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TIEROE: A Multidimensional Governance Framework for Inclusive Radio Frequency Spectrum Assignment in Developing Economies

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Abstract

Radio frequency (RF) spectrum has emerged as a strategic public resource underpinning digital transformation, broadband connectivity, artificial intelligence (AI), Internet of Things (IoT) ecosystems, cloud computing, and next-generation wireless communications. As governments increasingly pursue digital economy objectives, spectrum governance has evolved from a purely technical regulatory function into a critical policy instrument shaping innovation, competition, economic development, and digital inclusion. Despite the widespread adoption of auction-based spectrum assignment mechanisms, concerns persist regarding their ability to balance economic efficiency with broader public-interest objectives, particularly within developing economies characterized by persistent digital inequalities and unequal market participation. The existing spectrum governance literature remains fragmented across technology adoption, resource capability, digital inclusion, and regulatory perspectives, providing limited guidance on how regulators can simultaneously promote efficiency, affordability, competition, equity, and universal connectivity. This study develops the Technology–Inclusion–Equity–Resource Capability–Organisation–Environment (TIEROE) framework. The TIEROE framework serves as a conceptual governance model and diagnostic tool intended to assist policymakers and regulators in the design, evaluation, and comparison of spectrum assignment mechanisms across multiple dimensions. A qualitative research design was adopted, incorporating a systematic literature review, analysis of policy and regulatory documents, and an international comparative assessment of spectrum governance practices. The findings reveal that effective spectrum governance is shaped by six interdependent dimensions: technology, inclusion, equity, resource capability, organisation, and environment. These dimensions collectively influence the extent to which spectrum assignment contributes to digital transformation and sustainable development outcomes. The study contributes to spectrum governance research by integrating previously fragmented theoretical perspectives into a unified framework. It provides policymakers with a practical governance tool for designing inclusive spectrum assignment mechanisms. The TIEROE framework extends existing technology adoption and digital inclusion theories and offers a foundation for future empirical research on spectrum governance within developing economies.

Keywords: radio frequency spectrum; spectrum governance; digital transformation; digital inclusion; spectrum assignment; telecommunications regulation; digital equity; broadband; universal connectivity; TIEROE framework

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1. Introduction

1.1. Background and Context

The RF spectrum plays a vital role as a strategic resource fundamental to modern digital economies. Various technologies such as wireless communications, mobile broadband, satellite systems, Artificial Intelligence (AI), Internet of Things (IoT), cloud computing, autonomous systems, and emerging technologies rely on spectrum access [1–4]. As societies advance digitally, spectrum management has shifted from just a technical engineering task to a key policy area that impacts economic growth, innovation, social inclusion, industrial progress, and national competitiveness [5,6].

The rapid expansion of digital technologies has significantly increased the need for spectrum resources. Global mobile data traffic continues to grow exponentially, driven by widespread smartphone use, rising machine-to-machine communications, broadband expansion, and the deployment of Fifth-Generation (5G) technologies [2,7]. Emerging technologies such as autonomous vehicles, smart manufacturing, digital twins, precision agriculture, and AI-driven applications are expected to impose even greater demands on wireless infrastructure in the coming decade [8,9]. Consequently, governments and regulators face increasing challenges in efficiently allocating limited spectrum resources while supporting innovation, competition, affordability, and universal connectivity.

Historically, spectrum management mainly depended on administrative allocation methods where governments assigned frequencies based on technical considerations and public-interest goals [10]. With telecommunications liberalisation and market reforms, new assignment methods appeared, such as lotteries, first-come-first-served methods, comparative evaluations, and spectrum auctions [11]. Of these models, auctions have become the most common worldwide, mainly because they are seen to enhance allocative efficiency, maintain transparency, and generate public revenue [12].

However, there is growing evidence that auction-based license allocation can cause negative effects. High acquisition costs tend to favour established operators with better financial strength and market power, potentially creating barriers for new entrants and decreasing market diversity [11,13]. Often, these costs are transferred to consumers through increased service prices, undermining goals of affordability and universal access [14]. This issue is especially significant in developing countries, where telecommunications policy has broader roles beyond just economic efficiency.

In this paper, 'spectrum assignment' is used as a broad term to encompass the entire family of award mechanisms through which regulators grant rights to use spectrum. This includes, but is not limited to, auctions (market-based), administrative awards (also known as 'beauty contests'), lotteries, first-come-first-served approaches, and shared-access models like dynamic spectrum access (DSA) and Licensed Shared Access (LSA) [11,15,16].

1.2. Spectrum Governance and Digital Transformation

Digital transformation has become a strategic priority for governments worldwide. International organisations, including the International Telecommunication Union (ITU), the Organisation for Economic Co-operation and Development (OECD), the World Bank, and the United Nations (UN), have emphasised the importance of digital infrastructure for economic growth, social inclusion, public service delivery, and sustainable development [17–19]. In this context, spectrum governance directly affects the availability, affordability, and quality of digital connectivity.

South Africa offers a notable example for examining these issues. Although it has one of Africa's most developed telecommunications sectors, significant gaps still exist in broadband affordability, infrastructure access, digital literacy, and active digital participation [20,21]. The successful completion of South Africa's high-demand spectrum auction marked a

key step forward in deploying 4G and 5G networks. However, concerns persist about affordability, competition, transformation, and the involvement of historically disadvantaged groups [22].

Across the world, similar discussions have sparked growing interest in alternative approaches to spectrum governance. Dynamic spectrum access, spectrum-sharing arrangements, community network licensing, open-access infrastructure models, and licensing conditions aimed at inclusion have emerged as potential ways to encourage wider participation without compromising efficiency goals [23,24]. These developments indicate a growing trend from purely market-based assignment schemes to more inclusive forms of governance.

1.3. Research Gap

Although spectrum governance has attracted increasing scholarly attention, the current body of literature remains dispersed across various theoretical traditions. Frameworks for technology adoption, such as the Technology–Organisation–Environment (TOE) framework, address organisational readiness and innovation adoption but offer only limited treatment of inclusion and equity [25]. Diffusion of Innovation (DoI) theory addresses the spread of technology but provides only limited insight into regulatory governance structures [26]. The Resource-Based View (RBV) emphasises strategic resources and competitive advantage but pays less attention to public-interest objectives and equitable participation [27,28].

Similarly, Universal Service Obligation (USO) frameworks and Digital Inclusion theory emphasise accessibility and participation but provide limited explanation of organisational capability, technological readiness, and resource allocation dynamics [29,30]. Consequently, existing theories explain selected dimensions of spectrum governance but fail to provide an integrated perspective that addresses the complex interactions among technological, organisational, institutional, resource, inclusion, and equity considerations.

The fragmentation of existing theoretical frameworks leaves a substantial gap in understanding how regulators can effectively balance objectives such as efficiency, competition, affordability, inclusion, equity, and universal connectivity in contemporary spectrum-assignment environments. This study is structured around the following research questions (RQs):

RQ1: To what extent do existing RF spectrum assignment models promote competitive fairness and inclusive participation?

RQ2: How can regulators leverage spectrum assignment mechanisms to support new entrants and universal connectivity objectives?

RQ3: What dimensions should constitute an inclusive RF spectrum assignment framework that balances efficiency, affordability, competition, equity, and digital inclusion?

Thus, the primary objective of this study is to develop a multidimensional governance framework to explain and guide inclusive RF spectrum assignment decisions in developing economies.

1.4. Contribution of the Study

The study offers three main contributions. Firstly, it introduces the Technology–Inclusion–Equity–Resource Capability–Organisation–Environment (TIEROE) framework, a conceptual governance model and diagnostic tool, offering a systematic method for designing, evaluating, and comparing spectrum assignment mechanisms across six interdependent dimensions. Secondly, it synthesises findings from the literature on technology adoption, resource capability, digital inclusion, and governance into a single theoretical framework. Thirdly, the TIEROE framework is intended for use by telecommunications regulators, such as ICASA in South Africa or the FCC in the United States. This framework

provides a practical tool to assist regulators in the design, evaluation, and justification of spectrum assignment decisions. Additionally, it offers a standardised language to facilitate communication among regulators, policymakers, and industry stakeholders.

