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Fuzzy Routing in Communication Network Optimization: An Adaptive Algorithm for the Internet of Things (IOT)

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Abstract

The increasing complexity of Internet of Things (IoT) networks presents significant challenges in optimizing communication and routing efficiency. Traditional routing protocols struggle to adapt to dynamic topologies, energy constraints, and varying data transmission needs. Fuzzy routing has emerged as a promising solution, utilizing fuzzy logic to enhance decision-making under uncertainty.

Simulation results in recent studies suggest that fuzzy routing methods outperforms conventional protocols reducing energy consumption while extending network lifetime. Adaptive routing enhances the reliability of data transmission as well as minimizes congestion with only a minor increment in end-to-end delay due to hierarchical routing. The scenarios seem to provide examples of how fuzzy logic can devise IoT networks to be more resilient and scalable.

Future research must be directed toward the promising area of merging machine learning with fuzzy routing, leading to self-optimizing and predictive algorithms. Such advancement would improve the real-time adaptability, as well as work toward reducing the latency and increasing the efficiency and sustainability of IoT communications.

Keywords: Fuzzy routing, Communication network, Internet of Things.

1. Introduction:

The concept of IoT was sectioned by Kevin Ashton in 1999 and started being used in different areas from early 2010 onwards, due to the technological boom and connectivity. It became popular and started presenting some challenges to the communication networks, primarily regarding the optimization of data-transmission routes. Considering that IoT networks consist of a vast number of interconnected devices, node mobility, erratic network quality, and, real-time, low-latency data transmission have become pertinent issues limiting their acceptance. These factors make the selection of a route a complex task, especially under dynamic conditions and constrained resources, much like many other IoT networks.

In this respect, the application of Artificial Intelligence (AI) techniques (such as fuzzy logic) has become an attractive way to optimize the route selection process in communication networks. Fuzzy logic was developed in the 1960s by Lotfi Zadeh in an early attempt to cope with uncertainty and imprecision in control systems. The idea focuses on measuring variables by degrees of truth, unlike conventional logic, which allows for only two values: true and false. This openness is what has made fuzzy logic worthy of consideration in areas such as control systems and signal processing, and communication networks more recently.

Fuzzy routing started to emerge at the end of the 90s up to early 2000, where there were several attempts to analyze how the complexities posed by the fuzziness in some of the communication network parameters can be used to achieve enhanced performance of communication networks in dynamic and unpredictable situations. The underlying factor was the application of fuzzy logic regarding variations in network parameters such as traffic, signal quality, available energy, and delays.

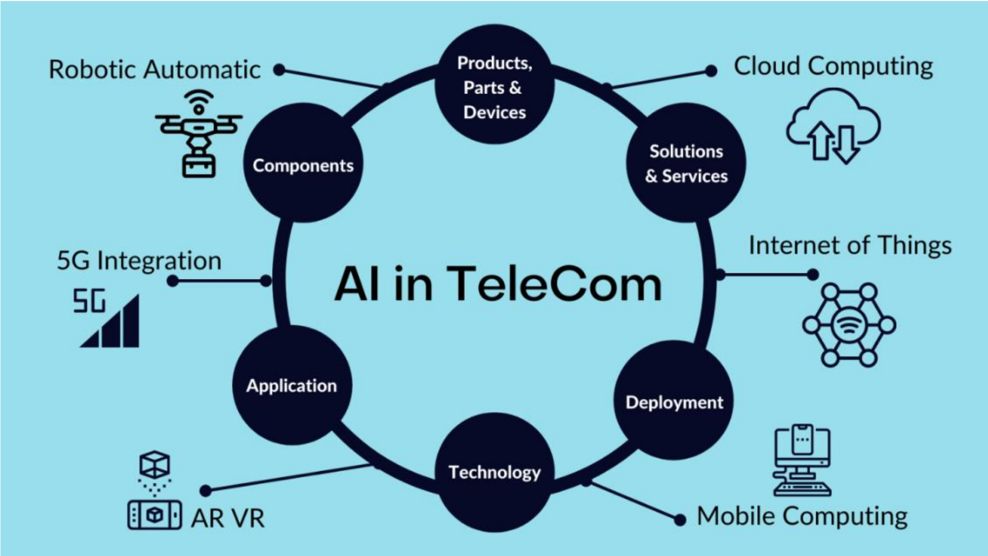

Figure 1. Application of AI in Telecommunications networks

Source: LinkedIn

Over time, various fuzzy routing algorithms were developed and applied to mobile and ad hoc networks, aiming to optimize route selection for more stable and efficient communication.

