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Social Value of Technology Simulation: Path Exploration of Positioning Antenna Optimization to Empower Ecological Watershed Management

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Abstract: In the context of global ecological governance transitioning from “end-to-end control” to “intelligent prevention”, signal instability of positioning antennas in complex geographic environments has become a key technological bottleneck restricting the effectiveness of eco-basin governance. In this study, the performance defects of the traditional single-frequency signal receiving antenna are systematically optimized by introducing electromagnetic simulation technology, and a dual-frequency microstrip antenna array simulation model is constructed to support the cooperative reception of multi-satellite signals. Experimental results show that the optimized antenna achieves significant improvement in signal reception stability and positioning accuracy, providing reliable technical support for real-time accurate monitoring in ecological watershed management. Based on the above technical results, this paper further discusses the practical path of technical simulation empowering ecological watershed management, which provides new ideas for the innovation and practice of watershed management policy.

Keywords: Technology Simulation; Antenna Performance Optimization; Ecological Watershed Management; Signal Stability.

1. Introduction

1.1. Background and Significance of the Study

Ecological watershed management is a key link in maintaining regional ecological balance and realizing sustainable use of water resources [1]. In key no-take areas, the frequent occurrence of illegal angling activities poses a serious threat to the stability of watershed ecosystems [2]. Although navigation antenna technology has been applied to the monitoring work of law enforcement departments, the single-frequency satellite positioning antennas commonly used in existing devices often cause significant reduction in positioning accuracy due to signal blockage, interference and attenuation in complex geographic environments, such as mountainous canyons and dense forests, making it difficult to effectively support the real-time monitoring needs of illegal fishing behaviors [3].

In recent years, the rapid development of simulation technology provides a new research path for hardware performance optimization. In the field of positioning antenna design, simulation technology can comprehensively assess the adaptability of different technical solutions through multi-scenario simulation, so as to identify and solve potential problems at the early stage of research and development. In this paper, taking the dual-frequency microstrip antenna array design as an example, optimizing its performance in complex environments with the help of simulation can not only effectively reduce the R&D cost, but also accelerate the transformation process of the technical achievements into practical applications, providing more reliable technical guarantee for ecological protection work. Thus, the research of positioning antenna optimization based on simulation technology is of great theoretical and practical significance for improving the effectiveness of ecological watershed management.

1.2. Domestic and Foreign Research Status

Foreign research on the optimization of satellite positioning antenna performance in complex environments started early and achieved remarkable results. With the help of advanced simulation technology, developed countries carry out a large number of simulation experiments for multi-mode and multi-frequency antennas, which improves the antenna's ability to receive signals in complex environments [4]. Domestic positioning antenna technology and ecological watershed management has also made great progress, but there is still room for exploration in the optimization of positioning antenna performance in complex environments and the deep integration of ecological watershed management.

1.3. Research Methods and Innovations

This study adopts a mixed research methodology, integrating multifaceted methods such as literature research, simulation and case analysis, and social science research methods[5]. The innovations are as follows: first, focusing on positioning antenna optimization and ecological watershed governance, the simulation technology is used to propose targeted antenna optimization solutions; second, from the perspective of social governance [6], combined with institutional analysis and policy process theory, the practical path of technology simulation-enabled eco-watershed governance is proposed.

2. Literature Review

2.1. Current status of Technology Application in Ecological Governance

In recent years, the application of digital technology in ecological governance has been deepening. The introduction of digital twin theory in the field of public governance has provided new methodological support for real-time monitoring and dynamic simulation of ecosystems [7].

However, the complexity of the ecological watershed environment poses a serious challenge to the localization and monitoring technology. Variable topographic conditions, climatic characteristics and complex interactions of ecological elements lead to the difficulty of existing technologies in meeting the needs of refined governance in terms of data collection accuracy and information transmission stability.

