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Research on Simulation and Evaluation Technologies of Emergency Wireless Communication Systems

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Abstract: This article has conducted a thorough study on the problems existing in the current simulation and evaluation technology of emergency wireless communication systems, and proposed a targeted simulation modeling method for emergency wireless communication systems. It has built a simulation model for emergency wireless communication systems, and effectively combined channel simulation with network simulation. In addition, according to the system characteristics and task features of emergency wireless communication, this article has constructed an evaluation index system suitable for emergency wireless communication systems, and proposed an evaluation method for emergency wireless communication system effectiveness based on fuzzy comprehensive method, forming a simulation evaluation architecture specifically designed for the uniqueness of emergency wireless communication systems.

1. Introduction

Emergency wireless communication systems refer to wireless communication network architectures specifically designed for mergency scenarios, featuring high reliability, fault tolerance, and rapid deployment capabilities[1]. These systems enable real-time transmission of critical information in complex environments such as disaster zones and emergency situations. They provide essential communication support for emergency rescue coordination, rescue coordination, situational awareness, and other vital operations, playing an indispensable role in modern emergency management systems.

Simulation and evaluation technologies play an indispensable role in the overall design and analysis of emergency wireless communication systems[2]. They significantly enhance research and development efficiency and quality during the system development phase, while effectively reducing costs and risks. This provides a solid foundation for stable operation and performance optimization of the systems. However, current research on emergency wireless communication simulation and evaluation still shows deficiencies in studying overall system performance and interactive effects [3].

This paper thoroughly investigates the existing problems in current emergency wireless communication simulation and evaluation research and innovatively proposes a simulation architecture for emergency wireless communication systems. We present an effective joint method for channel simulation and network simulation. Additionally, we propose a performance indicator system and evaluation methodology for emergency wireless communication systems, forming a specialized simulation and evaluation framework tailored to the unique requirements of emergency wireless communication systems.

2. Simulation and Modeling Technologies for Emergency Wireless Communication Systems

2.1 Node Model

The node model is responsible for modeling each node within the network, with each node model configured with one or more communication/switching device models as required. In emergency wireless communication networks, each communication node loads and executes corresponding communication protocols to accomplish functions such as service message access, transmission control, and route maintenance.

The node model can be divided into four parts[4], including the application layer module, transport layer module, network layer module, and link layer module. Among them, the application layer module and transport layer module consist of transmission functions and reception functions; the network layer module includes transmission functions, reception functions, routing functions, and maintenance functions; the link layer module consists of access components for various communication methods such as tropospheric scatter access, meteor burst access, and ultra-shortwave access, with each communication method's access component including transmission functions and reception functions.

The network model completes the modeling of multi-method, multi-route network topologies[5]. Connections between nodes can be configured as needed. In this paper, communication links are exemplified by typical emergency wireless communication methods such as tropospheric scatter, meteor burst, and ultra-shortwave.

The network model can construct communication networks and configure communication resources according to simulation requirements, with link deployment types divided into single communication mode and multi-communication mode.

