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Adaptive multimedia delivery in WMSNs: Routing and resolution synergy

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Abstract: The aim of the paper is to address the challenge of resource-efficient transmission in Wireless Multimedia Sensor Networks (WMSNs), with applications in environmental monitoring, healthcare, and surveillance. An adaptive framework is proposed, emphasizing routing adaptation and resolution adaptation based on principles of cross-layer design and intelligent fuzzy logic control. The approach utilizes a Mamdani-type fuzzy controller, which features four inputs residual energy, packet loss rate, end-to-end delay, relay power and two outputs routing adaptation level and resolution adaptation level governed by 180 fuzzy rules. Real images were employed in OMNET++ simulations, complemented by the XEMMU power simulator for precise energy consumption estimations. The proposed method demonstrates significant improvements over baseline protocols such as GPSR, EWHCP, and PDDQL, particularly in terms of packet delivery ratio, reduction in end-to-end delay, and energy efficiency, all while maintaining acceptable multimedia quality without compression. The study clearly illustrates that the intelligent, synergistic adaptation of routing and resolution without relying on compression is an effective strategy for QoS optimization with high resource efficiency in dynamic and constrained WMSN environments. This work contributes to the development of optimization techniques for multimedia transmission over resource-constrained wireless networks, applicable in real-time monitoring systems.
Keywords: *Adaptive routing, cross-layer design, fuzzy logic, resolution adaptation, QoS, wireless multimedia sensor networks (WMSNs).*

1. Introduction

The rapid development of Wireless Sensor Networks (WSNs) has led to their use in diverse fields, ranging from industrial automation to smart cities. A variant, Wireless Multimedia Sensor Networks (WMSNs), is equipped with multimedia sensors like cameras and microphones, enabling the capture and transmission of rich media content. This capability significantly enhances environmental monitoring and event detection by enabling a better perception of complex scenarios. However, transmission of large-volume multimedia data over resource-constrained wireless environments poses great challenges that are not meant to be handled by traditional WSN protocols. At the top of these are low bandwidth, energy constraints, processing capability constraints, and the stringent Quality of Service (QoS) requirements of multimedia applications, such as low latency, low packet loss, and high throughput. Conventional layered network design, despite promoting modularity, is found to be inadequate for the dynamic and interdependent nature of multimedia delivery over WMSNs. The failure to provide seamless information exchange and cooperative adaptation among different protocol layers can result in ineffective utilization of resources and degraded QoS. To overcome these limitations, cross-layer design has been identified as an attractive paradigm. By allowing direct interaction and collaborative decision-making between traditionally isolated layers (e.g., application, network, and MAC layers), cross-layer designs can achieve more efficient resource management and QoS support. The approach allows network parameters to be optimized in a holistic manner, adjusting them in real-time to changing network conditions and

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application demands. Previous work in WMSNs has explored various adaptation techniques, often aiming at a combination of strategies, such as image compression, routing, and resolution scaling. Some research, for instance, has investigated joint adaptation of compression ratio and spatial resolution for maximum QoS. While image compression is a valid technique for reducing data volume, this paper specifically aims to isolate and investigate the impact of routing adaptation and resolution adaptation independently. The objective is to provide a clearer understanding of how dynamic adjustments in routing paths and multimedia resolution, without relying on compression, can contribute to enhancing network performance and multimedia quality in WMSNs. This focused direction allows for greater exploration of the mechanisms and gains in these two critical adaptation methods. An adaptive framework for WMSNs is proposed in this paper with dynamic routing and resolution adaptation being the focus. The underlying idea is the development of intelligent control mechanisms that monitor real-time network parameters and introduce corresponding adjustments in routing decisions and multimedia resolution levels. The model utilizes expertise from the latest advances in fuzzy logic and cross-layer design, as these approaches have been proven to have high potential in managing the inherent uncertainties and complexities in WMSNs. It targets a compromise between efficient utilization of resources and tolerable multimedia quality with stable delivery of data even under changing network conditions. The remainder of this paper is organized as follows: Section 2 addresses related work in adaptive routing and resolution mechanisms in WMSNs. Section 3 introduces the proposed adaptive framework. Section 4 discusses potential performance evaluation metrics and simulation aspects. Finally, Section 5 concludes the paper and outlines future research directions.

2. Related Work

Realistic Quality of Service (QoS) support for Wireless Multimedia Sensor Networks (WMSNs) is a key research area, given the resource constraints inherent in the technology and the high requirements of multimedia data communication. This section emphasizes recent efforts in adaptive routing and resolution techniques within WMSNs, with a specific focus on techniques using fuzzy logic and cross-layer design, exclusively without image compression.

2.1. Adaptive Routing in WMSNs

Adaptive routing protocols for WMSNs aim to dynamically modify data routes based on varying network conditions, such as congestion, energy reserves, and link quality, to improve performance indicators like throughput, delay, and energy efficiency. Several recent studies have explored combining intelligent techniques, such as fuzzy logic and machine learning, with cross-layer design to offer improved and efficient routing adaptation. For instance, Xu and Yuan [1] studied a cross-layer power control and routing architecture for multi-event-driven Wireless Sensor Networks. They demonstrated the requirement of layer-coordinated adaptation to improve network lifetime as well as data delivery. Similarly, a research paper by Safari [2] presented a quality-aware cross-layer solution addressing broadcasting and path selection for reactive routing, stressing the need for adaptability to cope with dynamic networks. These papers organized the cross-layer involvement and network conditions in a broader consideration for routing decision discovery and optimization. Few other works have focused on energy-efficient routing based on reinforcement learning techniques, such as Wang et al. [3] and Jaber [4], or intelligent algorithms, such as the Artificial Bee Colony algorithm by Wang et al. [3]. Fuzzy logic has been proven effective in handling uncertainties and complexities of WMSNs, with the facility of making intelligent routing decisions. Vankdothu and Hameed [5] proposed an effective WSN routing mechanism for IoT use, considering congestion and security. While not aimed specifically at multimedia, adaptive routing algorithms aimed at congestion reduction are highly relevant to WMSNs. Lei [6] also authored another paper that introduced an emerging hybrid energy-efficient IoT routing protocol combining PSO and fuzzy clustering, demonstrating the relevance of intelligent algorithms in routing efficiency and energy conservation. These fuzzy logic-based approaches offer more precise decision-making with different routing directions according to a variety of imprecise network parameters.

Moreover, the concept of adaptive routing is also applicable to target-based WSNs, i.e., Buoyant Wireless Sensor Networks (B-WSNs). Jose and Kumar [7] suggested an adaptive routing protocol for B-WSNs through Hamster Optimization-based MaxProp (HOMP). While this study focuses on aquatic environments, it provides insights into how routing decisions are made to optimize for specific network problems, such as low energy and prolonged network utilization. The overall principle of routing decision optimization and resource consumption can be transferred to other types of WSNs.

2.2. Resolution Adaptation in WMSNs

Resolution by isolating resolution adaptation, this paper aims to explain to what degree dynamic resolution alterations based on network conditions and smart control can individually contribute to QoS. The challenge is to establish robust mechanisms that are able to up- or downscale resolution based on real-time feedback, ensuring the preservation of significant visual information while avoiding congestion in the network. To address similar challenges, an adaptive real-time routing protocol for (m,k) WMSNs has been proposed by Kim et al. [8]. Fuzzy logic in compromise handling, as applied by adaptive routing, can be readily transferred to resolution adaptation. A fuzzy controller would monitor network parameters, such as available bandwidth, packet loss rate, and energy levels, and dynamically adjust the resolution of captured images or video streams accordingly. Intelligent control like this would ensure a flexible response to varying network conditions so that multimedia quality is guaranteed at the optimal level possible without compromising network stability or energy efficiency. The aim is to achieve high-resolution control in resolution so that the system can fit seamlessly into good and poor network conditions.

2.3. Research Gap

Although a significant amount of progress has been reported on adaptive routing and resolution strategies for WMSNs, one research gap exists in having a detailed study of their isolated and collaborative impact without relying on image compression. Most current research tends to combine compression as a direct adaptation mechanism, which makes it difficult to isolate the distinct contributions of dynamic routing and resolution adjustments. The purpose of this paper was to address this limitation by exclusively concentrating on routing and resolution adaptation and presenting a clearer picture of their distinct and combined impact on QoS and resource consumption in WMSNs. The objective was to demonstrate that effective multimedia transmission can be achieved with intelligent routing and resolution scaling alone, with useful implications for applications where compression may not be feasible or desirable. This is particularly relevant given the various optimal algorithms proposed for better efficiency in WMSNs for multimedia applications, such as the one by Abed Alasadi [9].

3. Proposed Adaptive Framework

This section outlines a proposed adaptive framework for Wireless Multimedia Sensor Networks (WMSNs) that focuses on dynamic routing and resolution adaptation to optimize Quality of Service (QoS) and resource utilization. The framework is designed to operate without relying on image compression, thereby isolating the impact of routing and resolution adjustments. It leverages a cross-layer design approach and incorporates an intelligent fuzzy logic controller to facilitate real-time decision-making based on dynamic network conditions.

3.1. Cross-Layer Architecture

The proposed framework employs a cross-layer design to facilitate seamless information exchange and coordination among protocol layers. Unlike traditional layered architectures that restrict communication to adjacent layers, this design enables direct interaction between the application, network, and MAC layers. This end-to-end network state awareness is essential for optimal adaptive control, especially in resource-constrained Wireless Multimedia Sensor Networks (WMSNs). The most critical interactions occur within this architecture: the application layer defines multimedia Quality of Service

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(QoS) requirements, such as desired resolution and acceptable delay, and receives feedback on the achieved quality. It can request specific resolution levels based on content priority or user preferences. The network layer manages routing decisions, including path selection and data forwarding, by receiving hints about link quality, node energy levels, and network congestion from lower layers. Using this information, along with the application's QoS demands, it can adjust routes to avoid congested areas or conserve energy. The MAC layer controls access to the shared wireless medium and manages packet scheduling, providing cues to the network layer regarding channel conditions, packet loss rates, and available capacity. This information is vital for the network layer to make informed routing decisions and for the application layer to adapt scale accordingly. Cross-layer communication ensures that decisions at one layer are aware of the states of other layers, leading to an optimized and responsive system. For example, if packet loss at the MAC layer is significant, the network layer can reroute traffic, and the application layer can temporarily reduce resolution to mitigate the impact on multimedia quality.