2.2. The Value of Simulation Technology in Hardware Optimization

Simulation technology shows unique application value in the field of hardware performance optimization. Taking the communication field as an example, the mature application of multi-physical field coupling simulation technology significantly improves the performance optimization efficiency of communication equipment [8]. By simulating the effects of different environmental variables on signal transmission in the R&D stage, it can effectively reduce the cost of trial and error, shorten the R&D cycle, and improve the practical application efficiency of the equipment. Especially in the design of new communication antenna, simulation technology by simulating the antenna radiation characteristics and signal reception performance under different frequency bands and environmental conditions, for the antenna structure optimization and parameter adjustment to provide a scientific basis, thus enhancing its anti-interference ability and signal transmission stability in the complex electromagnetic environment.

2.3. Limitations of the Existing Positioning Antenna Technology

The current widely used single-frequency satellite signal receiving antenna (e.g. GPS antenna) has obvious performance deficiencies in complex environments. Because it only supports the signal reception of a single satellite system, it lacks an effective compensation mechanism when the signal is interfered, resulting in a significant decrease in positioning accuracy. In urban high-density building areas, GPS signals are susceptible to reflections and occlusions from buildings, resulting in multipath effects that further exacerbate positioning deviations [9]. In addition, a single antenna has limited anti-jamming capability in weak signal environments, and it is difficult to effectively extract the target signal from noise, which seriously restricts the reliability of the positioning system. These technical deficiencies limit the effectiveness of its application in complex scenarios such as ecological watershed management.

2.4. Importance of Positioning Accuracy and Signal Reliability for Ecological Watershed Management

In the practice of ecological watershed governance [10][11][12], high-precision positioning technology is the key support for combating illegal angling activities. Accurate positioning information can help law enforcement departments to quickly lock the target location and take timely intervention measures, so as to effectively protect the ecological resources of the watershed. On the contrary, the lack of positioning accuracy may lead to inefficient law enforcement and make it difficult to curb the damage of illegal activities to the ecosystem. At the same time, the reliability of signal transmission directly affects the stability of the monitoring system, ensuring the continuity and accuracy of data and providing real-time support for governance decisions. Taking water quality monitoring as an example, signal interruption or distortion may lead to the absence of critical data, delaying the timing of governance. Therefore, improving positioning accuracy and signal reliability is an important technical guarantee for realizing effective governance of ecological watersheds.

2.5. “Technology Enabled Governance” Theoretical Spectrum

Heeks' theory of digital governance emphasizes the transformative role of information technology in public governance, arguing that the in-depth application of digital technology can reconfigure the mode, process and structure of governance, and thus enhance governance effectiveness [13]. In the ecological watershed governance scenario, the positioning antenna optimization technology, as an important part of the digital governance system, can realize the digital monitoring and intelligent management of the watershed ecology through the integration of the Internet of Things, big data and other technologies, which can significantly improve the accuracy and timeliness of governance.

Granovetter's “technology embeddedness” theory reveals the social attributes of technology application, pointing out that technology does not exist independently, but is embedded in specific social relations and institutional environment [14]. In eco-watershed governance, the application of antenna technology is affected by multiple factors such as social relations among governance subjects and policy institutions. For example, there are significant differences in the acceptance and application of the technology among different subjects such as governments, communities and enterprises, which are closely related to their roles and interests in the social governance network.

Ostrom's theory of “polycentric governance” provides a new analytical framework for understanding eco-watershed governance. The theory emphasizes that the effective governance of public affairs requires the collaboration of government, community organizations, enterprises and other subjects to form a governance network. The application of positioning antenna optimization technology can change the information acquisition and interaction between governance subjects, and then reconfigure the structure and function of the governance network. For example, community residents participate in the supervision of illegal fishing behaviors through optimized positioning technology, forming a collaborative governance mechanism with government law enforcement departments, which reflects the innovation of governance mode under the empowerment of technology.