2.1.1 Single-communication-mode Link Deployment

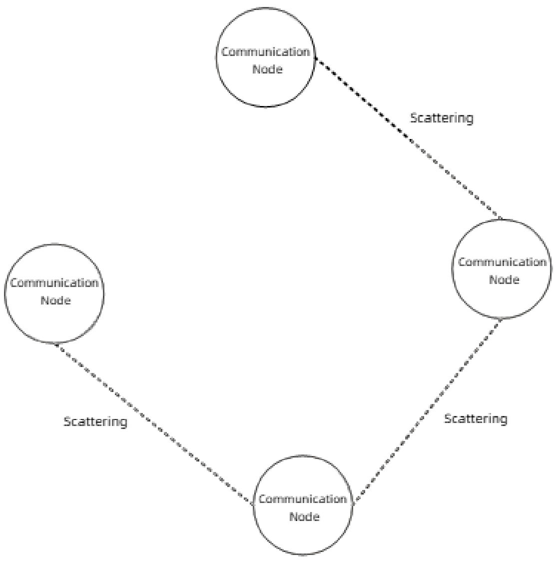

Fig.1 Chain deployment with a single communication method

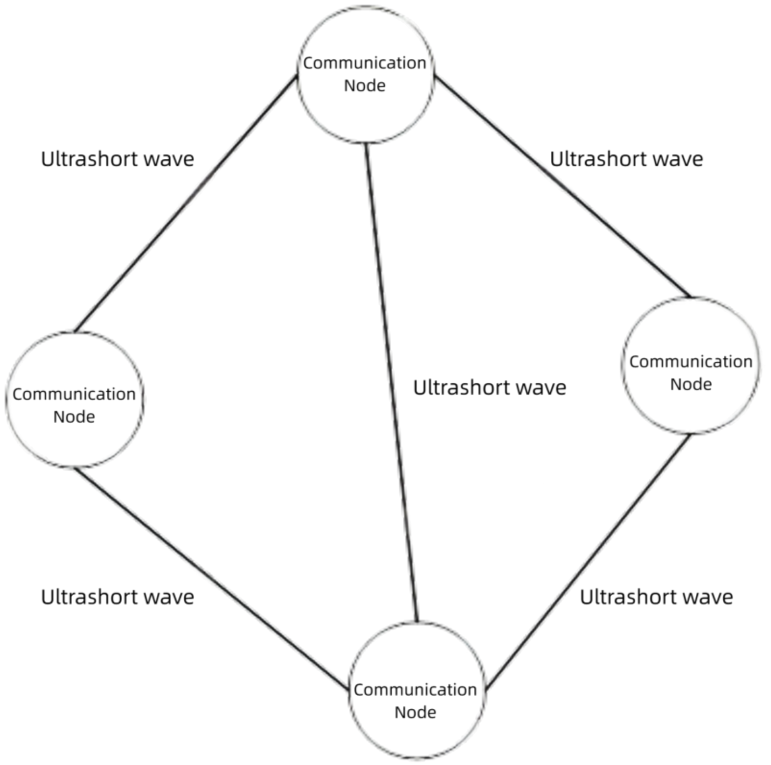

Fig.2 Mesh deployment with a single communication method

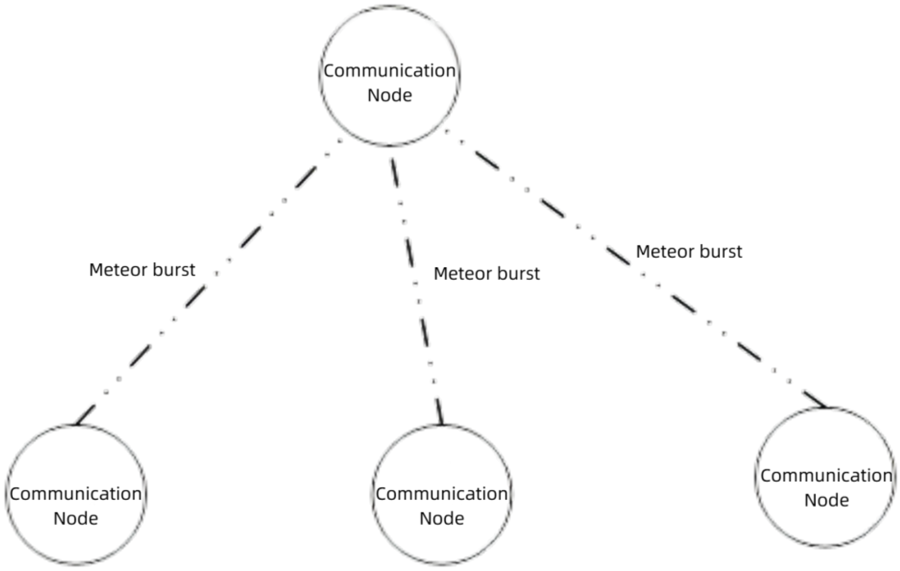

Fig.3 Star-shaped deployment with a single communication method

The network is deployed using individual communication methods including tropospheric scatter, meteor burst, and ultra-shortwave (VHF/UHF) respectively. The schematic diagrams of the network topologies are shown in Figures 1to 3.