The remainder of this article is organised as follows. Section 2 reviews the literature on spectrum governance and establishes the theoretical foundation for the TIEROE framework. Section 3 outlines the research methodology. Section 4 presents the findings. Section 5 discusses the theoretical and policy implications. Section 6 concludes the study and identifies areas for future research.

2. Literature Review and Theoretical Foundations

2.1. Radio Frequency Spectrum Governance in the Digital Economy

As countries advance their digital economy programmes, the strategic value of the radio frequency spectrum has increased. It is now widely recognised that broadband infrastructure plays a key role in boosting economic productivity, encouraging entrepreneurship, improving the delivery of public services, and promoting broader social development [5,18]. Empirical studies by bodies such as the World Bank, the OECD and the ITU consistently show a positive relationship between broadband penetration, economic growth and digital inclusion, particularly in developing economies, where digital technologies help extend access to markets, information and essential public services [18,21].

A review of key international policy documents [1,10,18,21] demonstrates a strong and consistent emphasis on 'efficiency' and 'investment' as primary objectives of spectrum governance, frequently presenting spectrum auctions as the preferred approach [12,23]. For example, the International Telecommunication Union's focus on harmonisation [1] and the World Bank's advocacy for market-based solutions [3] exemplify a neoliberal institutional logic. Nevertheless, this discourse frequently neglects the unique challenges faced by developing economies, where institutional capacity to regulate complex auctions is limited and market concentration remains high [6]. Research by Mfupe et al. identifies a policy–practice gap, in which the anticipated benefits of these models do not materialise due to bureaucratic inertia and insufficient technical expertise. A critical examination of the implicit assumptions within these international policy frameworks enables a more nuanced understanding of their applicability and limitations in developing contexts [31].

Despite its critical role, the radio frequency spectrum is inherently limited. Rapid growth in mobile data usage, machine-to-machine communications, AI-driven services, cloud computing, and digital infrastructure has intensified competition for scarce frequency bands [2,7]. Consequently, regulators face the complex challenge of achieving spectrum efficiency, fostering innovation and competition, ensuring service affordability, and securing universal connectivity in increasingly complex telecommunications environments.

Historically, spectrum governance primarily addressed technical coordination and the management of signal interference [10]. However, with the expansion of the telecommunications sector, the spectrum has been recognised as a valuable economic resource capable of generating significant commercial and social benefits. As a result, decisions on spectrum assignment now substantially influence market structure, investment patterns, innovation trajectories, and access to digital services [11,12].

The transition from administrative assignment methods to market-based spectrum assignment marked a fundamental shift in regulatory policy. Spectrum auctions have been widely adopted on the basis that they enhance allocative efficiency and transparency [12]. However, growing concerns about affordability, market concentration, digital exclusion, and participation disparities have reignited debate over the effectiveness of current spectrum governance models [13,17].

These ongoing discussions reflect the broader tension between economic efficiency and the pursuit of public-interest objectives. While regulators seek to maximise investment and spectrum utilisation, there is a growing expectation that telecommunications policy should also advance social inclusion, equitable participation, and sustainable development. The central challenge is to identify governance strategies that effectively balance these competing priorities.

Key Spectrum Governance Concepts

For conceptual clarity, the following definitions are used, as adapted from the ITU [1] and the World Bank [21]. Allocation refers to the process by which a government designates a specific frequency band for a particular service or category of services, such as mobile or broadcast. Assignment denotes the process by which a regulator grants the right to use a specific frequency or channel to a particular entity, such as an operator. Authorisation or licensing is the formal, legally binding instrument that grants this right and specifies the conditions of use, including duration, coverage, and technical parameters. Monitoring and enforcement comprise the ongoing activities of observing spectrum use to ensure compliance with license conditions, managing interference, and applying sanctions for non-compliance.

2.2. Spectrum Assignment Models

Spectrum assignment is the regulatory process by which rights to use specific frequency bands are granted to operators, service providers, or other authorised users [23]. Over time, multiple assignment methods have emerged, each reflecting different assumptions about efficiency, competition, fairness, and public-interest objectives.

2.2.1. Lottery-Based Assignment

Lottery-based assignment mechanisms distribute licences randomly among eligible applicants. Historically, such lotteries were implemented to enhance procedural transparency and limit administrative discretion [10]. These methods are relatively straightforward and cost-effective to administer and may also mitigate perceptions of regulatory bias.

However, lottery methods have been criticised for failing to distinguish between capable and incapable licensees. Because selection is random, the spectrum may be allocated to entities that lack the financial resources, technical expertise, or organisational capacity to deploy networks effectively [11]. Consequently, lottery methods often lead to inefficient utilisation and may encourage speculative behaviour.

2.2.2. First-Come-First-Served Assignment

Under first-come-first-served (FCFS) methods, licences are allocated in the order applications are received [24]. Although administratively straightforward, FCFS systems assume equal access to information and regulatory processes. In practice, organisations with greater regulatory expertise often enjoy advantages over smaller market participants.

Furthermore, FCFS methods provide limited assurance that licensees possess the resources necessary to utilise spectrum effectively. As demand for spectrum has increased globally, FCFS approaches have become increasingly unsuitable for assigning high-demand frequency bands.

2.2.3. Comparative Evaluation

Comparative evaluation mechanisms (beauty contests) allocate spectrum based on qualitative criteria rather than financial bids [11]. Evaluation criteria typically include

infrastructure commitments, service quality targets, coverage obligations, technological capabilities, innovation potential, and socio-economic contributions.

The main benefit of comparative evaluation is that it enables regulators to incorporate public-interest goals directly into assignment decisions; coverage obligations, universal service commitments, transformation targets, and developmental priorities can all be integrated into the evaluation criteria [13].

However, comparative evaluation approaches are frequently criticised for potentially introducing subjectivity, reducing transparency, and increasing opportunities for regulatory discretion [23]. Consequently, many countries have shifted toward market-based assignment methods.

2.2.4. Spectrum Auctions

Spectrum auctions remain the dominant method of assignment worldwide [12]. Auctions are based on the principle that scarce resources should be allocated to the operators willing to pay the highest price.

Auctions offer several advantages, including transparency, revenue generation, and allocative efficiency. Globally, governments have generated significant public revenue through spectrum auctions and have supported the deployment of advanced telecommunications infrastructure [4].

However, a growing body of evidence indicates that auction outcomes can conflict with broader development objectives [11,14]. Elevated spectrum prices can constrain investment capacity, increase barriers to market entry, and raise consumer costs [14,17]. According to GSMA studies, excessive spectrum pricing can impede network expansion, limit coverage, and compromise affordability objectives, particularly in developing economies [14,17]. As a result, there is increasing focus on alternative assignment models that seek to balance efficiency with objectives of inclusion, affordability, and competition.

2.3. Emerging Paradigm: Inclusive Spectrum Governance

Recent research identifies a new paradigm in spectrum governance scholarship. Rather than viewing spectrum solely as an economic commodity, scholars increasingly conceptualise it as a strategic public resource that advances broader societal and developmental objectives [23].

Inclusive spectrum governance recognises that assignment decisions affect affordability, accessibility, competition, participation, innovation, and digital inclusion. Inclusive spectrum governance, as used in this paper, refers to the proactive design of assignment mechanisms to enable meaningful participation by a diverse range of stakeholders. This includes but is not limited to: (i) end users (by ensuring affordability and access), (ii) rural and underserved communities (by promoting universal connectivity), (iii) smaller operators and new entrants (by lowering barriers to entry), and (iv) historically disadvantaged groups (through equity-focused interventions). Meaningful inclusion, as defined by Sharp [30], goes beyond mere access to infrastructure and encompasses digital literacy, service usage, and the ability to benefit from digital opportunities. Consequently, spectrum governance should be evaluated not only on economic efficiency but also on its contribution to meaningful digital participation and equitable development.

Several emerging governance approaches illustrate this shift. Dynamic Spectrum Access (DSA) enables multiple users to share spectrum resources based on real-time availability [24,32]. Spectrum-sharing frameworks aim to improve utilisation efficiency and lower barriers to participation [13]. Community network licensing models offer opportunities for local communities and smaller operators to participate in service provision [33].

Open-access infrastructure models promote competition by minimising infrastructure duplication and reducing barriers to market entry.