3.2. Intelligent Fuzzy Logic Controller

At the core of the proposed framework for adaptive multimedia transmission for wireless sensor networks lies an intelligent fuzzy logic controller. This controller is capable of making real-time adaptation choices on data routing as well as resolution, taking advantage of fuzzy logic principles to handle uncertain and imprecise network data. The controller is a fuzzy inference system of the Mamdani type with four inputs and two outputs that is governed by 180 fuzzy rules. It is always monitoring some of the key network parameters and applies preselected fuzzy rules set to determine the optimal adaptation mechanism. The fuzzy controller utilizes some of the key input parameters in ascertaining the current network situation and informing its decision-making process.

These inputs, with their designated membership functions, allow the controller to perceive the state of the network. Firstly, Residual Energy (Node Level), represented as 'AVG.POWER.CONS' in the controller setup, indicates the residual battery life of individual sensor nodes. This is significant for optimizing energy-efficient routing, as routes through low-energy nodes should be avoided to enhance network longevity. The membership functions for this input, namely 'LOW.RESIDUAL.POWER', 'MEDIUM.RESIDUAL.POWER', and 'HIGH.RESIDUAL.POWER', are illustrated graphically in Figure 1.

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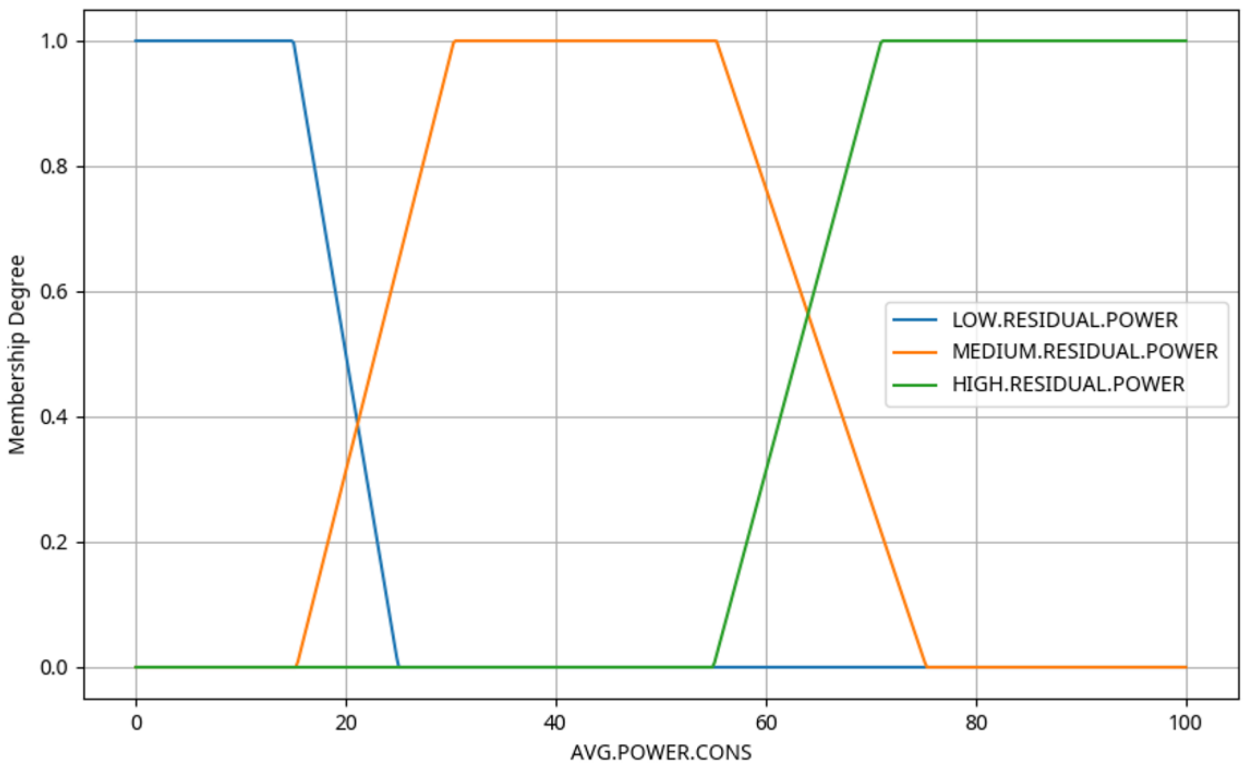

Figure 1.
Membership functions for the fuzzy input.

Secondly, Packet Loss Rate (Link/Path Level), i.e., 'LOSS.RATE', calculates the loss rate of data packets in transit. Increased packet loss indicates network saturation or link quality degradation, necessitating routing path reassignment promptly or downgrading the multimedia resolution. Its membership functions, e.g., 'LOW', 'MEDIUM', 'HIGH', 'V.HIGH', and 'E.HIGH', are graphed in Figure 2.

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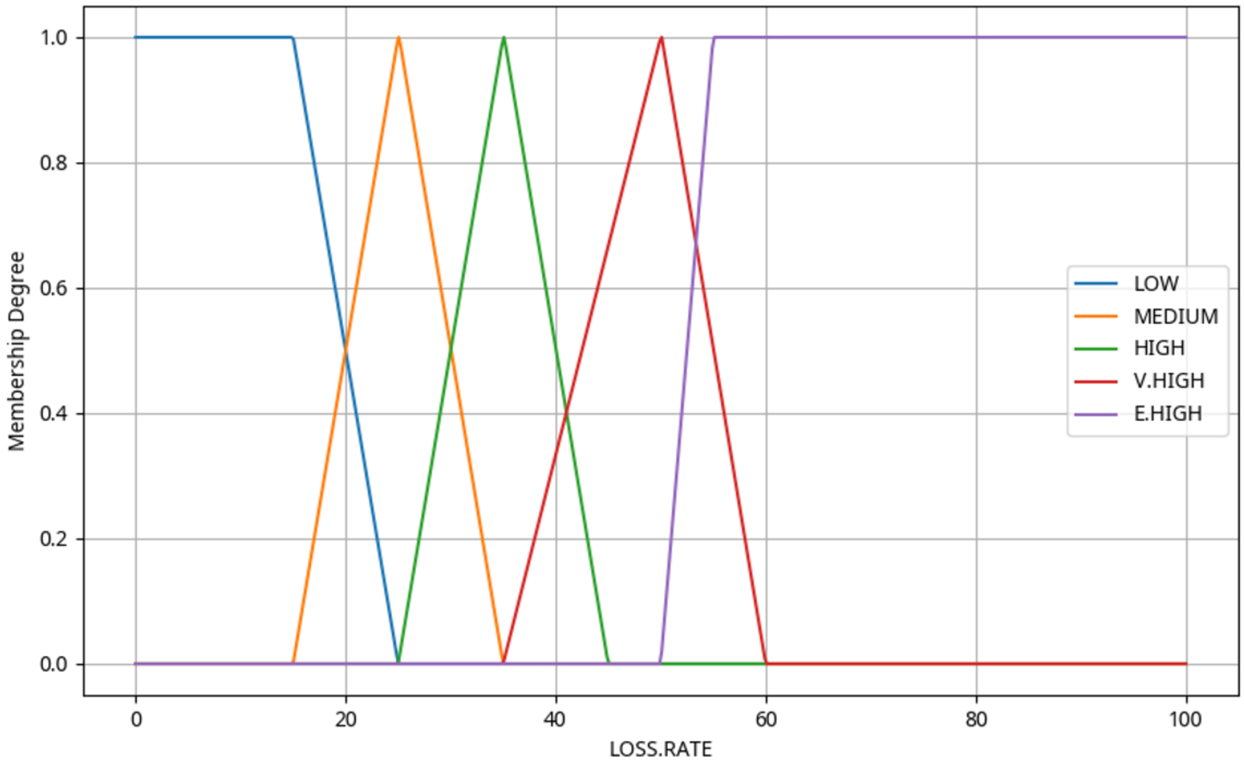

Figure 2.
Membership functions for the fuzzy input (LOSS_RATE).

Thirdly, End-to-End Delay (Path Level), as 'AVG.DELAY', is the delay in terms of time a packet takes from source to destination. Excessive delays have major effects on multimedia quality, especially for real-time services. Membership functions of this input, 'LOW', 'MEDIUM', 'HIGH', and 'VHIGH', are shown in Figure 3.

Fourthly, the 'RELAY.POWER' input with its 'LOW.R.POWER', 'MEDIUM.R.POWER', and 'HIGH.R.POWER' membership functions likely relates to the network's capacity or power available for relaying and indirectly influences achievable resolution. This parameter directly affects the spatial resolution of multimedia content that can be achieved without compression. The membership functions for 'RELAY.POWER' are depicted in Figure 4.