2.1.2 Hybrid-communication-mode Link Deployment

The topology of hybrid-communication-mode link deployment is illustrated in Figure 4. Communication nodes are interconnected through multiple communication links, with the hybrid communication network typically adopting either a tree topology or mesh network structure.

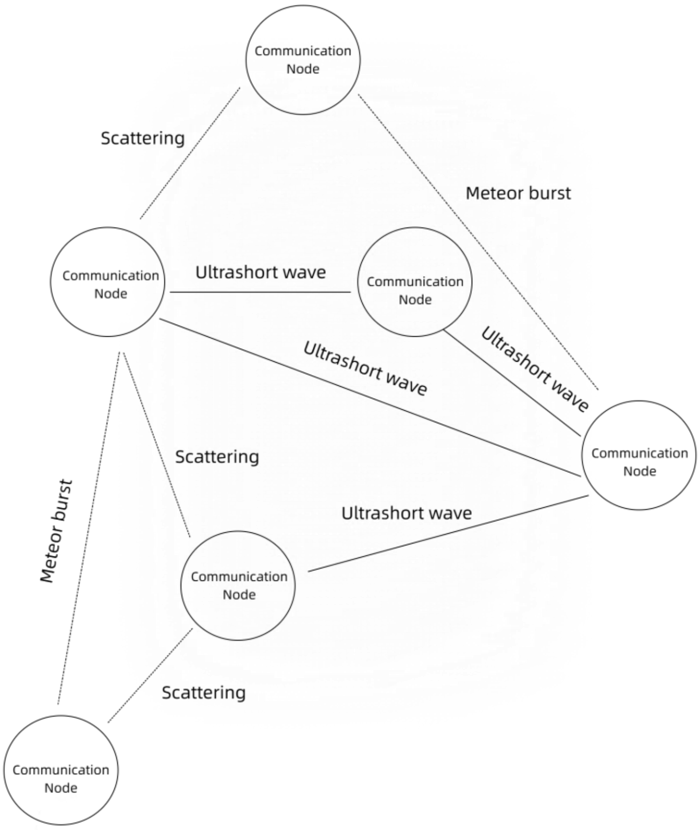

Fig.4 Multi-communication mode link deployment

2.2 Channel Model

To realistically simulate the transmission characteristics of communication channels in complex environments, modeling must incorporate terrain and meteorological effects to replicate the transmission performance of various communication methods under different conditions.

2.2.1 Tropospheric Scattering

This paper proposes a tropospheric scattering channel propagation loss calculation method combining terrain data with parameter computation, based on the typical propagation principles given in Recommendation P.617-3 [6] published by the ITU Radiocommunication Sector.

The tropospheric scattering link loss mainly consists of several components, including basic transmission loss, ground reflection loss, atmospheric absorption loss, antenna misalignment loss, and antenna-medium coupling loss [7].

The basic transmission loss occupies a central position in the tropospheric scattering link loss, with its comprehensive expression as follows.

$$L_b = M + 30\lg f + 30\lg\Theta + 10\lg d + 20\lg(5+\gamma H) + 4.343\gamma h \tag{1}$$

In the formula, f represents the frequency(MHz); d represents the communication distance(km); Θ stands for the scattering angle($mrad$); H indicates the vertical offset between the scattering point and the transceiver line-of-sight(km); h specifies the scattering point's altitude above ground(km); M , γ are meteorological and atmospheric stratification parameters respectively.

