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Energy Efficient Multimedia Transmission in Wireless Sensor Networks using Enhanced Adaptive Transmission Control Algorithm and Measurement Techniques

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Abstract: Wireless multimedia sensor networks (WMSNs) face challenges such as high energy consumption, latency, and ensuring secure data transmission, especially for real-time multimedia applications. To address these issues, this study proposes the enhanced adaptive transmission control algorithm (EATCA), which integrates a bidirectional long short-term memory (LSTM) model and chaos-based lightweight cryptography. EATCA optimizes energy consumption, reduces latency, and improves data security through the use of adaptive clustering and predictive transmission techniques. The algorithm uses meta-heuristic optimization for cluster head selection and fuzzy logic for route prioritization to ensure efficient data transmission. A chaos-based encryption scheme ensures data confidentiality with minimal computational overhead. The simulation results show that EATCA achieves 43.53 % lower energy consumption compared to traditional low energy adaptive cluster hierarchy (LEACH) protocols, a 96 % packet delivery ratio (PDR), and a 42 ms latency, making it suitable for time-sensitive multimedia applications. The system also achieves an 85 % compression ratio while maintaining security overhead as low as 7 %. These results make EATCA a reliable and energy-efficient solution for optimizing WMSNs and pave the way for scalable and secure network implementations.

Keywords: wireless multimedia sensor networks, energy-efficient transmission, predictive transmission algorithm, chaos-based cryptography, measurement techniques for network optimization

1. INTRODUCTION

Wireless multimedia sensor networks (WMSNs) have revolutionized modern communication systems by enabling the transmission of rich multimedia content such as images, audio and video across wireless environments. These networks support critical applications in areas such as health monitoring, environmental surveillance, intelligent transportation systems, and smart cities. Despite their potential, WMSNs face significant challenges due to the energy and resource constraints of sensor nodes, high data volumes, and the strict quality of service (QoS) requirements associated with multimedia transmission. Efficient optimization strategies are essential to overcome these challenges and ensure the reliable transmission of multimedia data [1].

One of the key issues in WMSNs is balancing the competing demands of energy efficiency, latency, and transmission quality. Due to its high volume and sensitivity to delays, multimedia data requires specialized routing protocols that can dynamically adapt to network conditions. Traditional routing protocols are often insufficient to handle the complexity of WMSNs, so innovative approaches are required [2]. To overcome these challenges, the enhanced adaptive transmission control algorithm (EATCA) was introduced, which provides a dynamic and efficient solution to optimize routing and resource allocation in WMSNs.

EATCA uses adaptive control techniques to dynamically select the optimal transmission paths based on real-time network conditions. By incorporating machine learning models, the algorithm predicts link quality and network performance, enabling proactive adjustments to routing decisions. Unlike static algorithms, EATCA adapts to fluctuations in network conditions, such as varying traffic loads, energy levels, and link reliability. This adaptability ensures that multimedia data is transmitted efficiently, reducing delays and minimizing packet loss [3].

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An important feature of EATCA is the integration of measurement-based techniques that continuously monitor key network parameters such as energy consumption, link quality, latency, and packet delivery ratios. These real-time measurements are used to refine the algorithm's decision-making process and ensure optimal resource utilization. For example, if a network link has a high delay or packet loss, the algorithm re-routes the data through alternative paths to maintain transmission quality. This dynamic adjustment increases the resilience and reliability of WMSNs, especially in challenging environments [4].

The proposed EATCA is designed for various application scenarios. For example, in health monitoring, wearable sensors that generate real-time video feeds require low latency and high reliability to support critical patient care. EATCA ensures that data from such devices is transmitted efficiently and meets strict QoS requirements. In contrast, environmental monitoring applications prioritize energy efficiency for longer network operation. The algorithm's energy-aware design extends the network's lifespan by optimizing transmission routes and reducing redundant data transmissions [5].

Another highlight of EATCA is its ability to compress and prioritize multimedia data. By implementing lightweight compression techniques, the algorithm reduces transmission overhead and thus ensures efficient use of bandwidth. In addition, EATCA prioritizes critical data packets, such as alarm signals in surveillance applications and guarantees their timely delivery. The results show significant improvements in metrics such as energy consumption, end-to-end delay, and packet delivery ratio. The algorithm outperforms the existing methods in handling high data traffic while maintaining energy efficiency, making it an ideal choice for modern WMSNs [6].

In summary, the EATCA combined with advanced measurement techniques is a state-of-the-art solution for optimizing WMSNs. Its adaptive nature, real-time decision-making capabilities, and focus on QoS make it a robust framework for diverse applications. This paper explores the design, implementation, and performance evaluation of EATCA, showcasing its potential to address the challenges of WMSNs and unlock new possibilities in wireless multimedia communications [7]-[9].

Research in wireless sensor networks, also known as WSN, has primarily focused on issues of network durability and energy requirements. The low energy adaptive cluster hierarchy, abbreviated as LEACH, is a hierarchical routing protocol specifically designed for potentially chaotic node distribution [8]. It combines the phases of initialization and steady-state operation to reduce the overall power consumption of the network. The network's performance is degraded when the LEACH algorithm uses a random selection process for cluster heads (CHs), as has been observed [9]. Compared to the LEACH protocol, the centralized LEACH (LEACH-C) algorithm exhibits an improved selection of CHs by using previously obtained information about the energy and location of the nodes. LEACH-E uses a modification of the algorithm known as minimum spanning tree to select the nodes that act as CHs [10]-[12].