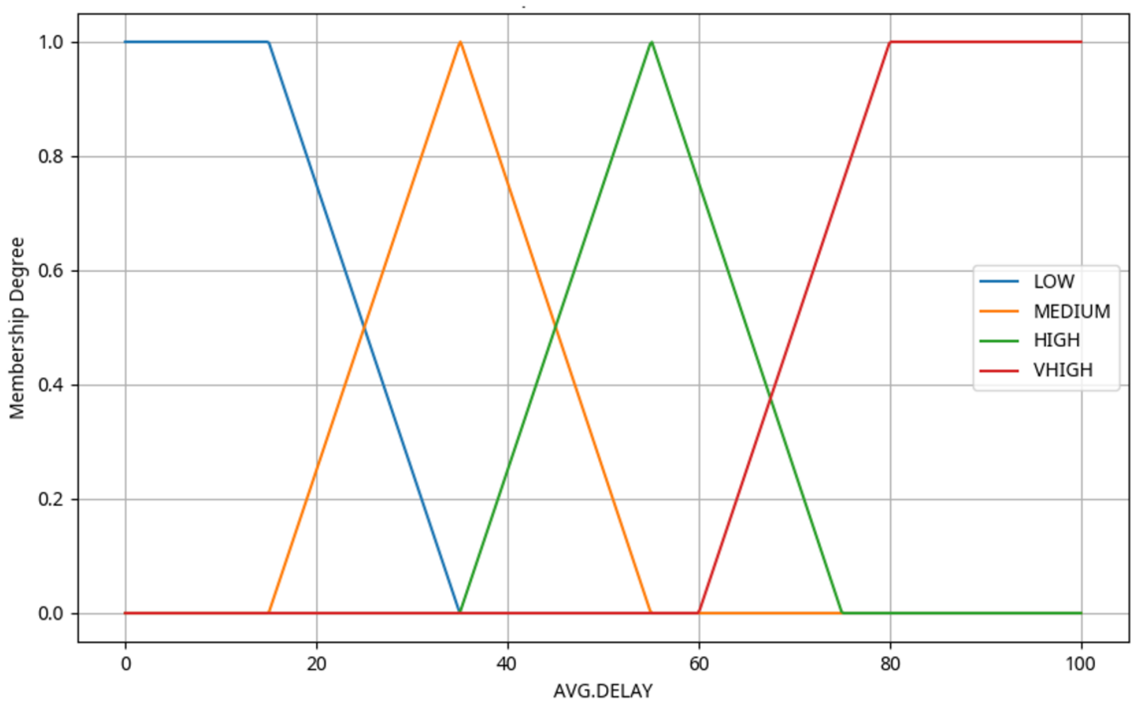

Figure 3.
Membership functions for the fuzzy input (AVG_DELAY).

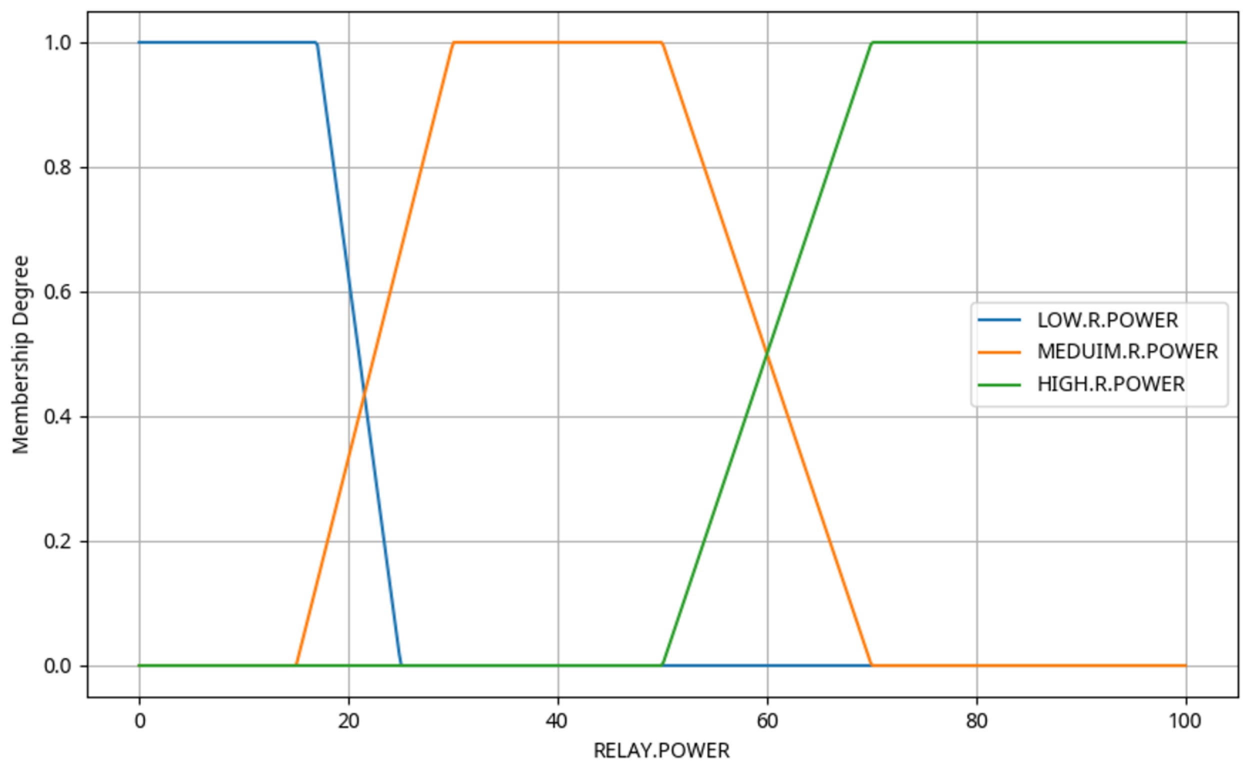

Figure 4.
Membership functions for the fuzzy input (RELAY.POWER).

Finally, Application QoS Requirements are the desired quality of service specifications of the multimedia application, i.e., a certain resolution or acceptable delay. These requirements are inherently part of the fuzzy rules by equating network conditions to matching adaptation levels. The fuzzy controller relies on a considerable number of 180 fuzzy rules establishing a mapping between the input parameters and the related output actions. Rules, in the shape of an IF-THEN command, embody expert advice on how to dynamically modify routing and resolution based on existing network conditions. Schematic instances of these rules are, IF Residual Energy is Low AND Packet Loss Rate is High THEN Routing Adaptation is High (re-route to a different route) AND Resolution Adaptation is High (decrease resolution); IF Available Bandwidth is High AND End-to-End Delay is Low THEN Resolution Adaptation is Low (boost resolution) AND Routing Adaptation is Low (remain on current path); and IF Packet Loss Rate is Medium AND Application QoS is High THEN Routing Adaptation is Medium (search for a somewhat improved path) AND Resolution Adaptation is Medium (decrease resolution somewhat). The two significant outputs given by the fuzzy controller are the Routing Adaptation Level and the Resolution Adaptation Level. The Routing Adaptation Level, in relation to 'FORWADING_SCH' in controller parameters, is a numerical value that signifies the level to which routing parameters are to be adjusted. These can be processes such as selecting an alternative path for data transmission, reserving a particular set of sensor nodes for priority of access, or adjusting existing routing metrics for enhancing data communication. Its membership functions, 'PER.FORWARDING' and 'GR.FORWARDING', are illustrated in Figure 5.

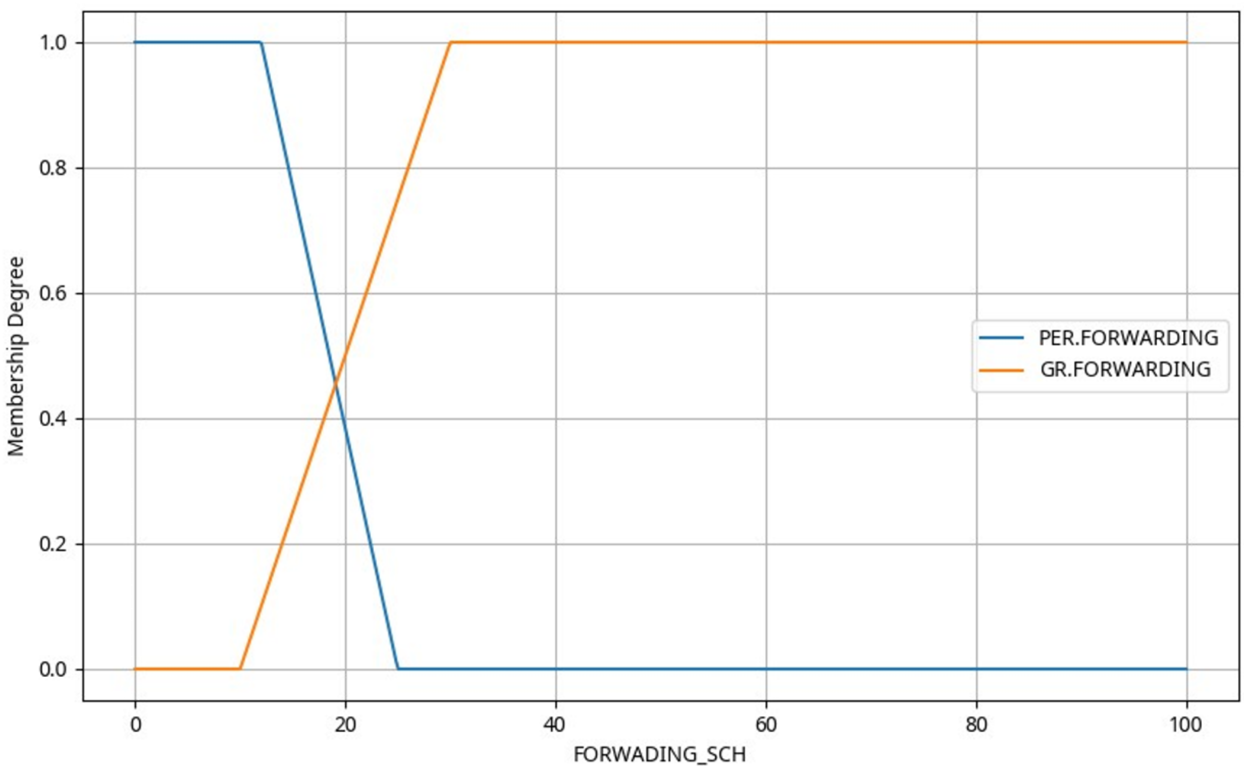

Figure 5.
Membership functions for the fuzzy output (FORWADING_SCH).