Based on the above analysis, it can be concluded that the key parameters affecting tropospheric scattering propagation loss are Θ, H and h, and h. These critical parameters are primarily determined by the elevation profile between the transmitting and receiving stations. A geometric analysis model of the terrain profile for a typical tropospheric scattering link is illustrated in Figure 5.

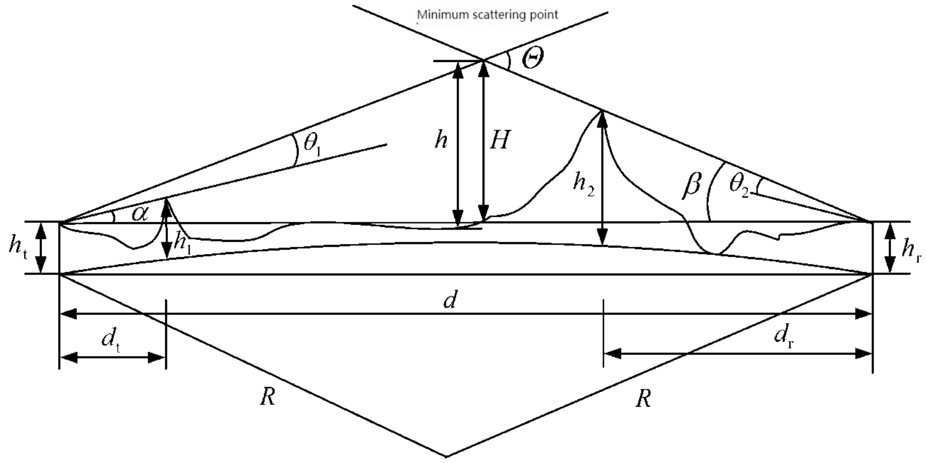

Fig.5 Topographic profile of the tropospheric scatter link

In the terrain profile diagram shown in Figure 5, d represents the distance between transmitting and receiving antennas in the tropospheric scattering communication link(km); h_t , h_r denote the elevation heights of transmitting and receiving station antennas respectively(km); h_1 , h_2 indicate the elevation heights of key obstructing terrain features for transmitting and receiving stations(km); d_t , d_r specify the distances from transmitting and receiving stations to their respective key obstacles (km); l_t , l_r represent the horizontal distances from transmitting and receiving stations to the lowest scattering point(km); θ_1 , θ_2 stand for the angles between the local horizon and propagation path at transmitting/receiving stations, also known as elevation angles (rad); α , β are the angles between the propagation path and the line connecting transmitting/receiving stations (rad).