In the last decade, IoT development has taken place in such a way as to accelerate the need for more efficient and adaptive routing solutions. In an interdependent network made up of internet-connected devices, IoT specifically requires reliable communication solutions to deal with network heterogeneity and dynamics. Routing optimization has grown even more pertinent in the case of IoT networks due to the changes in topology, power consumption of devices, and real-time communication requirements.

By admitting routing decisions with incomplete and varying data, fuzzy logic can optimize routing by taking into account many factors together, including signal strength, network load, energy consumption, and latency. Thus, fuzzy logic presents a new alternative solution for these challenges in an IoT environment. This process not only makes the network more efficient but also provides greater stability and lower latency—essential aspects for the optimal performance of IoT applications such as real-time monitoring and control of critical systems.

Kiamansouri et al. (2022) presented a novel approach to optimizing data transmission in IoT networks by addressing key challenges such as energy consumption, network lifetime, and packet delivery efficiency. Their method introduced a two-level clustering mechanism combined with fuzzy logic and content-based routing. In the first-level clustering, fuzzy logic was applied to select Cluster Heads (CHs) based on three parameters: residual energy, node capacity, and number of neighbors, ensuring energy balance and efficient data aggregation. The second-level clustering selected Super Cluster Heads (Super CHs) using a centrality-based approach, further optimizing network efficiency by reducing energy consumption at the CH level. The content-based routing process classified data into high and low -volume types and routes them via different paths based on parameters such as energy, distance, traffic load, and angular deviation. Three routing modes were proposed, considering source and destination locations to ensure stable and energy-efficient data transmission. The proposed method was simulated in MATLAB and compared with existing clustering and routing protocols like HEED, FLCFP, FBCFP, and ELCP. The results demonstrated significant improvements over these methods in terms of average energy consumption, number of alive nodes, network lifetime, and packet delivery rate, though with a slightly increased end-to-end delay compared to HEED. The study highlights the advantages of using fuzzy logic for CH selection and content-based hierarchical routing for IoT networks, leading to optimized energy consumption, extended network lifetime, and improved data transmission efficiency overcoming challenges regarding dynamic data transmission and making it a promising approach for efficient IoT-based wireless sensor networks.

As the number of connected devices grows, so do the challenges of ensuring firmware stability, secure connectivity, energy efficiency, and seamless network scalability. Bannoura et al. (2024) explored the complexities of integrating IoT devices into wireless sensor networks, particularly in smart home applications. In this study the authors addressed these issues by introducing a fuzzy logic-based decision algorithm designed to optimize IoT performance. This approach prioritized data based on importance, adjusts sensor refresh rates dynamically, and manages energy consumption more efficiently, helping to extend device lifespan. The researchers developed a two-part fuzzy controller, with one component focusing on task prioritization and the other on battery management, ensuring that critical data is processed without unnecessary power drain. The study also details a structured process for testing and deploying IoT firmware, from internal trials to large-scale field implementation. A case demonstrated how this system enhances network resilience by improving data transmission, reducing packet loss, and enabling self-healing network topologies. The findings suggest that integrating fuzzy logic into IoT networks significantly improves efficiency, reliability, and long-term sustainability. For future research, the authors suggest to enhance this system further by incorporating machine learning and deep learning techniques to predict failures and improve real-time decision-making, paving the way for smarter, more adaptive IoT networks.

Sharma et al. (2022) presented an intelligent strategy to distribute network traffic efficiently among controllers in Software-Defined Networking (SDN). In SDN, the separation of the control plane from the data plane introduces complexities in assigning switches to controllers, especially as network conditions fluctuate.