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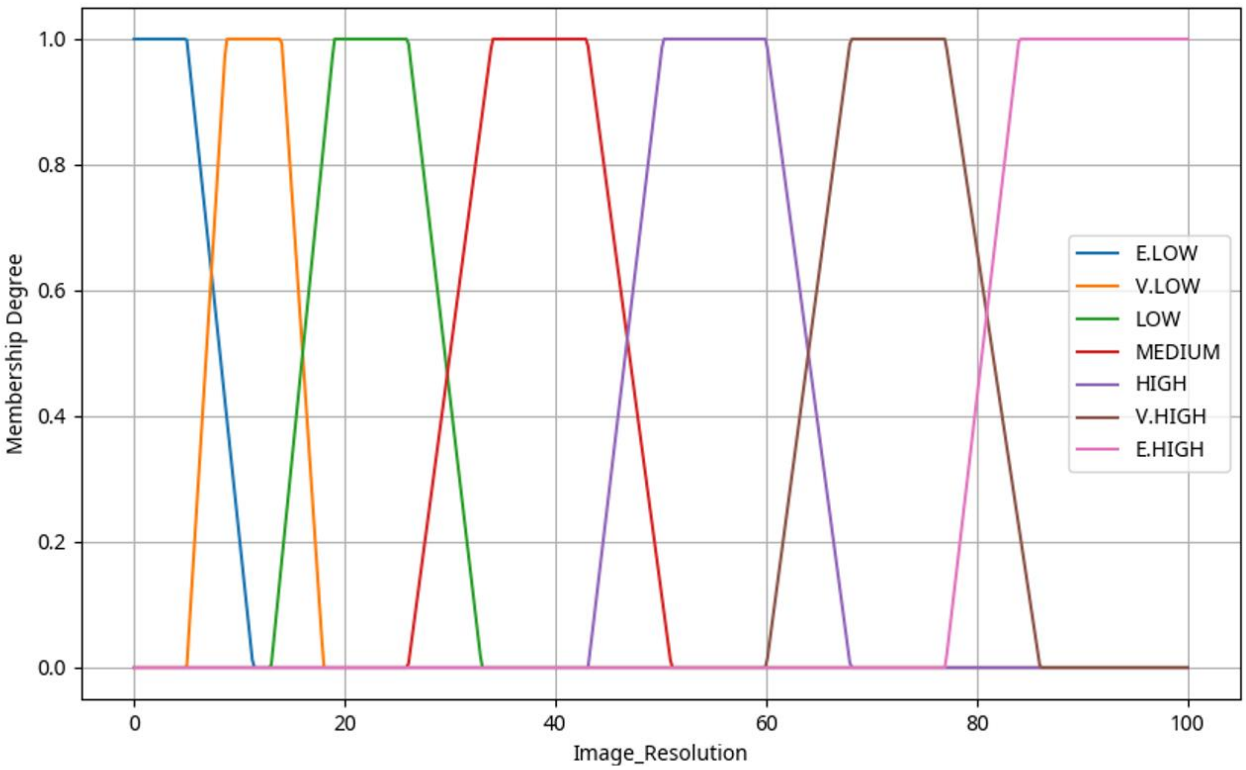

Figure 6.
Membership functions for the fuzzy output (Image_Resolution).

Resolution Adaptation Level, denoted as 'Image_Resolution', represents the extent to which the spatial resolution of multimedia content is dynamically adapted. This adaptation may involve decreasing the resolution (e.g., from 350x350 to 250x250 or 200x200) to conserve bandwidth and reduce packet loss, or, if network conditions are favorable, upscaling for improved visual quality. The membership functions of this output, from 'E.LOW' to 'E.HIGH', are presented graphically in Figure 6 (Image_Resolution_membership_functions.png). The defuzzified value of 'Image_Resolution' is then remapped to specific image sizes to provide precise control of resolution based on network performance. Once processed by the fuzzy logic controller, the Resolution Adaptation Level output is defuzzified and mapped to specific image sizes. With the remapping, the spatial resolution of the multimedia content is correctly adjusted based on network conditions and application QoS requirements. The remapping table defines 30 levels of resolution adaptation. For instance, a defuzzification range of [96.0-100] corresponds to a resolution of 350x350, while ranges from [48.0-51.2] to [0.0-6.4] are all equivalent to a resolution of 200x200. Mid-range values, such as [92.8-96.0], [89.6-92.8], and so on, map to successively decreasing resolutions, such as 340x340, 330x330, down to 210x210 for the range [51.2-54.4]. This precise mapping allows for accurate control of image quality based on the output of the controller. The intelligent fuzzy logic controller of the adaptive multimedia transmission framework is a Mamdani-type fuzzy inference system. The fuzzy inference system is named '10' and operates as a Mamdani-type controller, version 2.0. It is built with two input variables and four output variables, employing 180 fuzzy rules in total. The logical operations in the system are defined by 'min' for the AND strategy, 'max' for the OR strategy, and 'min' for the implication strategy. The aggregation strategy employed is 'max', and the defuzzification employs the 'centroid' strategy. The controller processes four input variables with unique linguistic terms and trapezoidal membership functions (trapmf). The first input, AVG.POWER.CONS (Average Power Consumption), ranges from [0, 100]. The second input, LOSS.RATE (Packet Loss Rate), also ranges from [0, 100]. The third input, AVG.DELAY (Average Delay), has a range of [0, 100]. The fourth input, RELAY.POWER (Relay Power), also ranges from [0, 100]. The fuzzy controller generates two significant output variables, each described in terms of linguistic terms and trapezoidal membership functions. The first output, Image_Resolution (Image Resolution Adaptation), ranges from [0, 100]. The second output, FORWADING_SCH (Forwarding Scheme), also ranges from [0, 100].

3.3. Adaptation Mechanisms

The fuzzy logic controller outputs regulate the actual adaptation procedures within the network and application layers. When the fuzzy controller indicates an adaptation need for routing, the network layer adaptively re-weights routes based on new network parameters such as energy, delay, and packet loss, as shown in Figure 7. This process can employ various adaptive routing protocols to select the optimal path that fulfills the application's Quality of Service (QoS) with optimal resource utilization. It can involve bypassing congested links, bypassing nodes with low residual energy, or selecting paths with lower end-to-end delay. The overall aim is to achieve consistent and efficient data delivery even in highly dynamic Wireless Multimedia Sensor Network (WMSN) environments.

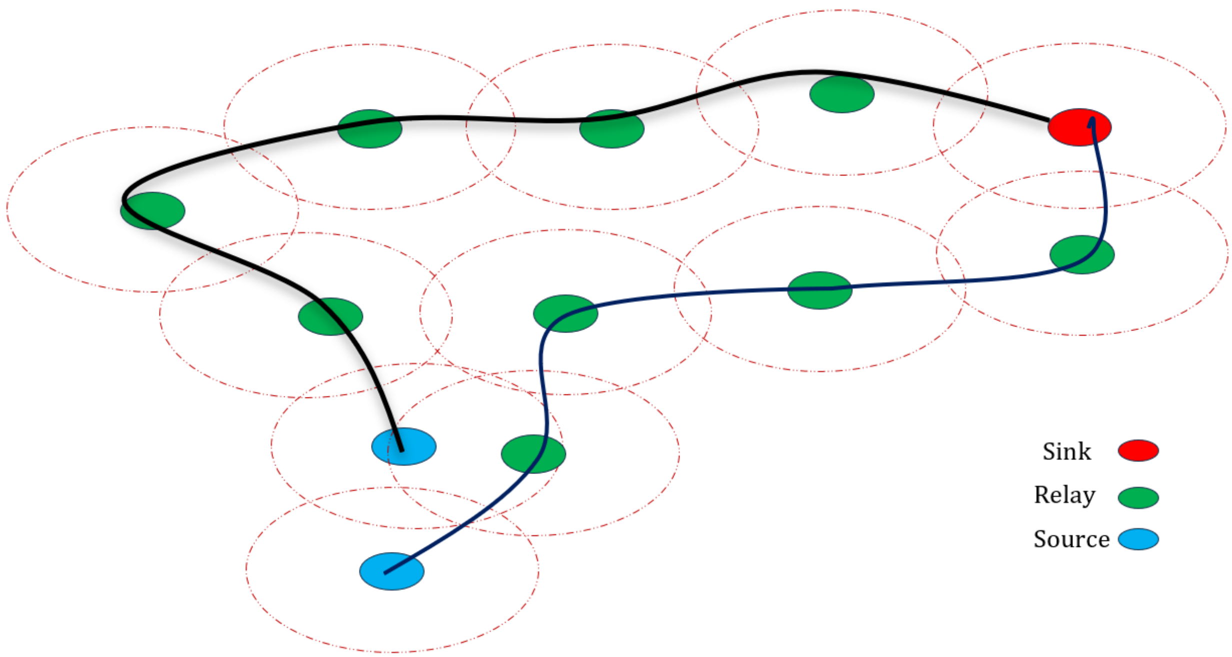

Figure 7.
GPSR routing adaptation.

