose a robust interference management protocol relevant to the context of the developing countries (see Figure 10).

(vi) *WSD-GLSD Communication Protocol*. We propose utilising the IETF standard Protocol to Access White Space (PAWS) databases [46], unlike the FCC and Ofcom approaches.

(vii) *Categories of WSD*. We propose modifying the approach used by the FCC by introducing additional WSD classes in the system.

(viii) *Maximum WSD Transmit Power*. We propose higher WSD transmit power levels particularity in rural areas, than those proposed by the FCC and Ofcom.

(ix) *Number of GLSD Administrators*. We prefer the multiple GLSD providers approach which is similar to both the FCC and Ofcom approaches.

(x) *Coexistence Algorithm*. We prefer to modify/hybridise the approach used by the FCC by introducing the ITU statistical model [47] instead of the R-6602 propagation curves [48]. This approach provides sufficient protection to the primary users in both grade B and grade C coverage contours. For example, viewers in marginal areas who cannot receive grade B quality can still be protected under grade C contours. In developing countries, the majority of rural TV viewers are located in fringe reception areas and make do with fairly poor reception quality or do their best to improve their reception by raising their mast height beyond the norm. We further modify the FCC approach by allowing operation of fixed WSD adjacent to an active TV channel; we have validated this proposal in [22], which was duly acknowledged by the FCC in their recent proposed rule-making [12]. The Ofcom approach, despite it robustness, is not preferred because there is a lack of reliable national dwelling address system that corresponds with the location TV license holders. In many developing countries it is normal to find several TV license holders living in one house. This problem could inhibit the process of identifying the location of TV receivers to be protected. Additionally, this approach involves massive countrywide pixel-by-pixel calculations which requires higher computing resources, which thus increases operational costs. However, we adopt incumbent receiver protection ratios used by Ofcom since they harmonise with ITU region 1 to which Africa belongs.

9. Conclusion

This article has proposed an efficient approach to enable formulation of technical spectrum management regulatory policy. The article presented a case study evaluation of dominant GLSD-based DSM frameworks preferred by leading and influential National Regulatory Authorities (NRAs) with the aid of Multicriteria Decision Analysis (MCDA) techniques. Finally, the authors proposed a sustainable DSM framework that utilises a simplified lightly managed license-exempt approach which is critical to allow new entrants and spur the creation of knowledge-based industries in the context of developing countries. These findings have been contributed to the discussion document towards a DSA regulatory framework prepared by the Independent Communications Authority of South Africa (ICASA). The proposed approach is suitable for the formulation of technical regulatory frameworks for enabling futuristic radio technologies such as those envisaged in 5G networks.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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