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Article

Application of Energy-Efficient Routing Protocols in Cognitive Networks

Abdujapparova M.B[1], Maksudov J.Sh[2], Sodiqov A.Sh[3]
[1]TUIT, PhD, Associate Professor, Head of the "TI" Department
[2]UNICON.UZ" LLC, PhD, Leading Engineer, EMCAS
[3]TUIT, Master's Student, 2nd year, "TI" Department

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Abstract: This article explores the role of power-aware routing in cognitive networks, highlights key approaches, and discusses the challenges and future directions for research and application.

Keywords: IoT, cognitive network, cross-layer design, OSI model

1. Introduction

Cognitive networks are adaptive, intelligent systems that employ cognitive radio technology to dynamically manage spectrum utilization and optimize network resources. A cognitive network is capable of sensing its environment, making decisions, and learning from past experience, which makes it particularly suitable for applications in wireless sensor networks, the Internet of Things (IoT), and non-terrestrial networks such as satellite constellations and unmanned aerial vehicle (UAV) systems [1]. However, these systems operate under significant constraints, particularly in terms of energy consumption. Battery-powered devices and nodes deployed in remote or non-terrestrial environments cannot be frequently recharged or replaced. Therefore, energy-efficient routing protocols are designed to optimize power consumption, extend network lifetime, and maintain overall system performance [2].

Energy efficiency in cognitive networks is critically important for several reasons:

a) Minimizing energy consumption at individual nodes can significantly extend the operational lifetime of the network, especially in environments where replacing devices is difficult; [3]
b) Efficient utilization of energy resources ensures stable network performance and reduces the need for frequent maintenance; [4]
c) Energy-aware routing reduces operational costs associated with recharging, replacing, or maintaining network nodes [5].

2. Materials and Methods

A key question arises: how can energy be conserved in the deployment of cognitive networks? One of the primary approaches is the adoption of cross-layer design. Cross-layer design breaks the traditional isolation between the layers of the OSI (Open Systems Interconnection) model. It enables cooperation and information exchange across different layers, thereby improving adaptability and efficiency [6]. This is particularly valuable in energy-efficient routing protocols, where energy-related metrics obtained from multiple layers support decision-making processes aimed at optimizing network lifetime and performance [7].

Inter-layer interaction Figure 1:

a) The Physical layer provides real-time information on energy consumption, signal strength, and noise levels. This information assists the routing layer in selecting paths that minimize power requirements, thereby enabling energy-efficient decisions; [8]
b) The MAC layer can coordinate with the routing layer to optimize medium access scheduling, reduce collisions, and conserve energy. For example, nodes with lower energy levels may be prioritized in scheduling schemes; [9]
c) Transport protocols can adjust packet sizes and retransmission strategies based on energy level information shared by the routing layer, further optimizing energy usage [10].

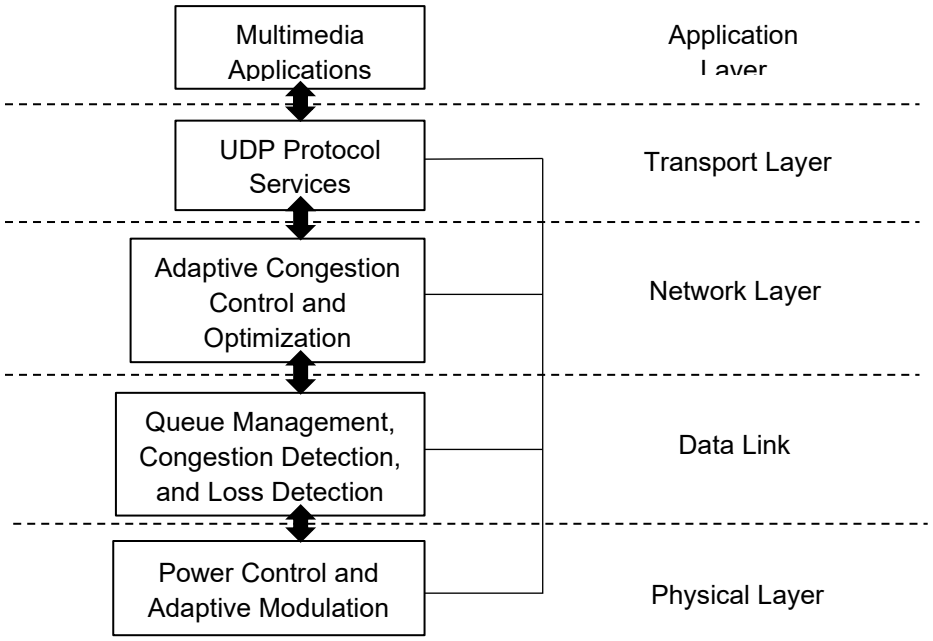

Figure 1. Interaction between Lower and Upper Layers

3. Results and Discussion

In cognitive networks, cross-layer design integrates spectrum management challenges with routing solutions. In other words, this approach enables data transmission by selecting energy-efficient routes that minimize interference, while ensuring balanced traffic distribution across nodes with the highest available energy reserves [11].

To illustrate the operation of this design, consider the example of deploying a wireless sensor network for environmental monitoring. Within such a scenario, the protocol sequentially identifies a sensor node with low energy consumption that must transmit data to a base station. It then determines a communication link with high signal quality requiring lower transmission power. Subsequently, it avoids peak traffic periods in order to reduce energy costs associated with collisions and retransmissions. Even if the selected path is slightly longer, the protocol prioritizes routes that pass through nodes with higher energy efficiency and reliable links. Through coordinated interaction among layers, efficient data delivery is achieved, balancing energy savings with overall network performance [12].

Cross-layer design proves highly effective for energy-efficient routing, as it enables the network to make holistic and context-aware decisions regarding energy utilization [13]. It integrates spectrum management, traffic control, and energy efficiency into a unified protocol framework, making it particularly suitable for dynamic and resource-constrained environments such as cognitive and non-terrestrial networks [14].

The evolution of energy-efficient routing protocols is closely linked to advancements in network technologies, artificial intelligence, and energy-efficient hardware systems. In the future, these developments are expected to enable the following capabilities:

1. Machine learning models (e.g., reinforcement learning) will be able to predict network conditions, user behavior, and energy consumption trends, enabling proactive routing and power management;
2. Real-time decision-making based on historical data and dynamic patterns will enhance the efficiency of inter-layer interactions;
3. Networks will develop self-learning capabilities, continuously improving energy-aware routing decisions without the need for manual configuration [15].

4. Conclusion

The future of energy-efficient routing protocols is highly promising. These protocols will play a crucial role in meeting the increasing demand for energy-efficient, adaptive, and secure communication systems in emerging technologies such as 6G, IoT, and non-terrestrial networks. Despite existing challenges, innovations in hardware, software, and collaborative learning will ensure that these protocols remain at the forefront of sustainable networking solutions.

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