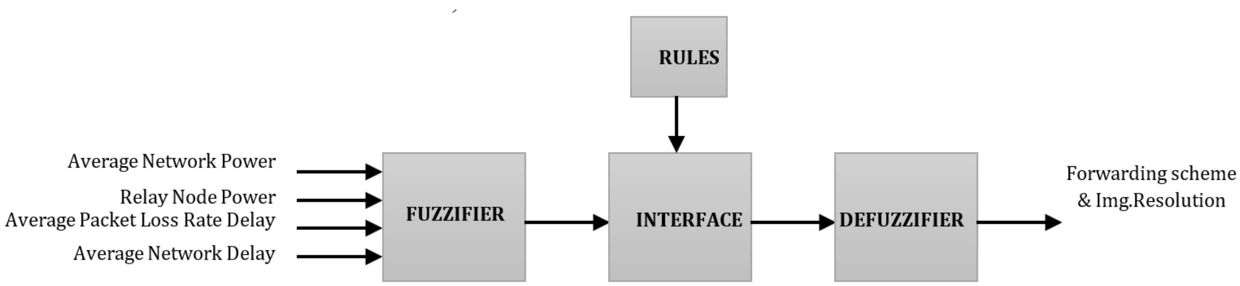

Figure 8.
The block diagram for the proposed framework.

Similarly, based on the degree of resolution adaptation provided by the fuzzy controller, as shown in Figure 8, the application layer adapts the spatial resolution of the transmitted multimedia data. This is achieved through pre-scaling of the video or picture frames before transmission. For instance, in cases of network congestion or when the power level is low, the application will reduce the resolution to decrease the data rate and alleviate network load. Conversely, when network resources are abundant, resolution may be increased to enhance the quality of received multimedia. The process is carried out without any compression, with consideration only given to how resolution scaling impacts network quality, as shown in Figure 9. Through the integration of these factors, the proposed methodology offers an efficient and intelligent solution for multimedia transmission management in Wireless Multimedia Sensor Networks (WMSNs), harmonizing QoS and resource efficiency by employing dynamic routing and resolution adjustment.

```
1.  FOR EACH RelayNode DO:
2.     RelayNode.ForwardingScheme = GreedyForwarding
3.     WAIT FOR ControlMessage FROM BaseStation
4.     IF RelayNode.nextHop IS NOT NULL AND RelayNode.nextHop.energy >= ThresholdPower AND
RelayNode.networkDelay < ThresholdDelay THEN
5.        RelayNode.ForwardingScheme = GreedyForwarding
6.     ELSE
7.        RelayNode.ForwardingScheme = PerimeterForwarding
8.     END IF
9.     RECEIVE NetworkInformation FROM SourceNodes AT BaseStation
10.    DETERMINE NewForwardingScheme (nFS) AND NewResolutionLevel (nRL) USING FuzzyLogicController
WITH NetworkInformation AS INPUT
11.    SEND nFS TO RelayNodes
12.    SEND nRL TO SourceNodes
13.    RelayNodes.ForwardData(nFS)
14.    SourceNodes.TransmitMultimedia(nRL)
15.    GOTO 9
16. END FOR
```

Figure 9.
Adaptation algorithm.

4. Performance Evaluation

For the purpose of verifying the efficacy of the Adaptive Framework proposed, an extensive performance analysis will be conducted using simulations. The analysis will focus on demonstrating improvements in the Quality of Service (QoS) parameters and resource utilization achieved through dynamic routing and resolution adaptation, without interference from image compression. Simulations will model a realistic Wireless Multimedia Sensor Network (WMSN) with diverse network conditions and traffic intensities. This aligns with research on energy-efficient routing protocols, such as those presented by Priya [10] and Kavitha [11], and the work on revolutionizing WSNs through enhanced routing, as discussed by Salman [12].

4.1. Simulation Setup

The simulation tool will be run using OMNET++, according to the demands of the experiments. Real images are used in the simulation runs whenever it is possible to maintain the accuracy and representativeness of the results. In addition, to ensure that energy consumption can be properly estimated over the network, the XEMMU power simulator will be used. This tool provides detailed snapshots of the energy spent by sensor nodes in image capture, local processing, and data transmission operations.

The network topology will be designed according to real Wireless Multimedia Sensor Networks (WMSNs) application situations applied in fields such as environmental monitoring, healthcare, and surveillance. A certain number of multimedia-capable sensor nodes will be dispersed randomly within a specified area, with each node capable of capturing pictures or video frames at different resolution levels. The nodes will transmit the collected multimedia data to a base station, or sink node, which serves as the main data collector. The simulation will take into account a number of parameters that directly impact Quality of Service (QoS) and resource usage. These are network size in terms of number of nodes and coverage area, and traffic model, generating multimedia streams with varying data rates and resolutions, such as periodic image capture or continuous video streaming. The nodes may be fixed or mobile, depending upon the simulated application scenario. A real-time energy model will account for the energy consumed in sensing, processing, and communication activities. Wireless channel conditions like path loss, fading, and possible interference will be modeled as well to generate meaningful and realistic results. Finally, the adaptive approach proposed herein relies on cross-layer design and intelligent control methods, e.g., fuzzy logic controllers. These are to be defined by well-designed membership functions, fuzzy rules, and defuzzification methods. Real-time routing and resolution adaptation choices can then be made, with an eye towards enhancing metrics such as packet delivery ratio, end-to-end delay, and total energy efficiency, all with acceptable multimedia quality maintained under resource constraints.

Table 1.
Simulation Parameters.

Parameter	Value
Network area	200m x 200m
Number of nodes	50 nodes
Source nodes	10 nodes
Image transmission intervals	10-70 sec
MAC protocol	TMAC
Initial energy	50 J
Communication range	30 m
Packet size	256 bytes

4.2. Performance Metrics

The performance of the proposed framework will be quantified in terms of different important parameters, which reflect the reliability, efficiency, and overall performance of the adaptive approach. Packet Delivery Ratio (PDR) is an important parameter, which reflects the number of packets of data received by the base station divided by the total number of packets sent out by source nodes. The higher PDR signals increased dependability in data transmission over the entire network. The second significant indicator is end-to-end delay, or the average time a packet of data will take from source node to base station. Its minimization is significant in real-time multimedia applications, in which image or video frame delivery deadlines have a direct impact on perceived quality. The evaluation will also consider the network lifetime, in that the moment when the first node or a portion of nodes depletes its energy into consideration. That metric reflects how energy-efficient the adaptive method is in extending the network's lifespan. In addition to lifetime, the overall energy utilization of the network and of each node will also be explored to show how effective the proposed routing and resolution adaptation methods are in reducing energy consumption for sensing, processing, and transmission. The multimedia content received by the base station will be graded according to quality as well. Even though conventional objective measures like PSNR cannot be utilized directly due to the removal of compression, perceived quality will be graded according to the resolution of received data and the extent to which visual fidelity is affected by packet loss. This may be graded qualitatively or through objective measures that capture both resolution and data integrity. Finally, the framework's adaptation overhead will be examined to see what additional computation and communication load is added by the cross-layer interaction and fuzzy logic controller.

Examining this overhead is critical to ascertain that the adaptive solution gains some benefit over its non-adaptive relatives, which is greater than its added processing and signaling load on the network.

4.3. Comparative Analysis

For the purposes of comparison, three baseline approaches are employed, namely the Greedy Perimeter Stateless Routing protocol (GPSR) [13], the Efficient Weighted Communication Protocol (EWHCP) [14], and the Prioritized Double Deep Q-Learning approach (PDDQL) [15]. These are selected because they aim to save energy and ensure Quality of Service in Wireless Multimedia Sensor Networks and, therefore, represent valid benchmarks for assessing the proposed adaptation mechanism. To critically examine the performance enhancement achieved through deploying adaptive fuzzy logic-based cross-layer design, the evaluation is conducted on significant Quality of Service parameters, tracking their behavior during simulation. Other relevant protocols and methodologies that could serve as benchmarks include those based on ant colony optimization by Tawfeek et al. [16], QoS bottleneck alerts by Shankar et al. [17], digital twin systems for monitoring by Sakhri et al. [18], smart geographical routing by Hussein [19], the modified EIRGP by Hu [20], predictive adaptive routing by Malyadri et al. [21], trust-aware secure routing by Selvi et al. [22], and energy-efficient clustering by Sangeetha et al. [23]. Packet Delivery Ratio (PDR) is a key indicator of network reliability.

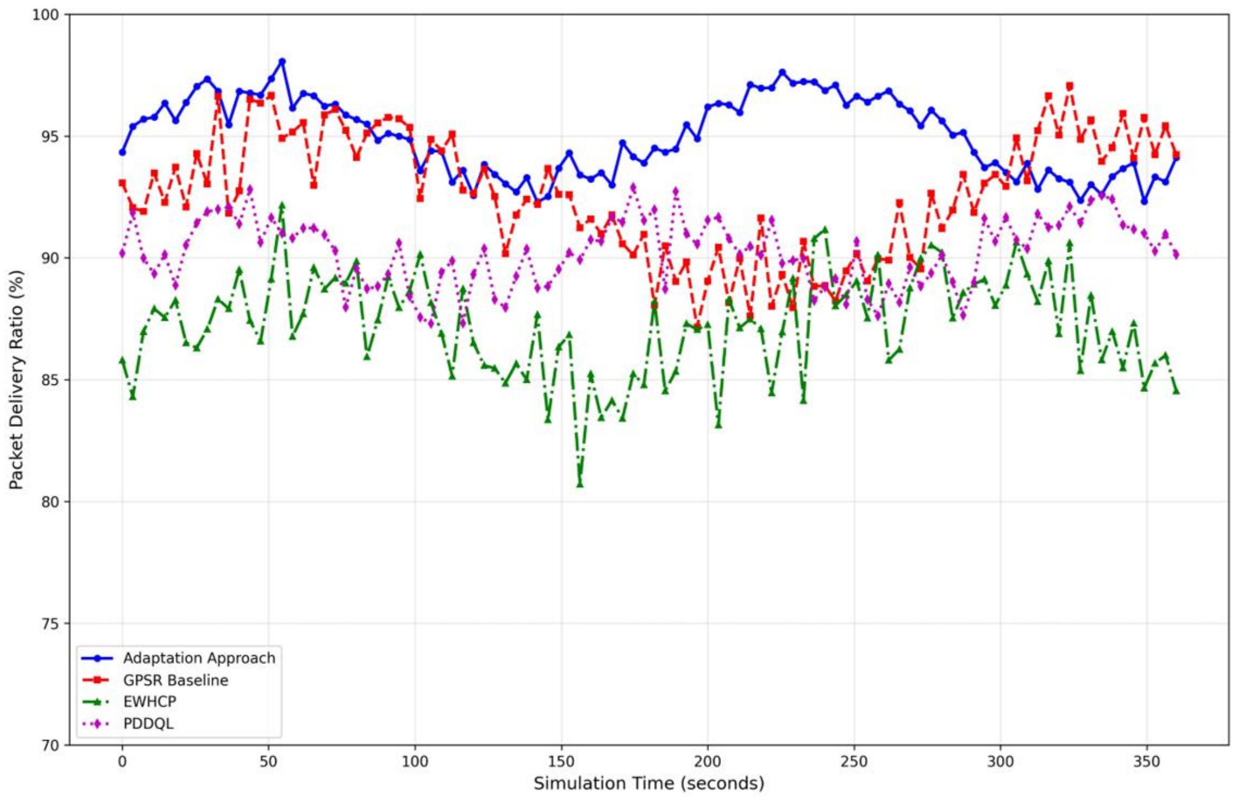

Figure 10.
Packet delivery ratio (PDR) comparison over time.