3. Impact of Positioning Antenna Optimization on Ecological Watershed Management

3.1. Technical Principles of Array Design and Social Value Correlation

In the practice of ecological watershed management, stable signal reception and accurate positioning are the core technical support to realize efficient supervision. This study establishes an effective connection between technical feasibility and governance needs based on a three-array microstrip antenna array design (hereafter referred to as "multi-node cooperative monitoring system") in the same dimension.

At the level of technical constraints, the study combines simulation conditions and resource constraints, adopts a planar zigzag layout, and optimizes the spacing of the array elements to $d = 0.75\lambda$ to balance the mutual coupling effect between the antennas [15]. Although three-dimensional spatial topology reconstruction is technically feasible, this study has significantly improved the signal reception effect through single-dimensional optimization, so the three-dimensional spatial factor is not included for the time being.

Aiming at the performance limitations of the traditional single-band antenna under multipath effect, the study adopts the dual-band signal reception scheme of BDS B1 and GPS L1, and the data fusion and algorithmic processing through the receiving equipment effectively improves the anti-jamming capability of the system.

On the demand adaptation mechanism, the study constructs the mapping function between the gain $G(\theta)$ of the multi-node cooperative monitoring system and the coverage C of the poaching monitoring:

$$C = \int_0^{2\pi} G(\theta) * \text{Pactivity}(\theta) d\theta \tag{1}$$

Among them, Pactivity(θ) is the azimuthal probability density function of poaching behavior, and the data come from the analysis of historical law enforcement records. Through this function, the study was able to optimize the design parameters based on the spatial distribution characteristics of poaching behavior, thus improving the monitoring coverage and providing more targeted technical support for ecological watershed management. This design not only improves the technical efficiency, but also enhances the community's ability to participate in governance through more accurate monitoring data, which promotes the transformation from a single government-led model to a multi-governance model, which is highly compatible with Ostrom's theory of "polycentric governance".

3.2. Social Governance Implications of Planar Array Electromagnetic Simulation Results

Based on the demand for wide-area coverage and signal reliability in ecological watershed governance, and the similarity of the frequency bands of BeiDou B1 (1561.098± 2.046 MHz) and GPS L1 (1575.42±1.023 MHz), the study sets the operating frequency band of the microstrip antenna to cover the above frequency bands and the related signals, and the center frequency is designed to be f_0=1570 MHz.

In the single-array element design, the dielectric substrate size is set to 79.91 × 79.91 × 4 mm, and the parameters are calculated and modeled based on the microstrip antenna size equation [16], as shown in Figure 1. The patch size variable parameters Table 1 are obtained by optimization through HFSS simulation software.

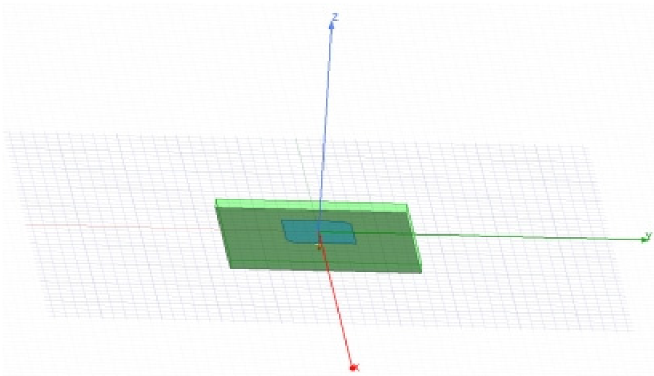


Figure 1. Simulation model

Table 1. Parameter values of individual array element variables

Name	Variable	Parameter variable name	Variable value /mm
Rectangular dielectric substrates	Lengths	X	79.91
	Thicknesses	H	4
Radiation patch	Lengths	L	28.99
	Height	W	28.87
Coaxial feedpoint	X-axis	X0	5.34
	Y-axis	Y0	0
Wavelength	1/4λ Working wavelength	λ0	47.77