International experiences further underscore the value of inclusive governance approaches. The Citizens Broadband Radio Service (CBRS) framework, implemented by the Federal Communications Commission (FCC) in the United States of America (USA), demonstrates the potential of shared-spectrum models to expand participation beyond traditional telecommunications operators [34]. Similarly, universal service initiatives in India and community connectivity programmes in Kenya exemplify efforts to align spectrum governance with broader development objectives. Collectively, these developments suggest that future spectrum governance frameworks should integrate technological, economic, organisational, and social considerations.

2.4. Theoretical Foundations

The available literature shows that spectrum governance has been examined from a number of theoretical perspectives. While these theories provide useful insights, each of them considers only certain aspects of spectrum governance.

2.4.1. Technology–Organisation–Environment (TOE) Framework

The Technology–Organisation–Environment (TOE) framework holds that technology adoption is shaped by technological readiness, organisational capability, and environmental conditions [25]. It has been widely applied in information systems and telecommunications research.

TOE offers valuable insights into innovation adoption and organisational preparedness. However, it gives limited attention to equity, affordability, and digital inclusion. Consequently, its explanatory power remains limited when applied to broader-spectrum governance challenges [25].

2.4.2. Diffusion of Innovation Theory

Diffusion of Innovation (DoI) theory explains how innovations spread across organisations and societies [26]. The theory emphasises relative advantage, compatibility, complexity, trialability, and observability as key determinants of adoption behaviour.

Although useful for understanding technological diffusion, DoI pays limited attention to governance structures, regulatory institutions, and resource-allocation mechanisms. Consequently, it cannot independently explain outcomes in inclusive spectrum governance.

2.4.3. Resource-Based View

The Resource-Based View (RBV) holds that competitive advantage stems from valuable, rare, inimitable, and non-substitutable resources [27,28]. In telecommunications markets, spectrum itself is a strategic resource capable of generating competitive advantage. The RBV effectively explains market concentration and resource accumulation but offers limited insight into inclusion, equity, and public-interest outcomes.

2.4.4. Universal Service Obligation Frameworks

Universal Service Obligation (USO) frameworks emphasise equitable access to communications services, regardless of location or socio-economic status [29]. These frameworks highlight affordability, accessibility, and universal connectivity as essential policy objectives. However, USO frameworks offer limited explanation of organisational capability, technological innovation, and spectrum assignment dynamics.

2.4.5. Digital Inclusion Theory

Digital Inclusion theory holds that meaningful participation in digital societies depends on more than connectivity alone [30]. Affordability, digital literacy, accessibility, and capability development are equally important. The theory contributes significantly to understanding participation outcomes but pays limited attention to governance structures and spectrum assignment mechanisms.

2.5. Theoretical Fragmentation and the Need for Integration

A critical review of the literature reveals significant theoretical fragmentation. Technology adoption theories address innovation readiness and organisational capability. Resource-based theories focus on strategic advantage and resource accumulation. Digital inclusion perspectives examine participation and accessibility. The governance literature examines regulatory structures and institutional influences [35].

Nonetheless, no single theory sufficiently explains how technological capability, inclusion, equity, organisational readiness, resource availability, and environmental factors interact to shape spectrum governance outcomes. This fragmentation poses a significant challenge, especially in developing economies where regulators need to balance these elements:

- Efficiency;
- Competition;
- Innovation;
- Affordability;
- Inclusion;
- Equity; and
- Universal Connectivity.

Consequently, a multidimensional governance framework capable of integrating these perspectives is required.

2.6. Development of the Conceptual TIEROE Framework

To address the identified theoretical gap, this study develops the Technology–Inclusion–Equity–Resource Capability–Organisation–Environment (TIEROE) framework. The framework proposes that inclusive spectrum governance outcomes are determined by six interdependent dimensions:

- Technology;
- Inclusion;
- Equity;
- Resource Capability;
- Organisation; and
- Environment.

Unlike existing theories, TIEROE integrates technological, organisational, institutional, economic, and social perspectives into a unified governance model that explains inclusive spectrum assignment outcomes as summarised in Table 1. The TIEROE dimensions are designed to fulfil both normative and decision-analytic functions. From a normative perspective, these dimensions suggest that effective spectrum governance should be assessed using all six criteria, rather than focusing solely on efficiency and revenue. From a decision-analytic standpoint, the dimensions offer a structured framework for identifying the strengths and weaknesses of various assignment approaches, which facilitates more transparent and balanced regulatory decisions.

The preceding review demonstrates not only fragmentation but also a fundamental divergence in the underlying assumptions of the dominant theoretical frameworks. While the TOE and RBV frameworks implicitly assume that market forces and organisational capabilities will drive efficient outcomes [25,27,28], theories of DI and USO are based on the premise that market failures require proactive state intervention to ensure equitable access [29,30]. This divergence creates a conceptual tension: efficiency-oriented frameworks provide limited guidance on operationalising inclusion, whereas inclusion-oriented frameworks often neglect the resource and organisational constraints faced by operators. This tension is especially pronounced in developing economies, where regulators must balance the competing priorities of attracting private investment and fulfilling public interest mandates [6,20]. The TIEROE framework is introduced as an integrative mechanism designed to explicitly bridge this gap.

Table 1. Comparative analysis of the theoretical foundations underpinning TIEROE.

Theory	Technology	Inclusion	Equity	Resource Capability	Organisation	Environment
TOE	✓	✗	✗	Partial	✓	✓
DOI	✓	Partial	✗	✗	Partial	✗
RBV	Partial	✗	✗	✓	✓	✗
USO	Partial	✓	Partial	✗	✗	Partial
Digital Inclusion Theory	Partial	✓	Partial	✗	✗	Partial
TIEROE	✓	✓	✓	✓	✓	✓

✓—integrates dimension, ✗—does not integrate dimension.

While the TIEROE framework shares the 'Technology,' 'Organisation,' and 'Environment' dimensions with the TOE framework [25], its conceptual contribution is the addition and re-framing of three further dimensions: Inclusion, Equity, and Resource Capability. The TOE framework primarily explains the adoption of innovation by an organisation. In this context, it would account for how effectively an organisation can adopt a spectrum license. In contrast, TIEROE shifts the analytical focus from the adopting organisation to the regulatory system that governs the assignment process.

Simply combining TOE with DI or RBV theories [27,36] would be insufficient. Such a combination would result in a theoretical hybrid that explains how resource differences create competitive advantage but does not address how regulators should act to mitigate resulting inequalities. TIEROE represents more than a combination; it is an integration that positions inclusion and equity on an equal conceptual footing with technology, organisation, and environment, explicitly framing them as primary governance objectives.

3. Materials and Methods

3.1. Research Philosophy

This study adopted an interpretivist research philosophy to explore the multidimensional nature of RF spectrum governance and assignment. Interpretivism assumes that social, institutional, and regulatory realities are constructed through human interactions, governance structures, policy decisions, and contextual experiences, rather than existing as purely objective phenomena [37,38]. Given that spectrum governance involves competing technological, economic, political, regulatory, and developmental interests, an interpretivist approach was considered appropriate for understanding how spectrum assignment contributes to digital transformation, competition, inclusion, and sustainable development.

Unlike positivist approaches, which seek causal explanations through quantitative measurement, interpretivism enables a deeper understanding of governance structures, institutional arrangements, regulatory objectives, and stakeholder interactions that shape spectrum assignment outcomes [38]. Spectrum governance is a complex socio-technical system in which decisions are shaped by technological developments, market dynamics, regulatory priorities, political considerations, and socio-economic objectives. Consequently, understanding inclusive spectrum governance requires a research approach capable of capturing these interdependencies.

The interpretivist paradigm further aligns with the objective of developing a novel theoretical framework. The TIEROE framework seeks to integrate multiple theoretical perspectives and to explain how diverse governance dimensions interact within spectrum assignment environments. Therefore, interpretivism provided the flexibility needed to synthesise evidence from academic literature, policy documents, regulatory frameworks, and international governance experiences.

3.2. Research Design

A qualitative exploratory research design was employed in this study. Exploratory research is particularly suitable when current theoretical explanations are fragmented, underdeveloped, or inadequate for explaining emerging phenomena [36]. As noted in the literature review, existing theories address specific aspects of spectrum governance but do not provide a comprehensive understanding of the interactions among technological, organisational, inclusion, equity, resource, and environmental dimensions within spectrum assignment processes. The exploratory design enabled the study to:

- Critically evaluate existing spectrum assignment approaches;
- Identify recurring governance challenges;
- Examine international spectrum governance practices;
- Synthesise diverse theoretical perspectives; and
- Develop the TIEROE framework.