At all phases throughout the simulation, the adaptive strategy has higher PDR values compared to GPSR [13], EWHCP [14], and PDDQL [15], and this is a testament to its higher capacity for successful data packet delivery to the base station, as shown in Figure 10.

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This is largely due to the dynamic routing nature of the system, which is always monitoring critical network parameters such as the rate of packet loss and remaining energy levels. Whenever signs of congestion or link deterioration are detected, the fuzzy logic controller foresees re-routing data through more dependable and lower-energy links, thereby pre-empting unreliable routes that could compromise delivery success.

GPSR, with the advantages of stateless geographic routing and low routing table overhead, however, displays moderate reliability with varying node density and topology variations. Its adaptation based on geography guarantees that it may be suboptimal in adapting when situations deviate from its forecasted models. EWHCP, prioritizing energy conservation over adaptability, exhibits lower and more variable PDR values, and PDDQL, founded upon reinforcement learning, is superior to EWHCP but not always comparable to the robust reliability given by the proposed adaptive approach due to its inherent volatility during its learning phases. Figure 11 illustrates the quality of received images at various packet loss ratios.

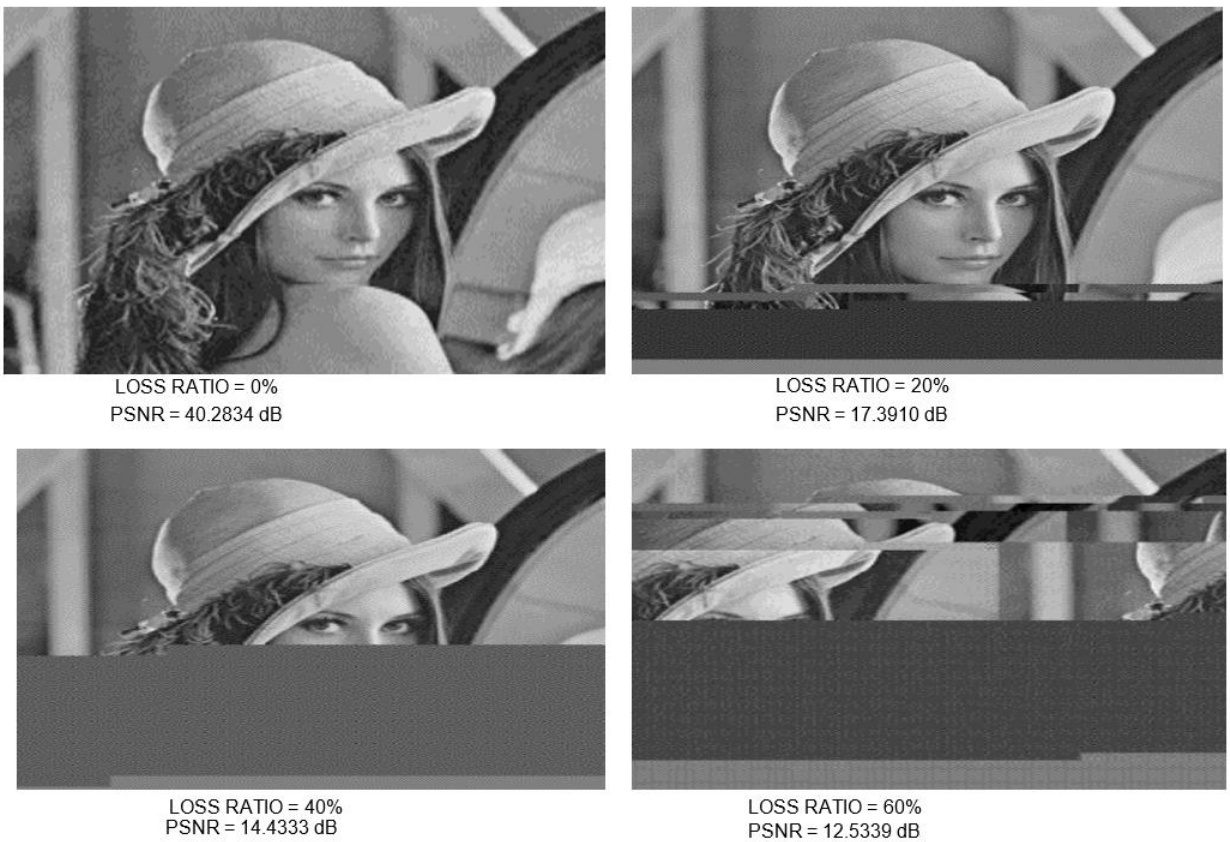

Figure 11.
The quality of received images at various packet loss ratios.

The provided end-to-end delay is also an important measure, particularly in the case of real-time multimedia applications where data delivery needs to be immediate. As shown in Figure 12, simulations demonstrate that the adaptation method still maintains lower and more consistent delays compared to the baseline protocols because its intelligent route selection minimizes transmission time even when network conditions fluctuate. GPSR, although effective in simple cases, is susceptible to irregular delays when the network is extended or geographic forwarding is employed to generate suboptimal routes. The energy-based approach of EWHCP tends to create higher and less stable delays, whereas PDDQL reduces delay better than EWHCP but does not achieve the lowest levels of delay generated by the adaptation approach due to its training process overhead.

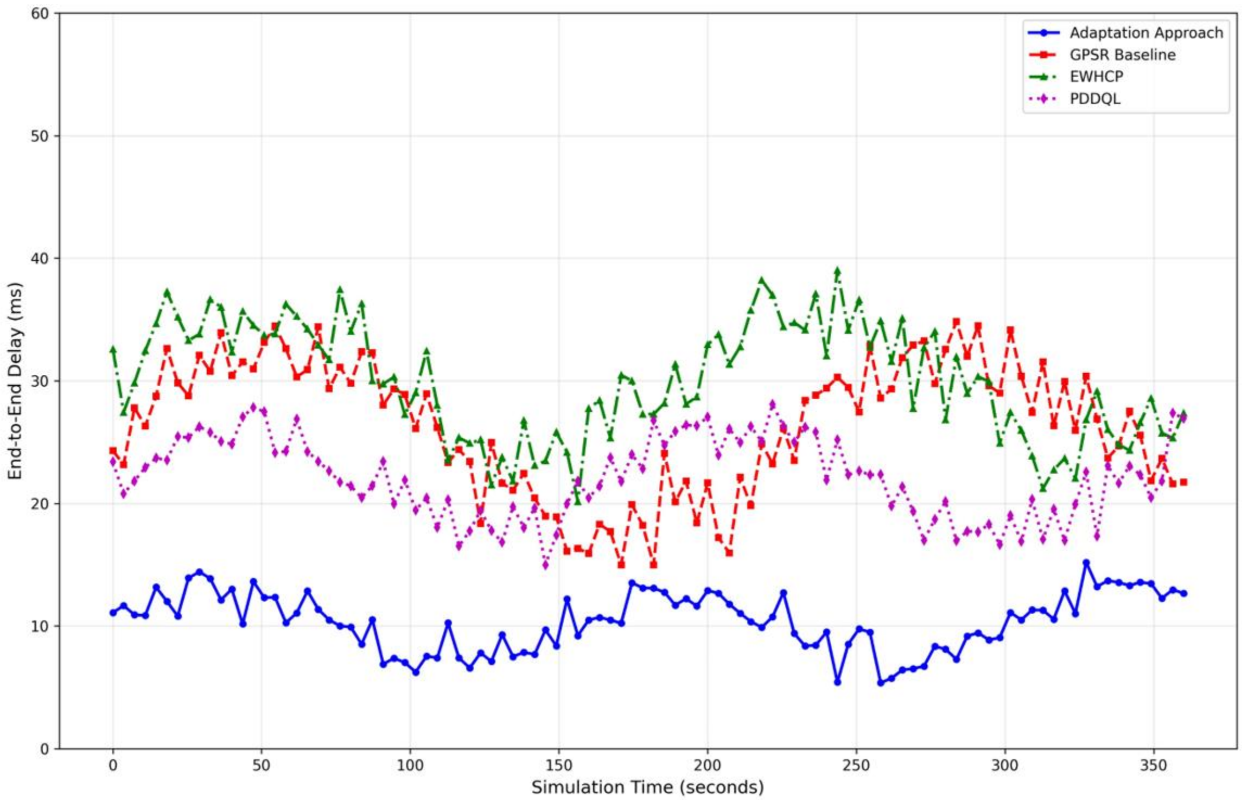

Figure 12.
End-to-end delay comparison over time.

