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Organization of Broadband Communication Systems in Rural Areas Based on Energy-Efficient Cognitive Systems

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Abstract: This article analyzes the challenges of providing broadband communication systems to settlements located in remote regions of developing countries, existing technological solutions, and promising approaches based on cognitive systems. In addition, the concept of energy-efficient industrial cognitive systems and their role in optimizing communication infrastructure are examined.

Keywords: Cognitive Systems, Broadband Communication, Rural Areas, Energy Efficiency, Spectrum Management.

1. Introduction

The rapid development of modern information and communication technologies is accelerating digital transformation in all sectors of society. However, in developing countries, the level of access to high-speed Internet services in rural and remote areas remains relatively low. The main reasons include high infrastructure deployment costs, low population density, and insufficient economic feasibility. Therefore, delivering low-cost and energy-efficient communication systems to remote regions has become a major challenge [1].

Deployment of telecommunication infrastructure in rural and remote areas is economically complex. The low-income user segment slows down the return on investment for operators. Furthermore, the instability of the electrical power supply also hinders the development of the network. Although optical networks provide high data rates, extending them to remote regions is often economically inefficient. Therefore, only a limited number of technological solutions are feasible [2].

2. Materials and methods

The first approach involves wireless cognitive radio communication technologies. Cognitive radio-based WRAN (Wireless Regional Area Network) technologies provide wide coverage in rural areas. Low-frequency bands allow signals to propagate over long distances, enabling coverage of large areas with a limited number of base stations [3].

The second approach involves wired communication systems based on cognitive technologies. Cognitive systems use artificial intelligence algorithms to optimize network load, reduce excessive energy consumption, and increase equipment lifetime.

This paper focuses on the second approach. Energy efficiency is one of the key performance indicators of modern communication systems. Particularly in regions with limited power supply, the use of energy-efficient technologies is essential [4].

3. Result and discussion

The efficiency of cognitive systems can be demonstrated using the following expression. Energy efficiency is one of the main indicators of telecommunication system performance and can be defined as [5]:

$$EE = \frac{R}{P}$$

where:
EE – energy efficiency (bit/J)
R – data transmission rate (bit/s)
P – total power consumption (W or J/s)

One of the most critical parameters is the total power consumption, since technological possibilities in remote regions are limited, and transmission rate may be constrained. Therefore, power consumption becomes the primary parameter that can be optimized [6].

In communication or cognitive networks, total power consumption represents the sum of energy consumed by all system components during operation and is expressed as:

$$P=P_{tx}+P_{eq}+P_{proc}$$

where:
Ptx – transmission power consumption
Peq – equipment power consumption
Pproc – data processing power consumption [7].

Cognitive systems optimize transmission power using adaptive power control mechanisms. Functions such as sleep mode (devices enter low-power state when no data transmission occurs) and dynamic hardware management (power allocation is adjusted according to network load) can significantly reduce power consumption. Artificial intelligence and machine learning algorithms also improve data processing efficiency [8].

The proposed approach provides the following advantages:
- Reduction of infrastructure costs
- Reduction of energy consumption
- Improvement of digital equality in rural areas [9].

Cognitive systems can also be effectively applied in industrial energy management, supporting sustainable development goals.

For the purposes of this study, we consider a rural settlement cluster consisting of small population centers separated by distances ranging from 5 to 20 km. Such distances are common in sparsely populated regions and require communication technologies capable of providing stable connectivity over extended coverage areas. The average number of users per settlement is assumed to be between 100 and 500 users, with an estimated broadband demand of 10–50 Mbps per user, which corresponds to the minimum broadband service requirements recommended for rural connectivity [10].

One of the major constraints in rural environments is limited power supply availability. Communication equipment must therefore operate under strict energy efficiency requirements. Typical base station power consumption ranges from 200 W to 800 W, depending on transmission power, signal processing complexity, and cooling requirements [11]. In remote areas, hybrid energy solutions such as solar panels combined with battery storage systems are frequently used to ensure continuous operation of communication nodes. Therefore, minimizing total power consumption becomes a primary design objective [12].

To assess the advantages of cognitive communication systems, it is useful to compare their technical and economic performance characteristics with traditional broadband technologies such as optical fiber access and LTE-based wireless networks [13]. The comparison focuses on key parameters including energy consumption, coverage area, infrastructure cost, and scalability potential [14]. Based on the defined rural scenario parameters, the following Table 1. quantitative comparison table can be constructed.

Table 1. Quantitative Comparison of Broadband Technologies for Rural Areas [15].

Technology	Typical Power Consumption	Coverage Range	Infrastructure Cost	Scalability	Suitability for Rural Areas
Optical Fiber Network	500–1000 W per node	up to 40 km (wired)	High (cable deployment)	Medium	Limited due to high cost
LTE / 4G Base Station	300–900 W	5–15 km	Medium	High	Moderate
Cognitive Wired Network with AI optimization	120–400 W	up to 40 km	Optimized	Very High	Very High

4. Conclusion

Networks modified using cognitive technologies enable the deployment of communication infrastructure in remote areas while maintaining energy efficiency. Although challenges related to infrastructure deployment remain, cognitive networks significantly reduce the operational costs of data transmission. Cognitive radio and energy-efficient cognitive systems represent promising solutions for the development of broadband communication infrastructure in rural areas. AI-based optimization algorithms enable efficient utilization of energy resources.

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