Qualitative approaches are widely used in telecommunications policy, governance, and digital transformation research because they enable detailed examination of complex institutional and regulatory environments [39]. Furthermore, conceptual framework development often relies on qualitative synthesis to identify recurring patterns across multiple evidence sources. The study was conducted in four sequential phases:

- Systematic Literature Review;
- Policy and Regulatory Document Analysis;
- International Comparative Analysis; and
- Framework Development and Theoretical Synthesis.

Figure 1 illustrates the development process of TIEROE.

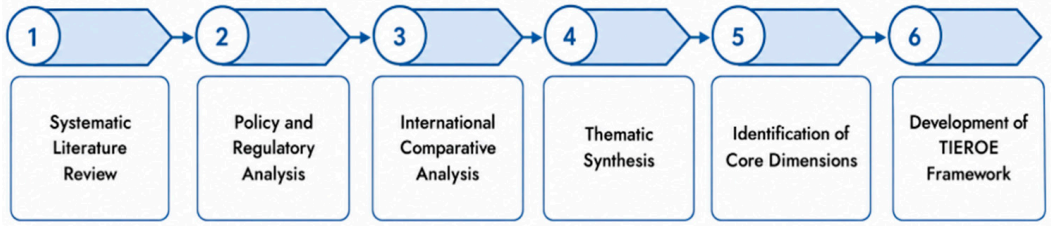


Figure 1. Research process for developing the TIEROE Framework.

3.3. Systematic Literature Review

The first phase comprised a systematic review of the academic literature on spectrum governance, spectrum assignment, telecommunications regulation, digital inclusion, digital transformation, universal service obligations, and technology adoption.

To ensure transparency and methodological rigour, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework [40] was followed. Although this study is conceptual rather than a formal systematic review, the PRISMA principles provided a structured approach to identifying, screening, and selecting relevant literature. PRISMA is illustrated in Figure 2.

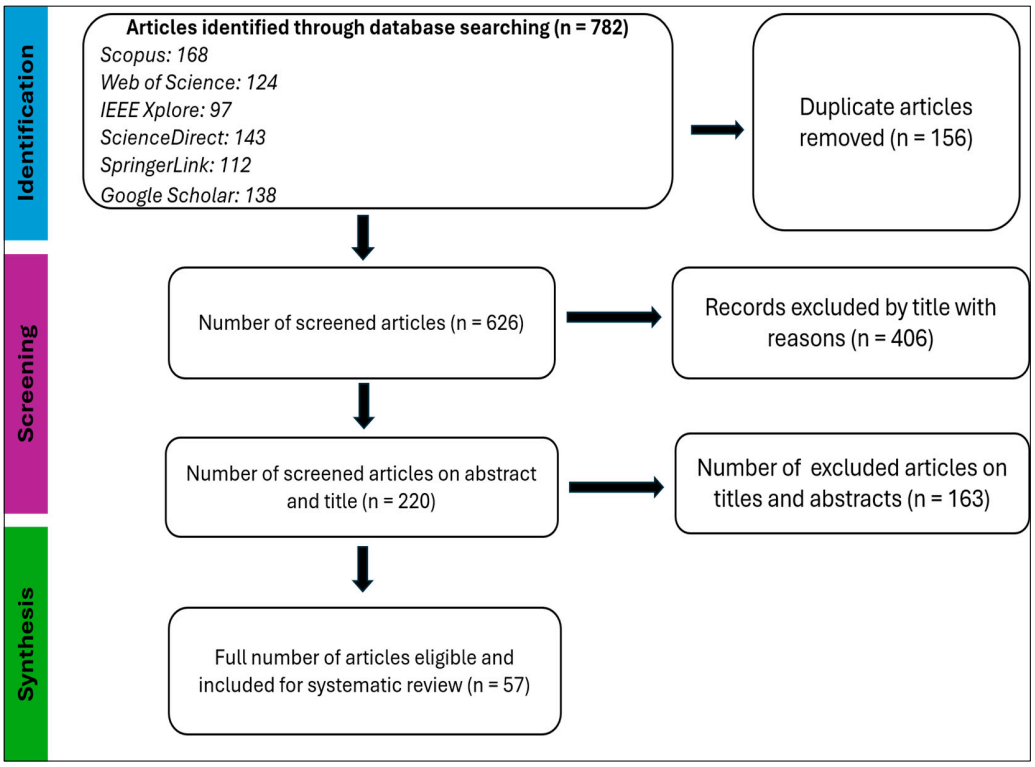


Figure 2. PRISMA flow diagram of the literature search and screening process.

Although the PRISMA flow diagram visually summarises the systematic literature selection process, the following subsections provide a detailed account of each stage, including identification, screening, eligibility assessment, and final inclusion of studies. This sequential discussion increases transparency and highlights the methodological rigour maintained throughout the review process.

3.3.1. Search Strategy

Literature searches were conducted using the following academic databases:

- Scopus;
- Web of Science;
- IEEE Xplore;
- ScienceDirect;
- SpringerLink; and
- Google Scholar.

The search strategy employed combinations of the following keywords:

- "radio frequency spectrum assignment";
- "spectrum governance";

- "spectrum auctions";
- "spectrum sharing";
- "digital inclusion";
- "telecommunications regulation";
- "broadband policy";
- "universal connectivity";
- "digital transformation"; and
- "spectrum management".

The review primarily focused on publications from 2020 to 2026 to ensure contemporary relevance. However, foundational theoretical works, including the TOE framework, DoI theory, and the RBV, were retained for their importance in shaping the study's conceptual foundations [41].

3.3.2. Inclusion and Exclusion Criteria

Studies were included if they:

- Addressed spectrum governance or assignment;
- Examined telecommunications regulation;
- Investigated digital inclusion or universal service;
- Discussed technology adoption or resource allocation; or
- Contributed theoretically or empirically to spectrum management.

Studies were excluded if they:

- Focused exclusively on engineering design without governance implications;
- Were unrelated to telecommunications or digital transformation;
- Lacked peer-review quality assurance; or
- Demonstrated insufficient relevance to the research objectives.

3.3.3. Screening Process

The screening process consisted of three stages:

- Removal of duplicate publications;
- Title and abstract screening; and
- Full-text assessment.

The resulting body of literature contributed directly to understanding spectrum governance, digital inclusion, competition policy, and digital transformation.

3.4. Policy and Regulatory Document Analysis

The second phase comprised document analysis. This method is a systematic approach to reviewing and evaluating written materials to generate empirical insights and theoretical understanding [42]. Document analysis was particularly suitable because spectrum governance is shaped by legislation, policy frameworks, regulatory instruments, strategic development plans, and international standards. The analysis incorporated:

- Electronic Communications Act 36 of 2005 [29];
- South Africa Connect Broadband Policy [20];
- Digital Economy Masterplan [32];
- ICASA Spectrum Licensing Frameworks [22];
- ICASA Dynamic Spectrum Access Regulations [32].
- ITU Spectrum Management Publications [1,16,24];
- OECD Digital Economy Reports [18,43];
- GSMA Spectrum Policy Reports [2,9,14];
- World Bank Digital Development Reports [3,20];

- UN Digital Economy Reports [20].

The analysis focused on identifying policy objectives relating to:

- Competition;
- Universal Access;
- Digital Inclusion;
- Affordability;
- Innovation;
- Infrastructure Development; and
- Spectrum Efficiency.

The findings were subsequently compared to identify recurring governance themes across countries.

3.5. International Comparative Analysis

To strengthen external validity and enhance the robustness of the proposed framework, the study incorporated an international comparative analysis, as shown in Table 2. Comparative policy analysis enables researchers to identify best practices, evaluate regulatory effectiveness, and generate transferable insights across contexts [44]. The study examined selected countries that have implemented innovative spectrum governance approaches.

Table 2. International cases included in the comparative analysis.