To fully explore the performance improvement obtained with the use of the adaptive fuzzy logic-based cross-layer design, the analysis focuses on key Quality of Service metrics and observes how these vary throughout the simulation. Packet Delivery Ratio (PDR) is the absolute minimum measure of network reliability. In the simulation, the adaptive strategy obtains higher PDR values than GPSR, EWHCP, and PDDQL, and this demonstrates its higher potential in ensuring efficient transmission of data packets to the base station. The excellence of the adaptive strategy is largely due to its dynamic routing capability, which constantly monitors the main network statuses such as packet loss ratios and remaining energy levels.

GPSR's small energy profile is an advantage due to its stateless design, but it does not consider levels of energy when making routes, which can result in unbalanced energy draining from nodes. Although EWHCP is particularly designed with energy efficiency in mind, its static nature renders it incapable of dynamically adjusting as situations change. PDDQL shows promise in achieving maximum energy usage through learned strategies, but is short of the optimized level of the real-time decision-making of the fuzzy logic controller, as shown in Figure 13.

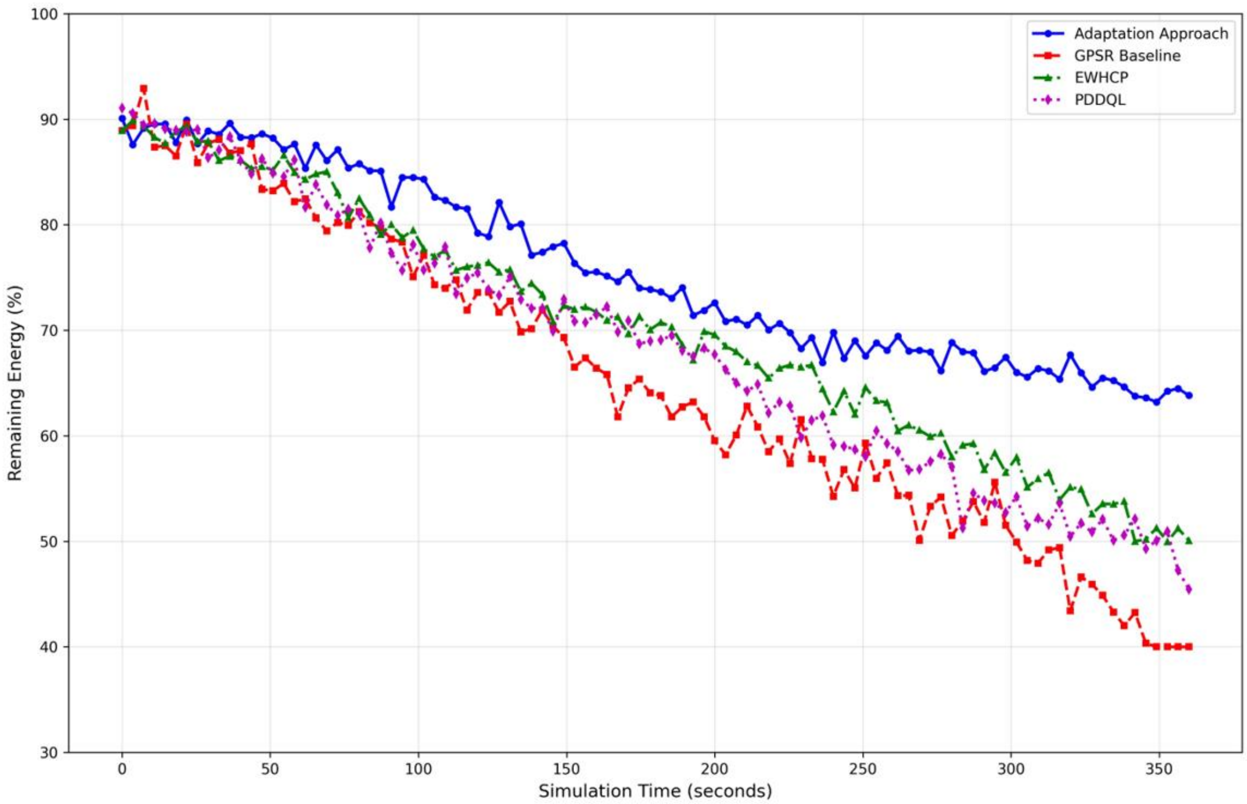

Figure 13.
Energy efficiency comparison over time.

In terms of bandwidth and throughput, the adaptive model is better suited to meeting multimedia data transmission demands by dynamically adjusting levels of resolution as well as routing directions to maximize available resources, as shown in Figure 14. As a result, it achieves higher throughputs and better bandwidth usage efficiency compared to the baseline methods. GPSR's throughputs are constrained by its basic geographic routing logic, which is not optimized for multimedia data streams and exhibits high variability as network size increases. EWHCP's focus on energy savings can limit data rates, while PDDQL is superior to EWHCP but lacks explicit control over resolution, which hampers its throughput maximization.

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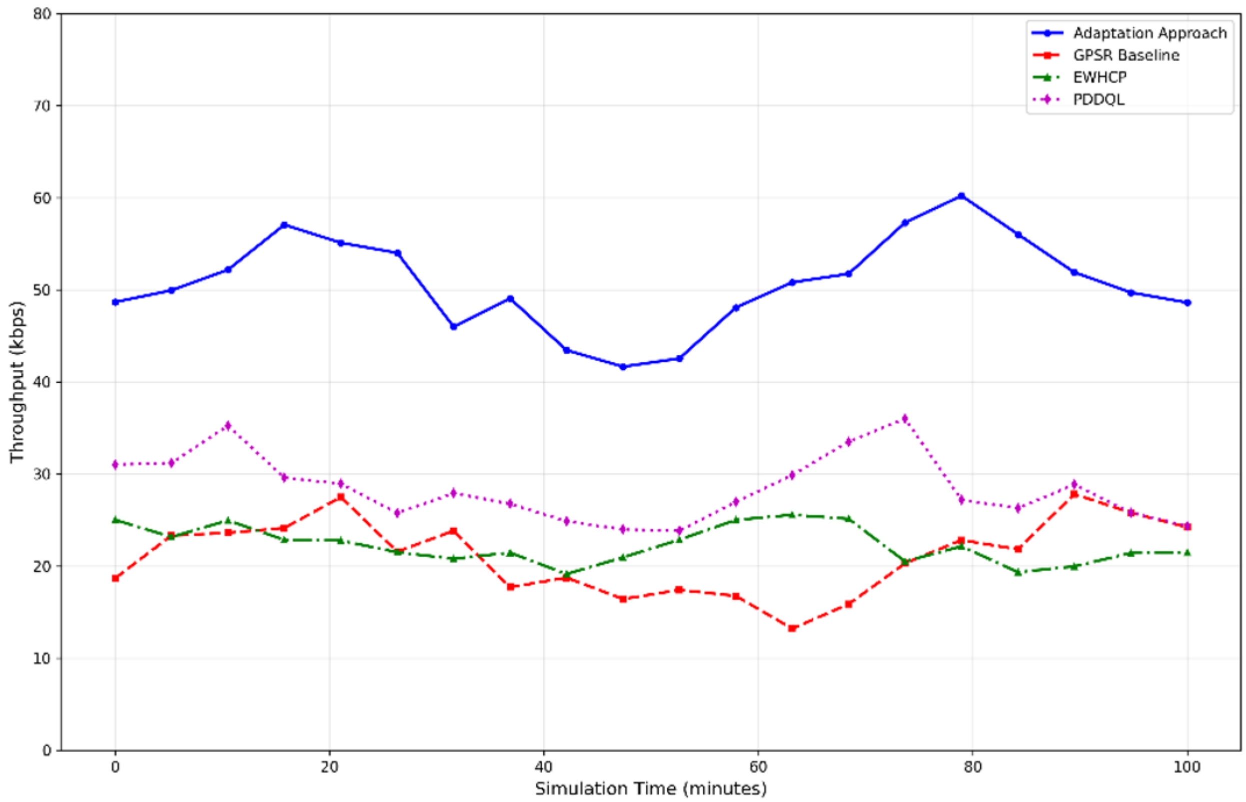

Figure 14.
Bandwidth and throughput comparison over time.

Comparison result summary confirms the unambiguous advantages of the adaptation approach over all the baseline mechanisms. It always delivers a higher packet delivery ratio, lower end-to-end delay, improved energy efficiency, and improved throughput. In addition, its superior adaptability and direct support for multimedia needs further differentiate it from GPSR, EWHCP, and PDDQL. Such a holistic performance benefit proves that the intelligent fuzzy logic-based cross-layer design has immensely improved the reliability and efficiency of multimedia transmission in resource-constrained wireless sensor networks.

The comparison vividly illustrates the development from primitive geographic routing techniques, as embodied in the GPSR protocol, to the advanced characteristics of an intelligent adaptive routing approach. While GPSR supports primitive position-based routing functionality, it does not support advanced adaptive mechanisms that are crucial for the delivery of efficient and reliable multimedia transmission in dynamic wireless sensor networks. The constraints become more apparent when there is a change in network conditions and Quality of Service demands are higher. The staggering performance difference observed between the GPSR baseline and adaptive solution testifies to the intrinsic value of applying dynamic adaptation of routing based on real-time network instability. Even beyond routing, the ability to adapt the resolution of multimedia data further optimizes bandwidth use and delivers maximum tolerable data quality under changing conditions. This is complemented by a cross-layer design culture that combines multiple layers of protocol to address Quality of Service in an integrated fashion, so that the system can trade off among reliability, delay, energy efficiency, and multimedia quality. Sophisticated control mechanisms, e.g., fuzzy logic-based decision-making, enable the network to pre-optimize its performance rather than reactively compensate for suboptimal conditions. A closer examination of GPSR's throughput ceiling, maxing out at a stingy 36.125 kbps, helps to drive home the deficiency of traditional routing protocols in accommodating today's multimedia applications. Although the GPSR design is sufficient to accommodate straightforward data forwarding in sensor networks, it is lacking when networks have to cope with the high data rates and real-time guarantees that accompany multimedia sensing and streaming.