The multi-node cooperative monitoring system adopts a "zigzag" planar layout, as shown in Figure 2, and the spacing of the array elements is fixed at d=142.74 mm, which is combined with the parameters of the single-array element for simulation and analysis. The results show that the maximum gain value of the single-array element antenna is 6.13 dB, while the maximum gain value of the multi-node system is increased to 6.81 dB, as shown in Fig. 3, which indicates that the latter has a significant advantage in the signal reception capability and coverage. In addition, the front-to-back ratio of the E-plane directional map of the multi-node system is better than that of the single-array element antenna, as shown in Fig. 4. And the mutual coupling effect between the array elements is low (-27 dB for the S12 parameter), as shown in Fig. 5, which meets the practical application requirements.

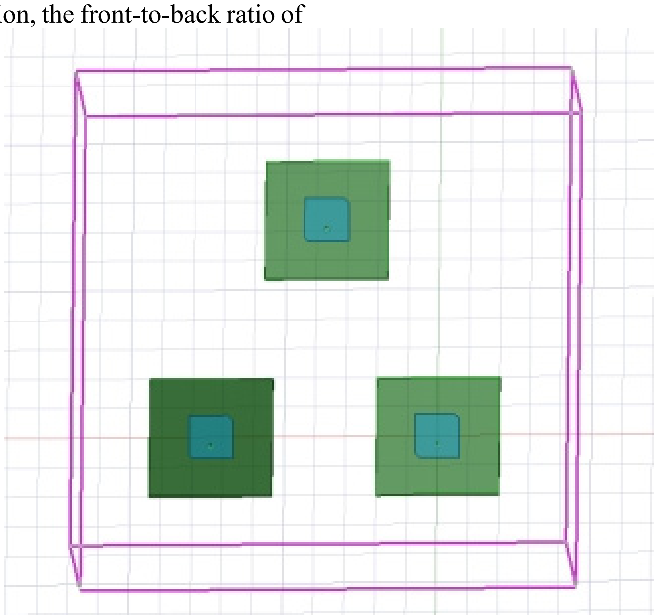
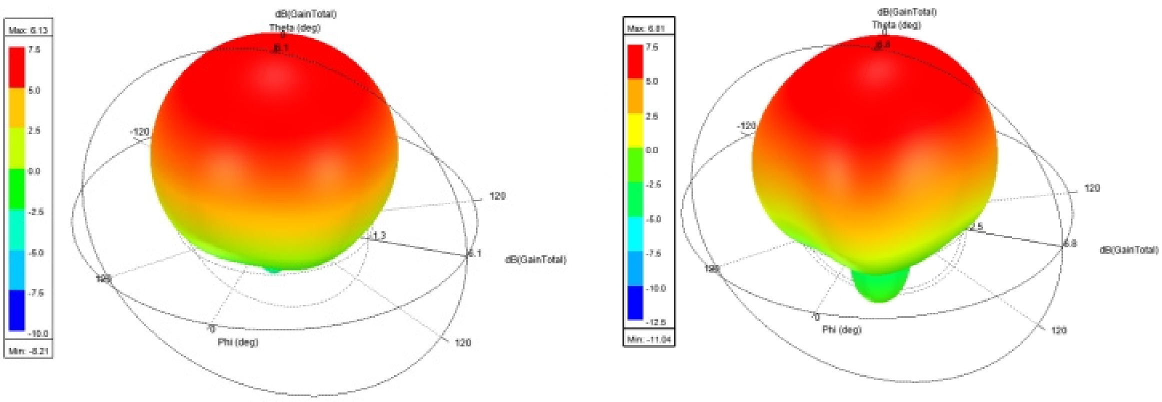
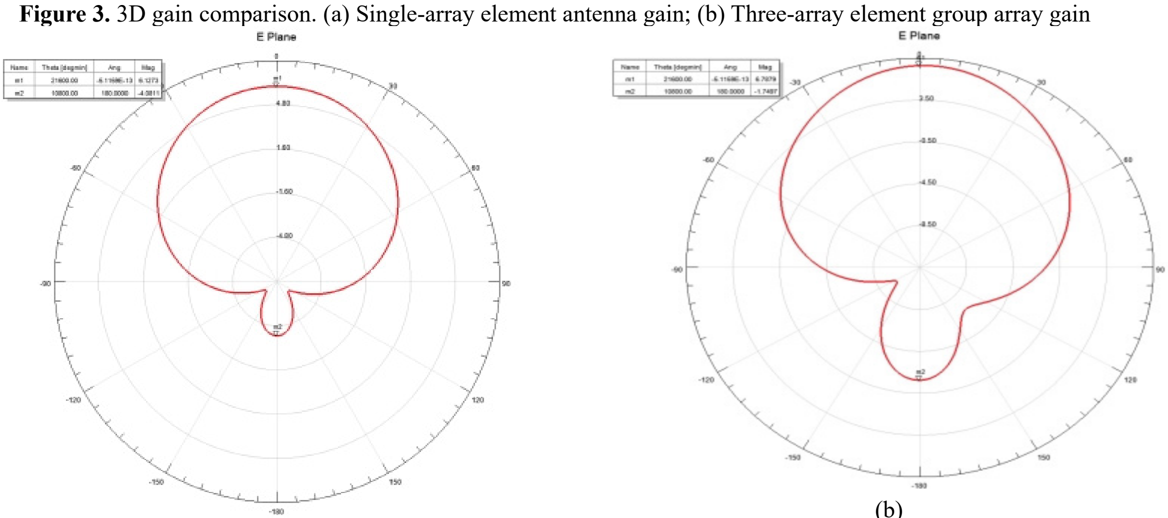