2.2.2 Meteor Burst

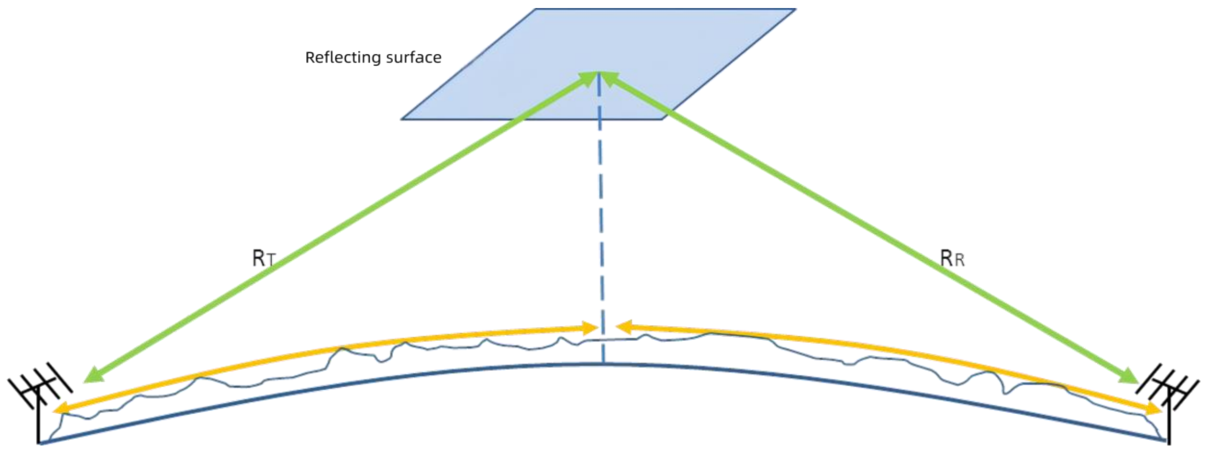

Fig.6 Meteor trail channel propagation diagram

In the early 1950s, Eshleman et al. proposed the most commonly used underdense meteor trail channel mathematical model [8]. A typical propagation schematic of the meteor trail channel is shown in Figure 6.

$$P_R(t) = P_R(0)e^{-t/\tau} \tag{2}$$

In the equation, $P_R(t)$ represents the received signal power, $P_R(0)$ denotes the initial power of the reflected radio wave, τ is the attenuation factor of the received power, $P_R(0)$ calculated as shown in Equation 3, τ calculated as shown in Equation 4.

$$P_R(0) = \frac{P_T G_T G_R \lambda^3 q^2 r_e{}^2 \sin^2\alpha}{16\pi^2 R_T R_R (R_T + R_R)(1-\cos^2\beta \sin^2\phi)} \tag{3}$$

$$\tau = \lambda^2 \sec^2\phi / 32\pi^2 D \tag{4}$$

By substituting $P_R(0)$ and τ into Equation 2, the received signal power of the meteor burst can be calculated as shown in Equation 5.

$$P_R(t) = \frac{P_T G_T G_R \lambda^3 q^2 r_e{}^2 \sin^2\alpha}{16\pi^2 R_T R_R (R_T + R_R)(1-\cos^2\beta \sin^2\phi)} \times \exp\left(\frac{-32\pi^2 D}{\lambda^2 \sec^2\phi} t\right) \tag{5}$$

P_T otes the transmit power, G_T represents the antenna gain of the transmitting equipment, G_R indicates the antenna gain of the receiving equipment, λ stands for the wavelength, q is the electron line density, D specifies the diffusion coefficient of the meteor trail column, R_T represents the distance from the transmitting equipment to the tangent point of the meteor trail plane, R_R denotes the distance from the receiving equipment to the tangent point of the meteor trail plane, α is the angle between the trail's electric field vector and the incident wave's electron vector, β indicates the angle between the trail's electric field vector and the plane, 2ϕ represents the angle between the incident and reflected waves, t is the time variable.

Not all meteor trails that appear can be utilized by the communication channel. To be available for signal transmission, a meteor trail must satisfy the following conditions:

The ionized meteor trail must occur within the common area where the antenna beams of both transmitting and receiving stations intersect;

The reflection angle of the radio wave must equal its incidence angle;

The signal strength of waves reflected or scattered by the ionized trail at the receiving point must exceed the reception threshold of the receiving equipment.

Based on the above conditions, the channel propagation model of meteor trails can be simplified, yielding the following calculation formula for the received signal power of meteor trails:

$$P_R(0) = 17.024 \times 10^{-7} \frac{\mathrm{P}_T q^2}{R_T R_R (R_T + R_R) f^3} \tag{6}$$

In the equation, P_R represents the received power, q denotes the electron line density, f indicates the operating frequency of the equipment.

Since the incident distance and reflection distance are approximately equal, the approximate formula can be derived as follows:

$$R_T = R_R = \left[\frac{l^2}{4} + \left(h + \frac{l^2}{8R} \right)^2 \right]^{1/2} \tag{7}$$