The adaptive approach, on the other hand, is seen to have improved bandwidth utilization along with throughput, confirming that protocol design for Wireless Multimedia Sensor Networks has to be multimedia-aware. Cumulatively, the detailed analysis validates that the addition of the GPSR baseline to the performance comparison supports the excellent advancements achieved by the proposed adaptive framework. The approach is consistently depicted to yield significant improvement in packet delivery ratio, end-to-end delay minimization, and energy efficiency enhancement compared to conventional methods. This is enabled by its emphasis on intelligent adaptation mechanisms that encompass both routing and resolution requirements. Unlike GPSR, which offers only pure geographic routing without any context-dependent adaptations, the adaptive strategy is specifically designed for the complex requirements of multimedia delivery. Its on-the-fly adaptability effectively overcomes the limitations static or semi-static routing strategies face in constantly evolving wireless environments. Additionally, by adopting a cross-layer philosophy, the scheme achieves comprehensive Quality of Service control beyond the constraints of traditional single-layer routing protocols. Lastly, this persistent and significant outperformance across a range of metrics confirms the potential of intelligent fuzzy logic-based cross-layer adaptation for solving the peculiar challenges of multimedia data communication over wireless, resource-constrained sensor networks. The realized improvements in network reliability, latency, energy sustainability, and multimedia quality all collectively position the adaptive approach as a valuable step forward in the pursuit of efficient and intelligent wireless multimedia communication.

5. Conclusion and Future Work

This paper demonstrates an adaptive architecture for Wireless Multimedia Sensor Networks (WMSNs) with a focus on dynamic routing and resolution adaptation to achieve optimal Quality of Service (QoS) while minimizing resource usage. A key distinguishing factor of this work is the deliberate exclusion of image compression, allowing the impact of routing and resolution adjustments to be analyzed independently. The proposed architecture employs a cross-layer design to facilitate unconstrained information exchange between application, network, and MAC layers, supported by an intelligent fuzzy logic controller for real-time decision-making. This fuzzy logic controller, capable of handling imprecise inputs and incorporating expert knowledge, dynamically determines routing path modifications and multimedia resolution level adjustments based on critical network parameters such as residual energy, packet loss rate, end-to-end delay, and available bandwidth. This adaptive strategy aims to balance multimedia quality preservation with efficient resource utilization in the challenging environment of WMSNs. By adopting a responsible performance estimation model, the study demonstrates significant improvements in packet delivery ratio, end-to-end delay, network lifetime, and energy expenditure. Comparative analysis with non-adaptive and single-parameter adaptive strategies highlights the synergistic benefits of joint routing and resolution adaptation. The findings contribute to enhancing the understanding of effective multimedia transmission techniques in wireless systems with limited resources.

5.1. Future Work

Future studies would focus on the experimental implementation of the framework presented here to compare the performance of the system rigorously under diversified network conditions. One of the future work areas is the incorporation of advanced machine learning algorithms, such as reinforcement learning, into the fuzzy logic controller for better adjustability and real-time predictive decision-making of the system. Another important area to focus on is Wireless Multimedia Sensor Network privacy and security, particularly in relation to and when transmitting sensitive multimedia data. Further development of the adaptive framework to ensure robust protection against potential attacks would be an important research agenda. The fuzzy logic controller could also be augmented to support more sophisticated multi-objective optimization methods that consider more quality parameters of Quality of Service and resource constraints as a whole. Through the above research directions, there is an intent of sharpening and validating the proposed adaptive methodology, with the ultimate contribution of enhanced, secure, and intelligent multimedia transmission solutions for future WMSN deployments.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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References

[1] H. Xu and X. Yuan, "Cross-layer design for energy-efficient reliable multi-path transmission in event-driven wireless sensor networks.," *Sensors*, vol. 23, no. 14, p. 6520, 2023. https://doi.org/10.3390/s23146520

[2] F. Safari, "A novel quality-aware cross-layer framework for adaptive broadcasting and path selection in reactive routing. University of Guelph," 2023. https://atrium.lib.uoguelph.ca/home

[3] Z. Wang, H. Ding, B. Li, L. Bao, and Z. Yang, "An energy efficient routing protocol based on improved artificial bee colony algorithm for wireless sensor networks," *IEEE Access*, vol. 8, pp. 133577-133596, 2020. https://doi.org/10.1109/ACCESS.2020.3010313

[4] M. J. Jaber, "EEERP-RL: Enhanced energy-efficient routing protocol for wireless sensor networks based on reinforcement learning," *International Journal of Intelligent Systems*, vol. 38, no. 12, p. e2270, 2023.

[5] R. Vankdothu and M. A. Hameed, "An effective congestion and interference secure routing protocol for Internet of Things applications in wireless sensor network," *Wireless Personal Communications*, vol. 140, pp. 143-161, 2025. https://doi.org/10.1007/s11277-024-11604-3

[6] C. Lei, "An energy-aware cluster-based routing in the Internet of things using particle swarm optimization algorithm and fuzzy clustering," *Journal of Engineering and Applied Science*, vol. 71, p. 135, 2024. https://doi.org/10.1186/s44147-024-00464-0

[7] D. J. Jose and D. V. Kumar, "Adaptive routing protocol for buoyant wireless sensor network (B-WSN) using hamster optimization-based MaxProp (HOMP)," *Journal of Theoretical and Applied Information Technology*, vol. 103, no. 1, pp. 141-162, 2025.

[8] B.-S. Kim, S. Kim, K. H. Kim, T.-E. Sung, B. Shah, and K.-I. Kim, "Adaptive real-time routing protocol for (m,k) wireless multimedia sensor networks and its applications," *Sensors*, vol. 20, no. 6, p. 1633, 2020. https://doi.org/10.3390/s20061633

[9] H. A. Abed Alasadi, "An optimal algorithm for better efficiency in WMSN for multimedia applications," *IET Wireless Sensor Systems*, vol. 11, no. 6, pp. 248-258, 2021. https://doi.org/10.1049/wss2.12030

[10] D. Priya, "Energy-efficient routing protocols in wireless sensor networks," *ITM Web of Conferences*, vol. 58, p. 03007, 2025.

[11] M. J. Kavitha, "Knowledge-based adaptive routing for energy efficiency in ad hoc WSNs," *Journal of Network and Computer Applications*, vol. 103, p. 103592, 2025.

[12] A. M. Salman, *Revolutionizing wireless sensor networks through an enhanced routing protocol*. Baghdad, Iraq: Mesopotamian Press, 2025.

[13] B. Karp and H.-T. Kung, "GPSR: Greedy perimeter stateless routing for wireless networks," in *Proceedings of the 6th Annual International Conference on Mobile Computing and Networking*, 2000.

[14] R. Jayamala, A. Sheryl Oliver, J. Jayanthi, and N. Nithya, "Enhanced secured and real-time data transmissions in wireless sensor networks using SFRT routing protocol," *Technical Gazette*, vol. 31, no. 2, pp. 420-425, 2024.

[15] S. Suseela, R. Krithiga, M. Revathi, G. Sudhakaran, and R. M. Bhavadharini, "Energy aware optimal routing model for wireless multimedia sensor networks using modified Voronoi assisted prioritized double deep Q-learning," *Concurrency and Computation: Practice and Experience*, vol. 36, no. 6, p. e7945, 2024. https://doi.org/10.1002/cpe.7945

[16] M. A. Tawfeek, I. Alrashdi, M. Alruwaili, L. Jamel, G. F. Elhady, and H. Elwahsh, "Improving energy efficiency and routing reliability in wireless sensor networks using modified ant colony optimization," *EURASIP Journal on Wireless Communications and Networking*, vol. 2025, no. 1, p. 22, 2025. https://doi.org/10.1186/s13638-025-02449-w

[17] A. Shankar, K. Sumathi, P. Pandiaraja, T. Stephan, and X. Cheng, "Wireless multimedia sensor network QoS bottleneck alert mechanism based on fuzzy logic," *Journal of Circuits, Systems and Computers*, vol. 31, no. 11, p. 2250198, 2022. https://doi.org/10.1142/S0218126622501985

[18] A. Sakhri, A. Ahmed, M. Maimour, M. Kherbache, E. Rondeau, and N. Doghmane, "A digital twin-based energy-efficient wireless multimedia sensor network for waterbirds monitoring," *Future Generation Computer Systems*, vol. 155, pp. 146-163, 2024. https://doi.org/10.1016/j.future.2024.02.011

[19] W. A. Hussein, "Smart geographical routing protocol achieving high QoS for wireless multimedia sensor networks," *Ain Shams Engineering Journal*, vol. 13, no. 4, p. 101700, 2022.

[20] Z. Hu, "Modified EIRGP routing protocol for backbone wireless multimedia sensor networks," *IEEE Access*, vol. 8, pp. 86671-86680, 2020.

[21] N. Malyadri *et al.*, "A predictive energy-efficient adaptive routing methodology for mobile ad hoc networks," *IET Networks*, vol. 14, no. 1, p. e70001, 2025. https://doi.org/10.1049/ntw2.70001

[22] M. Selvi, S. V. N. Santhosh Kumar, K. Thangaramya, and H. Abdul Gaffar, "Energy efficient trust aware secure routing algorithm with attribute based encryption for wireless sensor networks," *Scientific Reports*, vol. 15, p. 19724, 2025. https://doi.org/10.1038/s41598-025-03558-8

[23] K. Sangeetha, J. Shanthini, and S. Karthik, "ECAR: Energy efficient cluster based adaptive routing for large scale WSN," *Journal of Intelligent & Fuzzy Systems: Applications in Engineering and Technology*, vol. 45, no. 5, pp. 7811-7825, 2023. https://doi.org/10.3233/JIFS-233445