Figure 2. Simulation Model



(a) (b)

Figure 3. 3D gain comparison. (a) Single-array element antenna gain; (b) Three-array element group array gain



(a) (b)

Figure 4. E-plane orientation diagrams. (a) single-array element antenna; (b) three-array element grouped array

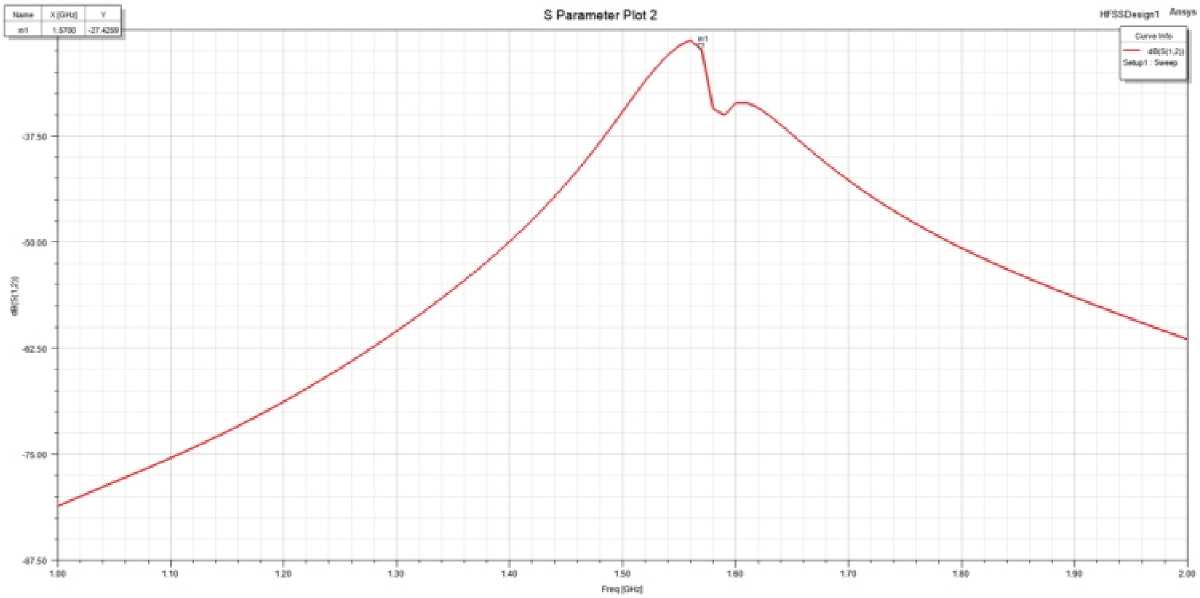


Figure 5. S (1,2) parameters

These technical achievements have far-reaching social significance for ecological watershed management. In the area of illegal fishing monitoring, the high-precision positioning capability enables law enforcement officers to quickly lock the target location, which significantly improves the efficiency of law enforcement, effectively curbing illegal fishing behavior and safeguarding the ecological safety of the watershed. In the field of ecological monitoring, stable signal transmission ensures the accuracy and continuity of monitoring data, providing a reliable basis for ecological environment assessment and scientific decision-making. From the perspective of governance structure, the optimized positioning technology not only strengthens the regulatory capacity of government departments, but also provides technical tools for communities and enterprises to participate in ecological governance, and promotes the formation and development of polycentric governance network.

3.3. Social Science Implications of Technological Evolution for Ecological Watershed Management

From the direction of technological evolution, the introduction of a mechanically adjustable mount for flexible adjustment of the spatial position of the array elements can significantly improve the adaptability of the system to complex terrain. However, this improvement requires collaborative innovation in the field of material science to enhance the weather resistance of the flexible substrate and ensure the long-term stable operation of the antenna in harsh environments. This technological upgrade not only improves system performance, but also has a profound impact on governance models. For example, in remote mountainous watersheds, the flexible and adjustable antenna system can monitor illegal activities more accurately and reduce the reliance on human patrols, thus restructuring the governance cost structure. In terms of governance supporting mechanism, the study proposes to establish an intelligent matching system of “antenna topology database and terrain GIS layer”, realizing the environmental adaptive optimization of antenna topology, and promoting the transformation of static array to intelligent