Country	Focus
USA	CBRS and spectrum sharing
India	Universal service and rural broadband
Kenya	Community networks and digital inclusion
Finland	Open-access infrastructure
Estonia	Digital governance leadership
Morocco	Emerging spectrum reforms

International cases were selected using a purposive sampling strategy to maximise diversity and relevance. The selection criteria included: (i) diversity of governance models (market-based, administrative, shared-access); (ii) representation from various developing regions (Africa, Asia, Americas, North Africa); (iii) availability of comprehensive documentation; and (iv) relevance to the digital inclusion and equity challenges addressed by TIEROE. Although generalizability is not asserted, this sample constitutes a valuable cross-section of innovative practices that may yield transferable insights.

- The comparative analysis examined:
- Spectrum-sharing frameworks;
- Dynamic spectrum access;
- Community licensing models;
- Universal service obligations;
- Infrastructure-sharing mechanisms; and
- Competition-enhancing interventions.

3.6. Data Analysis and Framework Development

The data underwent thematic synthesis. This qualitative analytical method involves identifying recurring patterns across multiple sources of evidence and leads to the de-

velopment of higher-order conceptual insights [45]. The analysis was conducted in three stages.

Stage 1: Open Coding

Evidence obtained from literature, policy documents, and international case studies was coded according to recurring concepts, which included:

- Competition;
- Inclusion;
- Accessibility;
- Affordability;
- Innovation;
- Governance;
- Regulatory Support;
- Resource Capability; and
- Infrastructure Development.

Stage 2: Axial Coding

Related concepts were grouped into broader categories. Continuous comparison revealed six recurring dimensions that appeared across all evidence sources. These dimensions included:

- Technology;
- Inclusion;
- Equity;
- Resource Capability;
- Organisation; and
- Environment.

Stage 3: Conceptual Integration

The six dimensions were integrated into a unified governance framework. The framework was subsequently named 'TIEROE'. The TIEROE dimensions were not predetermined; instead, they emerged inductively through a three-stage thematic analysis [45]. Following open coding of the literature, policy documents, and case studies, concepts such as 'technology adoption,' 'regulatory capability,' and 'market fairness' were identified. During axial coding, these concepts were consolidated into six higher-order themes. For instance, 'technology adoption,' 'network modernisation,' and 'spectrum efficiency' were grouped under the dimension of 'Technology.' Similarly, 'regulatory certainty,' 'policy stability,' and 'institutional effectiveness' were grouped under 'Environment.' The consistent emergence of these six high-level themes across multiple independent evidence sources established the foundation of the framework. The repeated appearance of these themes, coupled with the absence of new themes after thematic saturation, provides strong evidence for the conceptual validity of the framework.

3.7. Trustworthiness and Research Quality

To enhance methodological rigour, the study adopted the trustworthiness criteria proposed by Lincoln and Guba [46], as shown in Table 3.

Table 3. Trustworthiness criteria applied in the study.

Criteria	Application
Credibility	Triangulation of literature, policy documents, and international cases
Transferability	Detailed contextual descriptions
Dependability	Transparent research procedures
Confirmability	Evidence-based coding and framework development

Credibility was enhanced through methodological triangulation, drawing on academic literature, policy documents, regulatory frameworks, and international case evidence. Transferability was supported by detailed descriptions of spectrum governance environments and assignment practices. Dependability was strengthened through transparent documentation of search strategies, inclusion criteria, coding procedures, and framework development stages. Confirmability was ensured by grounding findings in multiple independent evidence sources and maintaining a clear audit trail throughout the analytical process.

3.8. Ethical Considerations

The study relied exclusively on publicly available secondary data, including academic publications, legislation, policy documents, regulatory reports, and international telecommunications frameworks. No human participants were involved, and no personal or confidential information was collected. Accordingly, formal ethical approval was not required. Nevertheless, the study adhered to principles of academic integrity, transparency, objectivity, and responsible scholarship. All sources were appropriately acknowledged, and care was taken to ensure accurate representation of policy positions, regulatory frameworks, and international experiences. The study therefore meets accepted standards of ethical conduct for conceptual and policy-oriented research.

4. Results

4.1. Overview of Findings

The analysis of the academic literature, telecommunications policy documents, regulatory frameworks, and international spectrum governance practices indicates that contemporary RF spectrum assignment is primarily shaped by economic efficiency objectives. In most countries, assignment mechanisms aim to maximise spectrum utilisation, stimulate infrastructure investment, foster technological innovation, and generate public revenues [4,11,12]. Although these objectives are significant, the evidence suggests that efficiency-oriented approaches alone do not adequately address broader developmental challenges, including affordability, digital inclusion, equitable participation, competition, and universal connectivity [6,17,21].

The analysis further revealed that inclusive spectrum governance cannot be adequately explained by a single theoretical perspective or assignment method. Instead, successful governance outcomes arise from the interaction of multiple technological, organisational, institutional, economic, and social factors. Across all evidence sources, six recurring dimensions consistently shaped spectrum assignment outcomes:

- Technology;
- Inclusion;
- Equity;

- Resource Capability;
- Organisation; and
- Environment.

Importantly, the findings indicate that existing assignment mechanisms seldom address all six dimensions simultaneously. Auctions primarily emphasise efficiency and revenue generation, beauty contests prioritise developmental commitments, while universal service interventions focus on access and affordability. Consequently, no single assignment model currently provides a comprehensive governance approach that balances efficiency, affordability, inclusion, competition, and equity objectives. The recurring emergence of these six dimensions across the literature, policy documents, and international case studies provided the empirical foundation for the development of the TIEROE framework, as shown in Table 4.

The convergence of findings across multiple evidence sources strengthens the conceptual validity of the TIEROE framework. The qualitative assessment of the TIEROE framework dimensions is further illustrated in Table 4.

Table 4. Evidence supporting the development of TIEROE.

Evidence Source	Technology	Inclusion	Equity	Resource Capability	Organisation	Environment
Academic literature	✓	✓	✓	✓	✓	✓
Policy documents	✓	✓	✓	✓	✓	✓
Regulatory frameworks	✓	Partial	✓	Partial	✓	✓
ITU publications	✓	✓	Partial	Partial	Partial	✓
International cases	✓	✓	✓	✓	✓	✓
Comparative analysis	✓	✓	✓	✓	✓	✓

✓—fully supports the development of the TIEROE framework, Partially—supports the development of the TIEROE framework in part.

4.2. Technology as a Driver of Inclusive Spectrum Governance

The analysis of evidence sources reveals new patterns regarding how technology shapes governance outcomes beyond simply enabling innovation. The first major finding concerns the central role of technology in shaping spectrum governance outcomes. Across all evidence sources, spectrum assignment was consistently linked to technological innovation, infrastructure deployment, network modernisation, and digital transformation [1,2,7,18]. The findings indicate that spectrum derives value primarily from its ability to support wireless technologies and digital services. The deployment of broadband networks, 5G infrastructure, IoT ecosystems, AI applications, cloud services, and future 6G technologies all depend on access to appropriate spectrum resources [1,7,47,48]. Consequently, spectrum assignment directly influences technological innovation and national digital transformation outcomes. The policy analysis revealed an increasing emphasis on technology-neutral licensing frameworks. Technology neutrality enables operators to select the most appropriate technologies without unnecessary regulatory constraints, thereby encouraging innovation and facilitating adaptation to rapidly evolving telecommunications environments [23,29].

International evidence further underscores the growing importance of dynamic spectrum management. The FCC's CBRS framework shows how shared-spectrum models can improve utilisation efficiency while expanding participation opportunities [34]. Similarly, South Africa's DSA regulations mark a significant shift towards more flexible spectrum governance that can accommodate future technological developments [32]. The findings

therefore suggest that technology should be viewed not merely as an operational component of spectrum governance but as a foundational enabler of digital transformation.

4.3. Inclusion as a Core Spectrum Governance Objective

The analysis uncovers a critical gap between policy rhetoric and practical outcomes regarding inclusion. The second major finding highlights the growing importance of inclusion in contemporary spectrum governance. Across the literature, policy documents, and international cases, digital inclusion emerged as one of the most significant challenges facing telecommunications regulators, particularly in developing economies [19,21,33]. The findings indicate that traditional assignment mechanisms often favour established operators with greater financial resources, infrastructure assets, and regulatory expertise [11,12]. While these operators contribute significantly to infrastructure deployment, their dominance may unintentionally restrict opportunities for smaller operators, community networks, and underserved populations.