From the above equation, it can be concluded that the incident distance l and reflection distance h depend solely on the great-circle distance between the transmitting and receiving stations and the altitude of the meteor trail. The calculation formula for the meteor trail altitude is given by:

$$h = 124 - 17 \lg f \tag{8}$$

2.2.3 Ultra-Shortwave

The Longley-Rice model[9], also known as the Irregular Terrain Model (ITM), is primarily used to predict median transmission loss caused by terrain irregularities in free space. This model is particularly suitable for communication scenarios with frequency ranges between 20MHz and 40GHz, and path lengths from 1km to 100km. In the Longley-Rice model, it combines the path geometry of topographic terrain with tropospheric diffraction characteristics to estimate median transmission loss. Specifically, it employs a two-ray ground reflection model to simulate transmission field strength within the radio horizon, and adopts the Fresnel-Kirchhoff knife-edge model to calculate diffraction loss. Meanwhile, the model applies forward-scatter theory to predict long-distance tropospheric scattering, and implements the Van der Pol-Bremmer method to estimate far-field diffraction loss for double-horizon paths. Furthermore, the model's development references the theoretical framework of the ITS Irregular Terrain Model. Therefore, this paper selects the Longley-Rice model as the ultra-shortwave channel model to meet the prediction requirements of relevant communication scenarios.

3. Emergency Wireless Communication System Effectiveness Evaluation Technology

3.1 Emergency Wireless Communication Support Capability Analysis and Evaluation Model

This paper focuses on the operational requirements of emergency wireless communication networks and addresses their capability demands in supporting typical services. By comprehensively applying evaluation techniques such as Analytic Hierarchy Process (AHP) and fuzzy comprehensive evaluation, it completes comprehensive effectiveness analysis and evaluation of emergency wireless communication networks, with particular emphasis on evaluating support capabilities. Through establishing an evaluation index system and comprehensive evaluation model, it achieves comprehensive assessment and analysis of emergency wireless communication networks' emergency response support capability [10].

The emergency wireless communication support capability analysis and evaluation model consists of three components: evaluation system construction, evaluation algorithms, and data integration.

The evaluation system refers to the collection of indicators for assessing emergency wireless communication networks, including throughput, transmission delay, packet loss rate, reliability, etc.

The evaluation algorithms refer to various specific calculation methods used in the evaluation process. This paper constructs and implements calculation methods for evaluation indicators.

Data integration involves consolidating and analyzing data from multiple simulations to evaluate the relationships between emergency wireless communication network performance and factors such as network topology structure, damage levels, and communication means configuration.

The emergency wireless communication system effectiveness evaluation technology integrates data from multiple simulation scenarios, various input data, and numerous simulation results. It conducts comprehensive analysis and processing of simulation data to obtain the overall effectiveness of emergency wireless communication systems.

3.2 Evaluation Indicator Calculation Methods

3.2.1 Principles for Constructing the Effectiveness Evaluation Indicator System

The determination of the effectiveness evaluation indicator system does not merely pursue quantitative expansion; its core lies in ensuring that the selected indicators can yield practical utility during the evaluation process. An ideal indicator system should guarantee objective and reasonable evaluation results while covering key areas of emergency wireless communication system performance. However, an excessively complex indicator system would significantly increase evaluation complexity and difficulty, particularly as data processing workload grows exponentially. Therefore, the establishment of primary effectiveness evaluation indicators must adhere to the following six principles[11]:

1) The completeness principle emphasizes that primary indicators should encompass all factors significantly influencing communication network effectiveness, comprehensively covering all aspects of emergency wireless communication network support capabilities. Insufficient preparation may lead to biased and distorted evaluation results, reducing credibility. Thus, expert consultation is essential when establishing primary indicators to ensure verification completeness.

2) The objectivity principle requires that effectiveness evaluation indicators must closely align with the actual support conditions of emergency wireless communication networks, truthfully reflecting equipment effectiveness. This demands objective analysis combined with practical considerations to ensure all indicators conform to real-world support scenarios.

3) The minimalism principle advocates selecting important and representative indicators as evaluation criteria, meeting assessment needs while avoiding overly complex indicators merely to reduce computational difficulty.

4) The independence principle demands relative independence among evaluation indicators to minimize conceptual overlap and redundancy. If multiple indicators included in the primary evaluation set are interrelated, redundancy occurs, increasing evaluation complexity.