array. This technical path not only improves the system efficiency, but also promotes the collaboration between the main governing bodies. Government departments, technology enterprises and research institutions can jointly participate in the construction and maintenance of the database and system, forming a multi-party synergistic governance pattern, which is highly consistent with the core proposition of the theory of “polycentric governance”.

4. Practical Path of Technology Simulation Enabling Ecological Watershed Governance

4.1. Innovation and Exploration of Technology Integration and Application Mode

The optimized positioning antenna technology can deeply integrate cutting-edge technologies such as the Internet of Things, big data and artificial intelligence, building a technological integration framework for ecological watershed management. The introduction of IoT technology realizes the interconnection of distributed monitoring equipment in the watershed, breaks the traditional phenomenon of information islands, and provides a technical basis for real-time data transmission and sharing. The application of big data technology provides data support for scientific decision-making in ecological watershed management through efficient storage and deep mining of massive positioning data and ecological monitoring data to extract information with decision-making value.

The advantages of artificial intelligence technology in data analysis and prediction further enhance the effectiveness of governance. For example, intelligent analysis of the spatial and temporal patterns of illegal fishing activities through machine learning models can predict the high incidence areas and time periods of illegal fishing, thus optimizing the allocation of law enforcement resources and realizing precise law enforcement.

From the perspective of social governance, the innovation of this technology integration and application model significantly improves the efficiency of synergy among governance subjects. Government departments, research institutions and enterprises can realize data sharing and business collaboration based on a unified platform, which promotes the digital transformation of the governance model. At the same time, the introduction of intelligent prediction function enhances the public's confidence in ecological governance, stimulates the enthusiasm of social forces to participate in ecological protection, and provides technical support for the construction of a multi-dimensional common governance pattern.