Several policy documents emphasised that connectivity alone does not constitute meaningful inclusion. Instead, inclusion encompasses affordability, accessibility, participation, digital literacy, and the ability to use digital services effectively. This observation aligns with Digital Inclusion theory, which holds that meaningful participation requires more than physical access to infrastructure [30]. International case studies from Kenya, India, and the USA illustrate efforts to broaden participation through community networks, universal service initiatives, and spectrum-sharing arrangements [49,50]. These interventions demonstrate that inclusive spectrum governance requires proactive regulatory strategies to expand participation opportunities.

4.4. Equity and Competitive Fairness

The third major finding concerns the role of equity in spectrum assignment environments. Although often discussed alongside inclusion, the analysis revealed that equity constitutes a distinct governance dimension requiring separate consideration. While inclusion focuses on participation, equity addresses fairness in both access to spectrum resources and the distribution of resulting benefits. The findings demonstrate that assignment outcomes are often influenced by unequal financial, technological, organisational, and institutional capabilities among market participants [11,14].

Auction-based assignment mechanisms were repeatedly identified as potentially reinforcing existing market inequalities. Large mobile network operators often have greater access to capital, infrastructure, and regulatory expertise, enabling them to acquire spectrum more easily than smaller competitors [14,23]. Recent research suggests that spectrum set-asides, reserved allocations, and inclusion-oriented assignment conditions can partially address these challenges [51]. Similarly, transformation-focused interventions adopted in several developing economies aim to expand participation by historically disadvantaged groups and underrepresented market participants. The findings therefore indicate that equity should be understood as creating conditions that enable meaningful participation despite structural differences in capability and market position.

4.5. Resource Capability and Effective Spectrum Utilisation

Resource capability emerged as the fourth critical dimension shaping spectrum governance outcomes. The findings consistently showed that assignment effectiveness depends not only on access to spectrum but also on the capacity to utilise it effectively. The Resource-Based View holds that organisations with valuable resources are better placed to achieve competitive advantage [27,28]. This perspective was strongly supported by the findings. Mobile network operators with stronger financial resources, technological capabilities, in-

frastructure assets, and human expertise were generally better placed to acquire spectrum, deploy networks, and expand service coverage.

However, resource disparities frequently limit participation by smaller mobile network operators, community networks, and new entrants. Several international cases revealed that infrastructure costs, financing constraints, and limited technical capabilities continue to pose significant barriers to market entry [21,50]. The analysis identified several interventions to address resource capability disparities, including infrastructure sharing, open-access networks, spectrum leasing, universal service funds, and capacity-building programmes. These mechanisms aim to reduce entry barriers while promoting more efficient resource utilisation.

4.6. Organisational Readiness and Assignment Effectiveness

The fifth major finding concerns the role of organisational capability in transforming spectrum resources into developmental outcomes. Across multiple evidence sources, successful spectrum utilisation was associated with strategic leadership, effective governance, regulatory compliance capability, innovation capacity, and long-term investment planning [25]. The findings further revealed that many assignment mechanisms focus primarily on allocation procedures while paying limited attention to organisational preparedness. However, access to spectrum alone does not guarantee successful deployment or service delivery. The analysis, therefore, suggests that organisational readiness is a critical intermediary between spectrum assignment and digital transformation outcomes. Organisations lacking strategic, managerial, or operational capabilities may struggle to translate spectrum access into meaningful service delivery, despite holding valuable licences.

4.7. Environmental Conditions and Governance Outcomes

The final dimension identified in the analysis concerns the broader environmental context in which spectrum governance occurs. The findings indicate that assignment outcomes are strongly influenced by regulatory certainty, policy stability, institutional effectiveness, market maturity, economic conditions, and broader developmental priorities [52,53]. Regulatory certainty emerged as one of the most important environmental factors. Stable, predictable regulatory environments encourage investment, facilitate infrastructure deployment, and support innovation. Conversely, regulatory uncertainty may discourage investment and constrain digital transformation initiatives. The comparative analysis demonstrated that countries with effective regulatory institutions, coherent digital strategies, and supportive investment environments generally achieved stronger connectivity outcomes [43,52].

4.8. Synthesis of Findings

The six dimensions identified in the analysis do not function as independent variables, as shown in Table 5. Rather, they operate as components of an interconnected governance ecosystem. Technology enables innovation and infrastructure deployment. Inclusion guarantees accessibility and participation. Equity ensures fairness and balanced opportunities. Resource capability determines the ability to utilise spectrum efficiently. Organisation influences deployment effectiveness. Environment defines the broader regulatory and institutional context.

Table 5. Qualitative assessment of evidence strength and nature for each TIEROE dimension.

Dimension	Strength of Evidence	Nature of Evidence	References
Technology	High	Consistent across all sources	[1,2,7,16,18]
Inclusion	High	Strong policy focus; mixed empirical	[18,21,30,33]
Equity	Medium	Emerging; clear theoretical basis	[11,14,24,51]
Resource Capability	High	Well-established in RBV literature	[21,27,36,50]
Organisation	Medium	Well-documented but often secondary	[25]
Environment	High	Consistently cited as critical	[43,52,53]

The findings in Table 5 suggest that deficiencies in any single dimension may undermine the effectiveness of the others. Consequently, inclusive spectrum governance requires the concurrent consideration of all six dimensions; see Table 6.

Kenya's community network approach has played a significant role in delivering affordable connectivity to underserved regions, illustrating how 'Inclusion' can be achieved through non-traditional service providers [49]. India's Universal Service Fund has supported infrastructure deployment in rural areas, highlighting the importance of 'Resource Capability' in addressing the urban–rural digital divide [50]. Estonia's leadership in digital governance demonstrates that a stable and supportive 'Environment' can facilitate digital transformation [43]. The case of Morocco, examined within a broader study on policy diffusion in the MENA region [54], illustrates how developing countries can tailor international practices to their specific institutional contexts. The USA's CBRS framework exemplifies how a 'Technology'-driven and 'Inclusion'-oriented strategy can generate new opportunities for a diverse range of market participants [34]. Collectively, these cases underscore the necessity for governance approaches that are responsive to local contexts.

Table 6. Primary functions of TIEROE dimensions.

Dimension	Primary Function	Expected Governance Outcome	Potential Evaluation Metrics
Technology	Innovation and infrastructure enablement	Digital transformation	Spectrum utilisation rate, 5G/4G coverage
Inclusion	Accessibility and participation	Universal connectivity	% population with access, affordability index
Equity	Fairness and balanced opportunity	Competitive fairness	Herfindahl–Hirschman Index (HHI)
Resource Capability	Deployment capability	Effective utilization	Investment in infrastructure, financing access
Organisation	Strategic and operational readiness	Service delivery	Network deployment timelines
Environment	Regulatory and institutional support	Sustainable governance	Regulatory certainty index

4.9. Emergence of the TIEROE Framework

The findings collectively demonstrate that inclusive spectrum governance cannot be adequately explained through technological efficiency or market allocation mecha-

nisms alone. Instead, effective spectrum governance emerges through interactions among six interdependent dimensions:

- Technology;
- Inclusion;
- Equity;
- Resource Capability;
- Organisation; and
- Environment.

These findings directly informed the development of the TIEROE framework, which is presented as a multidimensional governance model for inclusive spectrum assignment and digital transformation.

5. Discussion

This study addresses a significant gap in the spectrum governance literature by developing a multidimensional framework that explains how spectrum assignment can simultaneously support efficiency, competition, affordability, inclusion, equity, and universal connectivity. The findings indicate that current spectrum governance approaches remain fragmented across technology adoption, resource capabilities, digital inclusion, and regulatory perspectives. Accordingly, the discussion interprets these findings in relation to the three research questions and demonstrates the TIEROE framework's contributions to both theory and practice. It is further argued that spectrum governance should not be conceptualised solely as a resource allocation exercise. Instead, spectrum assignment constitutes a multidimensional governance challenge that encompasses technological innovation, institutional capability, social inclusion, economic development, and sustainable transformation objectives.

5.1. Examining Competitive Fairness and Inclusive Participation (RQ1)

The first research question examines the extent to which existing radio frequency (RF) spectrum assignment models promote competitive fairness and inclusive participation. The findings suggest that although traditional assignment mechanisms offer significant benefits, they are limited in achieving inclusive governance outcomes. Spectrum auctions remain the predominant international practice because they promote transparency, efficiency, and public revenue generation [4,12]. Nevertheless, evidence indicates that these advantages are often accompanied by unintended consequences, such as market concentration, high entry barriers, and reduced participation opportunities for smaller operators and underserved communities [11,15].