5) The operability principle stresses prioritizing indicators that facilitate quantitative calculation and precise determination, particularly quantitative data that can enhance evaluation efficiency and accuracy through testing.

6) The stability principle requires selected indicators to consistently describe system performance with strong relevance, avoiding arbitrariness and uncertainty, thereby ensuring evaluation result reliability and stability.

The determination of primary effectiveness evaluation indicators is a process that ensures high practicality and applicability of the established indicators, laying the foundation for effectively evaluating emergency wireless communication support effectiveness. This process is progressively refined, deepened, clarified, and comprehensive.

3.2.2 Determining Model Conditions

Based on the simulated communication data including tropospheric scatter and meteor burst, a multi-level fuzzy comprehensive evaluation is conducted to obtain baseline communication performance assessment conclusions. The process first requires establishing the evaluation object set, evaluation factor set, evaluation result set and weight set. The specific implementation steps are designed as follows:

For example, taking meteor burst communication as the evaluation object: first determine its evaluation object set, that is, the collection of objects for evaluating meteor burst communication system performance[12], represented by Formula (12).

$$F = \{F_1, F_2, ..., F_k\} \tag{9}$$

Secondly, establish the evaluation factor set:

$$\begin{aligned} &U = \{U_1, U_2, ..., U_m\}, \\ &U_i = \{u_{i1}, u_{i2}, ..., u_{in_i}\}, \quad i = 1, 2, ..., m \end{aligned} \tag{10}$$

u_{in_i} represents the evaluation factors in U_i, n_i denotes the number of evaluation factors in U_i. According to specific evaluation requirements, the assessment values of evaluation indicators are divided into l grades, with the evaluation result set expressed by Formula (13).

$$V = \{v_1, v_2, ..., v_l\} \tag{11}$$

Next, determine the relative importance of each factor in U and U_i during the comprehensive evaluation process. Let the weight set of each factor in U relative to U be $W = \{w_1, w_2, ..., w_m\}$, where w_i satisfies:

$$\sum_{i=1}^{m} w_i = 1, 0 \le w_i \le 1 \tag{12}$$

Similarly, determine the weight set of U_i as:

$$W_i = \{w_{i1}, w_{i2}, ..., w_{in_i}\} \tag{13}$$

3.2.3 Two-Level Fuzzy Comprehensive Evaluation

In the process of system effectiveness evaluation, many qualitative assessment indicators are often involved, which tend to be ambiguous and difficult to comprehensively and precisely address[13]. The fuzzy comprehensive scoring method can evaluate such fuzzy factors based on the concept of fuzzy transformation in fuzzy mathematics, thereby achieving effective consideration.

This method first establishes an evaluation set, then aggregates the evaluation matrices of various assessment indicators through expert scoring. Subsequently, using predefined membership functions, it converts evaluation values into membership degrees and membership weights. Finally, through fuzzy transformation operations incorporating indicator weights and capacities, specific evaluation results are obtained.

The main evaluation steps are designed as follows [13]:

First, conduct a first-level fuzzy comprehensive evaluation on the n_i factors in evaluation factor set U_i. If the evaluation membership matrix obtained through expert assessment is:

$$R_i = \begin{Bmatrix} r_{11}^i & r_{12}^i & \cdots & r_{1l}^i \\ r_{21}^i & r_{22}^i & \cdots & r_{2l}^i \\ \vdots & \vdots & \ddots & \vdots \\ r_{n_i 1}^i & r_{n_i 2}^i & \cdots & r_{n_i l}^i \end{Bmatrix} \tag{14}$$