4.2. Deep Integration Strategy with Ecological Monitoring System

The deep integration of positioning antenna optimization technology with the existing ecological monitoring system is a key path to improve the effectiveness of watershed management. As the core foundation of the ecological monitoring system, the optimized positioning antenna realizes accurate tracking and management of the monitoring equipment through high-precision positioning information, which significantly improves the accuracy of the monitoring data and the system operation efficiency.

In order to realize the integration of technology, the subsequent research can build a unified communication protocol and data interface standard to ensure the seamless connection between the positioning antenna and the ecological monitoring system. The real-time positioning data transmitted by the positioning antenna provides an important input for the data analysis and decision optimization of the monitoring system. This deep integration strategy not only improves the technical performance of the ecological monitoring system, but also promotes the synergy of multiple actors in ecological protection. Environmental organizations and scientific research teams can carry out research and protection work based on more accurate monitoring data, which promotes the formation of a good atmosphere for the whole society to participate in ecological protection.

5. Institutional Frictions and Adaptations in Technology Enablement

5.1. Policy Barriers in Technology Diffusion

During the diffusion of positioning antenna optimization technology, policy barriers have become a key factor constraining its widespread application. Among them, the data privacy controversy is particularly prominent. With the improvement of positioning accuracy, a large amount of personal activity data has been collected, triggering widespread public concern about privacy leakage. Residents in some areas are resistant to the deployment of location monitoring devices in their living areas, which brings significant resistance to the scaled-up application of the technology.

In addition, barriers to cross-sectoral collaboration have also seriously affected the effectiveness of technology diffusion. Eco-basin management involves a number of departments such as environmental protection, fisheries, and water conservancy, etc., and there are significant differences between the departments in terms of data sharing, equipment management, and law enforcement coordination, with a lack of effective synergistic mechanisms. For example, the environmental protection department focuses on the monitoring of ecological data, while the fishery department focuses on the monitoring of illegal fishing behavior, and this difference in data standards and application goals exacerbates the difficulty of inter-departmental collaboration, thus weakening the effectiveness of the governance of technology application.

5.2. Adaptive Reform Paths Based on the Theory of Institutional Change

Based on North's theory of “institutional change”, institutional change is a complex and systematic process that requires breaking through the path dependence of the existing system and constructing new institutional arrangements. To address the issue of data privacy, it is recommended to formulate special data protection regulations to clarify the norms of data collection, use and storage. For example, it can be stipulated that the positioning data is limited to ecological watershed governance purposes, and the data should be strictly encrypted to safeguard the security of personal privacy.

In terms of cross-sectoral collaboration, a unified coordinating body should be established to formulate cross-sectoral data sharing standards and cooperation rules. By clarifying the boundaries of responsibilities and the scope of authority of each department in ecological watershed governance, information communication and business synergy between departments should be strengthened. This kind of institutional innovation can not only promote the effective application of positioning antenna optimization technology, but also realize the synergistic evolution of technology and system, and provide institutional guarantee for the modernization and transformation of ecological watershed governance.

6. Summary

This paper focuses on the integration of technology optimization and social governance in ecological watershed governance. Aiming at the performance limitations of traditional single-frequency antennas in complex environments, we designed a multi-node collaborative monitoring system through simulation, optimized the key parameters, and significantly improved the antenna's signal reception capability and environmental adaptability. From the perspective of social science theory, the study introduces the theories of “technology-institution co-evolution” and “polycentric governance”, and systematically analyzes the impact of technology optimization on the power structure of governance subjects.

This paper not only provides technological optimization solutions, but also explores the application of social science theories in ecological governance, and provides new ideas for policy innovation and practice of ecological watershed governance.

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Nanchong Federation of Social Science Associations+Big Data and Satellite Positioning System Enabling the Construction of Ecological Civilization in the New Era-The Jialing River Basin as an Example+ NC24C103.

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