This finding aligns with the broader telecommunications policy literature, which suggests that efficiency-focused assignment approaches may unintentionally reinforce existing structural inequalities [6,21]. Large mobile network operators often have greater financial resources, infrastructure assets, regulatory expertise, and technological capabilities, enabling them to compete more effectively in auction environments. Although these outcomes may be economically efficient, they do not necessarily advance equitable participation or universal connectivity objectives.

These findings challenge the assumption that spectrum governance effectiveness can be assessed solely by revenue generation, investment levels, or spectrum utilisation efficiency. Instead, competitive fairness should be conceptualised as the extent to which governance arrangements enable meaningful participation across diverse stakeholder groups while preserving incentives for investment and innovation. From a TIEROE perspective, fairness arises from the interplay of inclusion, equity, resource capability, and organisational readiness. This perspective marks a significant theoretical shift from traditional spectrum

governance approaches, which generally emphasise assignment mechanisms rather than broader governance ecosystems.

5.2. Spectrum Governance to Support New Entrants and Universal Connectivity (RQ2)

The second research question examined how regulators can use spectrum assignment mechanisms to support new entrants and universal connectivity objectives. The findings indicate that universal connectivity cannot be achieved through spectrum assignment alone. While access to spectrum remains a prerequisite for service provision, participation is also shaped by organisational capability, financial resources, infrastructure availability, regulatory support, and institutional readiness [21,50]. This observation is particularly relevant in developing economies, where barriers to participation often extend beyond spectrum scarcity. Infrastructure deployment costs, financing constraints, technical skills shortages, and regulatory compliance requirements often limit participation by smaller operators, even when spectrum resources are available [21].

International comparability analysis offers valuable insights into alternative governance approaches to these challenges. The FCC's CBRS framework shows that spectrum sharing can broaden participation while maintaining efficiency [34]. Similarly, India's universal service programmes and Kenya's community connectivity initiatives show that spectrum governance can align with broader development objectives [49,50]. These findings support a broader interpretation of spectrum governance, in which assignment decisions are only one element within a larger governance ecosystem. Universal connectivity results not solely from spectrum access but from the interplay among technology, inclusion, resource capacity, organisational structures, and environmental support. This perspective extends traditional telecommunications policy by showing that inclusive connectivity requires integrated governance approaches rather than isolated regulatory interventions.

5.3. Towards a Multidimensional Spectrum Governance Framework (RQ3)

The third research question sought to determine the dimensions that should underpin an inclusive spectrum assignment framework. The results consistently identified six dimensions that influence governance outcomes:

- Technology;
- Inclusion;
- Equity;
- Resource Capability;
- Organisation; and
- Environment.

Each dimension uniquely contributes to spectrum governance effectiveness. Technology enables innovation and infrastructure deployment. Inclusion promotes accessibility and participation. Equity addresses fairness and balanced opportunity. Resource capability determines the ability to utilise spectrum effectively. Organisation influences deployment effectiveness and strategic alignment. Environment shapes the broader institutional and regulatory context.

Importantly, the findings indicate that these dimensions are mutually reinforcing rather than independent. Technological readiness may enhance connectivity outcomes, but only when supported by adequate organisational capability and resources. Similarly, inclusion objectives may be difficult to achieve without supportive regulatory environments and opportunities for equitable participation.

The findings therefore support the argument that spectrum governance should be conceptualised as a multidimensional governance challenge rather than a purely economic allocation problem. This perspective underpins the TIEROE framework.

Although the TIEROE framework demonstrates conceptual robustness, we recognise the necessity for empirical validation. The development of the TIEROE framework represents the primary theoretical contribution of this research. We plan to publish a subsequent paper that will utilise expert interviews, surveys, and case study testing to validate and refine the framework. The research propositions outlined in Section 5.6 will inform this empirical investigation.

5.4. Theoretical Contributions

The principal theoretical contribution of this study is the development of the TIEROE framework, a multidimensional governance model for spectrum assignment. Existing theories offer valuable but incomplete explanations of spectrum governance outcomes. The TOE framework explains organisational and environmental readiness [25]. DoI theory explains technological dissemination [26]. The RBV explains strategic resource accumulation and competitive advantage [28,29]. The USO frameworks emphasise accessibility and affordability [29], while Digital Inclusion theory focuses on participation and meaningful connectivity [30].

However, these theories remain fragmented. Each explains selected dimensions of spectrum governance while neglecting others. Consequently, none offers a comprehensive account of how technological capability, inclusion, equity, organisational readiness, resource availability, and environmental conditions interact. The TIEROE framework addresses this limitation by integrating these dimensions into a unified governance perspective.

TIEROE advances the literature on spectrum governance by prioritising inclusion and equity as central governance objectives, rather than treating them as secondary policy outcomes. Additionally, TIEROE incorporates organisational capability and resource availability into analyses of digital inclusion and spectrum assignment, thereby extending both RBV and DoI theory. Furthermore, TIEROE frames spectrum governance as an ecosystem-level phenomenon, in which outcomes arise from interactions across multiple dimensions rather than from isolated regulatory interventions. Together, these contributions position TIEROE as a novel theoretical framework for understanding inclusive spectrum governance.

In addition, the empirical validation of the TIEROE framework may be enhanced by employing a Multi-Criteria Decision-Making (MCDA) approach. MCDA offers a systematic, transparent, and adaptable methodology for evaluating alternative spectrum assignment strategies across the six TIEROE dimensions. In this methodology, each dimension receives a weight that reflects the strategic priorities of the relevant regulatory authority, facilitating objective comparison of policy and regulatory options. Further validation of the framework could formalise this process by modelling spectrum assignment as an MCDA optimisation problem, with the objective of maximising the overall value of a spectrum assignment strategy while adhering to the constraints defined by the TIEROE dimensions [55]. The utility of a strategy can be represented as a weighted combination of key policy objectives, such as spectrum utilisation efficiency, broadband coverage, equitable market participation, and other regulatory outcomes, with the relative importance of each objective determined by the regulator's policy priorities. This approach, which has demonstrated success in environmental and sustainability policy, provides a rigorous and customisable decision-support mechanism for broadband policy evaluation. Within this context, the TIEROE framework establishes the conceptual foundation for defining evaluation criteria, policy objectives, and decision constraints in the MCDA model, thereby supporting evidence-based, transparent, and context-specific spectrum management decisions [56].

5.5. Development of Research Propositions

The findings support the development of six propositions that can guide future empirical research.

Proposition 1 (P1). On technology and inclusive connectivity: Technological readiness enhances the positive relationship between spectrum assignment and inclusive connectivity outcomes.

Proposition 2 (P2). On inclusion and digital participation: Spectrum assignment mechanisms that prioritise inclusion have a positive impact on meaningful digital participation and the achievement of universal connectivity.

Proposition 3 (P3). On equity and competitive fairness: Equity-focused assignment methods enhance competitive fairness and promote market diversity.

Proposition 4 (P4). On resource capability and spectrum utilisation: Resource capability enhances the capacity of spectrum licensees to convert spectrum access into effective service delivery outcomes.

Proposition 5 (P5). On organisational readiness and deployment effectiveness: The moderating role of organisational readiness in the relationship between spectrum assignment and infrastructure deployment effectiveness.

Proposition 6 (P6). On environmental conditions and governance outcomes: Supportive regulatory and institutional environments contribute positively to achieving inclusive spectrum governance outcomes.

These propositions establish a pathway for future empirical validation of the TIEROE framework.

5.6. Policy Implications

The findings have several important implications for policymakers and telecommunications regulators. First, spectrum governance should be treated as a strategic instrument for digital transformation, not merely a mechanism for allocating scarce resources. Second, assignment methods should be evaluated against multidimensional criteria that go beyond efficiency and revenue generation. Affordability, competition, inclusion, equity, and universal connectivity should be treated as equally important governance objectives. Third, regulators should increasingly consider complementary mechanisms, such as spectrum sharing, dynamic spectrum access, infrastructure sharing, community licensing, and open-access frameworks, to broaden participation opportunities. Fourth, spectrum policy should be integrated into wider digital transformation strategies, as connectivity outcomes are influenced by education, digital literacy, organisational capability, infrastructure availability, and broader socio-economic conditions. The TIEROE framework therefore provides regulators with a practical governance tool to support more balanced and inclusive spectrum assignment decisions.