To address this, the authors propose a dynamic, cluster-based approach for controller assignment. The authors used fuzzy logic to form clusters and select cluster heads, allowing the system to consider multiple parameters in decision-making. This method aims to enhance Quality of Service (QoS) by reducing latency and packet loss.

Experimental results of this study indicated that this fuzzy logic-based clustering significantly improves average latency and can also reduce packet loss compared to traditional load balancing methods without clustering. Therefore, their study underscored the potential of intelligent clustering techniques in optimizing SDN performance.

Barreto (2023) explored the application of fuzzy logic to enhance load balancing within data centers. Traditional methods, such as Round Robin or Least Connections, often fall short in adapting to the dynamic nature of network traffic. Fuzzy logic offers a more nuanced approach by considering multiple server metrics—like CPU utilization, memory usage, and network bandwidth—to make adaptive load distribution decisions. By assigning linguistic variables to these metrics, fuzzy logic systems can evaluate server conditions more comprehensively. This study implemented a prototype in a simulated data center environment, collecting real-time server metrics and applying fuzzy rules to guide load balancing decisions. The results demonstrated that this approach effectively reduced response times and evenly distributed traffic across servers, showcasing the potential of fuzzy logic to improve resource utilization and system performance in data centers.

Gures et al. (2022) presented a fuzzy logic-based algorithm designed to adjust the handover margin in heterogeneous networks, which integrated Long-Term Evolution-Advanced macro cells and fifth-generation (5G) small cells. Given the disparities in transmission power, system capacity, coverage areas, and deployment densities between these two cell types, as well as the uneven traffic distribution caused by user movement, the proposed algorithm aimed to improve network performance. The algorithm leverages cell load and radio channel quality to dynamically adjust the handover margin. In addition, it introduced a two-step model for determining the target cell, which incorporates both the load level of the cells and the reference signal received power (RSRP). Simulation results indicated that the proposed approach outperforms several existing load balancing algorithms, demonstrating improved load distribution, higher throughput, and a reduced call dropping ratio (CDR), thereby offering a promising solution for enhancing HetNet performance.

The fuzzified routing, a technique on communication network optimization, plays the role of key technique for improving the efficiency of data transmission specifically to IoT networks. The complex nature of IoT environments, with their dynamic network topologies, heterogeneous devices, and energy constraints, requires adaptive routing mechanisms. Fuzzy logic-based route optimization is possible by assessing various network parameters simultaneously and, thus, a robust topology optimized framework is provided to the routing mechanism in fuzzy logic. Thus, incorporating fuzzy-based clustering combined with content-aware routing creates more load-balanced IoT networks with reduced energy consumption and improved performance as a network. It helps provide flexibility for IoT applications like smart cities, industrial automation, and remote healthcare monitoring that require real-time communication and lesser packet loss.

However, fuzzy routing also has the effect of computation overhead because of the complexity in its decision-making process, and it may slightly increase latency over traditional routing methods. Nevertheless, in IoT networks, where network longevity is one of the vital objectives, latency versus energy efficiency is mostly justified. Advanced fuzzy-based mechanisms employ multi-level clustering techniques with dynamic route selection, which achieves a balance of stabilizing data loss minimization. In fact, fuzzy logic can enhance network adaptivity to varying conditions by routing algorithm conditions, which consist of parameters such as remaining energy, signal strength, and levels of network congestion.

In a larger sense of the IoT, fuzzy routing will offer a solution to scalability and efficiency issues regarding connected devices. The intelligent and context-aware routing solution requirement would only increase with the expansion of IoT deployments. Rather than a rigid rule-based routing system, fuzzy logic emerges as a flexible alternative, allowing such networks to deliver performance under conditions of uncertainty and resource constraints. Optimized communication pathways and prevention of redundant transmission will ensure a more sustainable and resilient infrastructure of IoT. Future work might improve models by integrating machine learning and AI-driven optimization into self-learning routing protocols designed for predictive decisions and autonomous adjustment of the network.

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