From this, we obtain:

$$B_i = W_i \circ R_i = (b_{i1}, b_{i2}, \ldots, b_{il}) \tag{15}$$

B_i is the membership vector of U_i with respect to V ,and also represents the first-level fuzzy comprehensive evaluation result of U_i .The symbol "$\circ$" indicates the composition operation between two fuzzy sets. To comprehensively consider all evaluation indicators, this project employs the weighted average model $M(\bullet,+)$, expressed as:

$$b_{ik} = \sum_{j=1}^{n_i} w_{ij} \cdot r_{jk}, k = 1,2, \ldots, l \tag{16}$$

Based on the above results, by treating each U_i as a factor of U, and considering B_i as its single-factor evaluation vector, we construct the evaluation membership matrix from U to V as follows:

$$R = \begin{Bmatrix} B_1 \\ B_2 \\ \vdots \\ B_m \end{Bmatrix} = \begin{Bmatrix} b_{11} & b_{12} & \cdots & b_{1l} \\ b_{21} & b_{22} & \cdots & b_{2l} \\ \vdots & \vdots & \ddots & \vdots \\ b_{m1} & b_{m2} & \cdots & b_{ml} \end{Bmatrix} \tag{17}$$

From this, we obtain:

$$B = W \circ R \tag{18}$$

B epresents the membership vector of U with respect to V , which is essentially the second-level fuzzy comprehensive evaluation result for U .

Through the aforementioned evaluation process, we obtain the communication capabilities of various transmission methods - including tropospheric scatter, meteor burst, and ultra-shortwave communications - across different geographical regions and network configurations. These evaluation results serve as critical decision-making references for network system effectiveness verification and communication support solution formulation.

4. Experimental Verification

The simulation system, with reference to the network topology model, configures end-to-end simulation service parameters. The simulation duration is 1200 seconds, and the interval between each packet transmission during the simulation process is 30 seconds.

The evaluation team, based on the simulation process data, collects and analyzes the simulation results—including transmission success rate, delay, and throughput—as shown in Table 1.

Table 1 Simulation evaluation results

Primary Indicator	Secondary Indicator	Simulation Result	Evaluation Result
Node Communication Performance	Average Data Throughput Rate	12.7 Byte	0.83
	Average Waiting Time	10.5 s	0.61
	Maximum Waiting Time	28.4 s	0.75
	Maximum Transmission Distance	82.6km	0.98
Link Transmission Performance	Transmission Rate	32.7 Byte/s	0.32
	Bit Error Rate	10⁻⁴	0.79
Service Transmission Performance	Network Throughput	34.3 Byte	0.62
	Transmission Delay	15.3 s	0.75

The indicator weight vector is [0.16, 0.12, 0.06, 0.06, 0.15, 0.15, 0.2, 0.1], and the comprehensive support effectiveness is 0.675.

5. Conclusions

Through in-depth research on simulation and evaluation technologies for emergency wireless communication systems, this paper proposes a set of effective simulation modeling methods and an evaluation system that provides significant guidance for the design and performance optimization of emergency wireless communication systems.

First, the proposed simulation modeling method for emergency wireless communication systems successfully achieves effective integration of channel simulation and network simulation. It can more accurately simulate the operational status of emergency wireless communication systems in complex disaster-affected environments, providing strong support for system design and performance analysis.

Second, an evaluation indicator system suitable for emergency wireless communication systems was constructed. Considering the characteristics and operational requirements of emergency wireless communication systems, an effectiveness evaluation method based on fuzzy comprehensive assessment was proposed. This evaluation approach not only considers multiple aspects of system performance but also comprehensively assesses the overall system performance, providing a scientific basis for optimizing emergency wireless communication systems.

Finally, by establishing a simulation and evaluation architecture specifically tailored to the unique characteristics of emergency wireless communication systems, more comprehensive and in-depth simulation evaluation methods are provided for the development of emergency wireless communication systems. This helps reduce system development costs, improve system performance, and enhance the reliability and stability of emergency wireless communication systems.

The research results are expected to provide more effective support for the design and performance optimization of emergency wireless communication systems in China, including research, development, and application. This work holds significant importance for promoting the development of simulation and evaluation technologies for emergency wireless communication systems.

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