5.7. The Symbiotic Link: Wired and Wireless Network Collaboration

The efficiency of wireless spectrum utilisation is fundamentally constrained by the capacity of wired backhaul networks, such as fibre optic and microwave links, that connect cell towers to the core internet [21]. In developing economies, insufficient fibre backhaul in rural and underserved regions often renders spectrum licenses ineffective, as operators are unable to provide service without adequate backhaul infrastructure [50]. Consequently, spectrum policy should not be developed in isolation. Policies that promote open-access fibre networks, infrastructure sharing agreements, and the use of universal service funds to construct backhaul in underserved areas are essential complements to spectrum assignment [33]. The CBRS model in the United States and the open-access infrastructure approach in Finland exemplify governance frameworks that address this issue by reducing barriers to infrastruc-

ture deployment [34]. Accordingly, the TIEROE framework must explicitly account for the interdependence between wireless spectrum and wired infrastructure.

5.8. Navigating Trade-Offs and Tensions in TIEROE

The TIEROE framework does not assume perfect alignment among its six dimensions. In practice, significant trade-offs are inherent. For instance, an auction may maximise public revenue ('Resource Capability') but reduce affordability ('Inclusion') [14]. Similarly, a strict licensing regime may ensure quality of service ('Organisation') but limit competition and innovation ('Technology'). The framework's primary value is not in resolving these tensions, but in making them explicit and facilitating transparent discussion among stakeholders regarding the relative priority of each dimension. As Mfupe et al. [31] indicate, a multi-criteria decision analysis (MCDA) approach can quantify these trade-offs by assigning weights to different policy objectives. The regulator, guided by public consultation, must determine the acceptable balance between competing goals. The TIEROE framework offers a structured basis for this deliberative process.

5.9. Institutional Assumptions and Limitations

The TIEROE framework is predicated on several key institutional assumptions. These include the presence of a regulatory body, such as ICASA, that maintains a degree of independence from the executive branch; the availability of essential data, including demographic information, coverage maps, and spectrum usage data; the existence of an effective enforcement mechanism for licensing conditions; and a legal and policy environment encompassing competition law and the principle of universal service. Where these assumptions are not met, the applicability of the framework is substantially limited and necessitates adaptation to address governance deficits [6].

5.10. Alignment with Sustainable Development Goals

The findings demonstrate strong alignment between inclusive spectrum governance and sustainable development objectives. The framework directly supports:

- SDG 9 (Industry, Innovation and Infrastructure) through the promotion of broadband infrastructure, innovation, and digital transformation;
- SDG 10 (Reduced Inequalities) through emphasis on inclusion, affordability, and equitable participation; and
- SDG 17 (Partnerships for the Goals) through recognition of collaborative governance among regulators, operators, communities, development institutions, and international organisations.

Consequently, spectrum governance should be recognised as a key enabler of sustainable development in contemporary digital economies.

5.11. Conceptual Advancement of TIEROE

The study ultimately demonstrates that inclusive spectrum governance arises from interactions among technology, inclusion, equity, resource capability, organisation, and the environment. No single dimension is sufficient to achieve universal connectivity, affordability, competition, and digital inclusion outcomes on its own.

The TIEROE framework therefore advances spectrum governance scholarship by providing a multidimensional explanatory lens that integrates previously fragmented theoretical perspectives into a coherent governance model. Through this contribution, the framework lays a new foundation for future research, policy analysis, and regulatory practice in spectrum governance.

5.12. Implementing the TIEROE Framework: A Phased Approach

Regulators seeking to apply the TIEROE framework should consider the following phased approach:

Phase 1: Scoping and Stakeholder Engagement. Define the specific spectrum assignment challenge and engage stakeholders to identify their priorities across the six TIEROE dimensions.

Phase 2: Diagnostic Assessment. Apply the framework to assess the current assignment system. For example: Is the current system technologically neutral? Are there barriers to inclusion? Are assignment outcomes perceived as equitable?

Phase 3: Option Generation. Develop a range of potential assignment mechanisms, such as auctions with set-asides, beauty contests, or shared access.

Phase 4: Multi-Criteria Evaluation. Assess each option against the six TIEROE dimensions by developing appropriate proxy metrics, for example, Technology (spectrum efficiency), Inclusion (projected population coverage), Equity (number of operators), Resource Capability (estimated costs), Organisation (operator readiness), and Environment (regulatory certainty).

Phase 5: Decision and Monitoring. Select the preferred option based on the evaluation and establish a monitoring plan to track outcomes.

6. Conclusions

This research emphasises the RF spectrum as a vital public asset essential for digital growth, innovation, and socio-economic inclusion. Although current spectrum assignment methods have improved efficiency and expanded infrastructure, they often fall short of broader development goals, such as fairness, equitable access, and universal connectivity. The study shows that effective spectrum management requires a multidimensional approach. Outcomes depend not only on assignment processes but also on how six interconnected factors—Technology, Inclusion, Equity, Resource Capability, Organisation, and Environment—interact. These factors form the basis of the TIEROE framework, offering a comprehensive perspective for understanding and assessing spectrum governance.

The study shows that current assignment methods—especially market-based ones—favour incumbents with strong financial and organisational resources, limiting fair participation. As a result, fairness in spectrum management should be evaluated alongside efficiency, taking into account factors such as affordability, accessibility, market diversity, and genuine participation. Universal connectivity is achieved not only through allocation policies but also through broader governance systems that include spectrum sharing, infrastructure access, and inclusive regulatory measures. The TIEROE framework is the main theoretical contribution of this research, integrating previously isolated viewpoints into a unified, ecosystem-focused model. It enhances academic understanding by emphasising inclusion and equity as key governance goals and by viewing spectrum governance as a dynamic system influenced by technological, institutional, and socio-economic factors.

From a policy perspective, the study underscores the need to reframe spectrum governance as a strategic instrument for digital transformation. Regulators should adopt multidimensional evaluation criteria and increasingly deploy innovative approaches, including dynamic spectrum access, community licensing, and open-access models. Embedding spectrum policy within broader digital development strategies is essential to achieving sustainable and inclusive outcomes. Although the study is conceptual and based on secondary data, it lays a foundation for future empirical validation and comparative analysis. Further research is required to operationalise the TIEROE dimensions, test their interrelationships, and assess their applicability across diverse regulatory environments.

Although the TIEROE framework provides a comprehensive approach to commercial spectrum governance, its applicability is limited. The framework is specifically tailored for high-demand mobile communications bands. It does not address highly specialised areas such as satellite coordination, defence and public safety spectrum, or deep-space communications, where technical and security priorities frequently take precedence over socio-economic objectives. Furthermore, the framework is not suitable for unlicensed spectrum policy, for which a different governance model, namely the 'commons,' is more appropriate.

Future research is necessary to operationalise the TIEROE dimensions, examine their interrelationships, and evaluate their applicability in various regulatory contexts. The six propositions formulated in this study provide a structured framework for future empirical validation through case studies, surveys, or structural equation modelling (SEM) approaches.

In conclusion, the future of spectrum governance lies not merely in efficient allocation, but in ensuring that spectrum resources enable inclusive digital participation, equitable economic opportunity, and sustainable development. The TIEROE framework provides a robust foundation for advancing this paradigm and for guiding more balanced and inclusive spectrum governance practices.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
CBRS	Citizens Broadband Radio Service
DCDT	Department of Communications and Digital Technologies
DSA	Dynamic Spectrum Access
FCC	Federal Communications Commission
GSMA	Global System for Mobile Communications Association
ICT	Information and Communication Technology
ICASA	Independent Communications Authority of South Africa
IoT	Internet of Things
ITU	International Telecommunication Union
OECD	Organisation for Economic Co-operation and Development
RBV	Resource-Based View
RF	Radio Frequency
SDG	Sustainable Development Goal
SEM	Structural Equation Modelling
TIEROE	Technology–Inclusion–Equity–Resource Capability–Organisation–Environment
TOE	Technology–Organisation–Environment

USO	Universal Service Obligation
5G	Fifth-Generation Mobile Technology
6G	Sixth-Generation Mobile Technology

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