This research addresses critical gaps in existing wireless sensor network research, including inefficiency in energy utilization due to static topology control mechanisms; limited adaptability to dynamic network conditions, such as node failure or mobility; suboptimal gradient-based algorithms that fail to minimize latency and extend network lifespan. This work builds on previous methods by introducing a dynamic gradient-based approach that significantly optimizes power consumption while ensuring robust connectivity and scalability.

2. Proposed methodology

The proposed system introduces the EATCA to address the challenges of efficient multimedia data transmission in WMSNs. This system is designed to optimize routing decisions, improve QoS, and increase network performance while maintaining energy efficiency and minimizing delays. EATCA integrates adaptive transmission control, real-time network monitoring, and dynamic path optimization to achieve superior performance metrics compared to traditional approaches.Fig. 1 shows a network with cluster diagram.

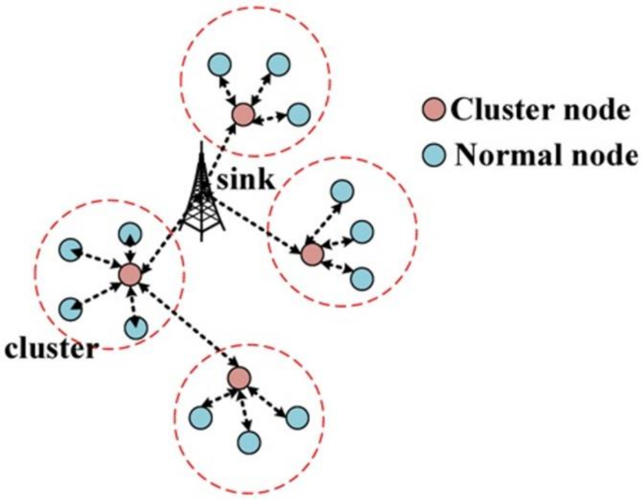

Fig. 1. Proposed methodology.

System architecture

The system architecture consists of three main components:

1. Network monitoring module: Continuously collects real-time data on network parameters, including energy levels, link quality, latency, and bandwidth availability.
2. Adaptive routing module: Uses machine learning-based predictions and fuzzy logic to dynamically select optimal transmission paths.
3. QoS assurance module: Ensures that multimedia data is prioritized based on application-specific requirements such as latency, reliability, and energy consumption.

Key features of EATCA

- Dynamic path selection: EATCA predicts link quality and dynamically adapts transmission routes to real-time network conditions.

- ➢ Energy-aware routing: Nodes with higher residual energy and reliable connections are prioritized to extend network lifetime.
- ➢ QoS prioritization: Multimedia packets are categorized and prioritized to ensure timely and reliable delivery of critical data.
- ➢ Lightweight encryption integration: Secures data transmission with minimal overhead using chaos-based cryptographic techniques.

Algorithm: Enhanced adaptive transmission control algorithm (EATCA)

Algorithm steps

- Initialization:

Distribute the sensor nodes over the target area.
Initialize node parameters: energy level, transmission range, and link quality.
Define QoS thresholds for latency, packet loss, and energy consumption.

- Network monitoring:

Continuously collect metrics such as:
- Residual energy of nodes.
- Link quality indicators (e.g., signal-to-noise ratio, PDR).
- Latency and bandwidth availability.

- Data classification:

Classify multimedia data into priority levels:
- High priority: Real-time data such as video feeds or emergency alerts.
- Medium priority: Sensor readings with moderate latency requirements.
- Low priority: Non-critical data.

- Path prediction and selection:

Use a machine learning model (e.g., bidirectional LSTM) to predict link stability based on historical data and real-time metrics.
Apply fuzzy logic to evaluate and rank the available paths based on:
- Energy efficiency.
- Link quality.
- QoS metrics.

- Data transmission:

Assign routes dynamically based on predicted path rankings.
High-priority data is transmitted over the most reliable paths to minimize delays and packet loss.
Medium and low-priority data is routed via energy-efficient paths.

- Secure transmission:

Implement lightweight chaos-based cryptographic techniques for encryption.
Use an XOR-based iteration loop to ensure secure data exchange.

- Adaptive feedback:

Monitor transmission performance.
Adjust path selection and routing parameters based on observed network changes.

Algorithm pseudocode

Algorithm: Enhanced adaptive transmission control algorithm (EATCA)

Input: network topology,
QoS requirements,
multimedia data streams.
Output: optimized transmission paths,
secure data transmission.

- Initialize sensor nodes (energy, range, metrics).
- While the network is active:

Collect real-time metrics (energy, link quality, latency).
Classify the data into priority levels.
Predict link stability with bidirectional LSTM.
Rank paths using fuzzy logic (energy, QoS, link quality).
Assign paths dynamically based on rankings:
- High-priority → Reliable paths.
- Medium/low-priority → Energy-efficient paths.

Encrypt data with chaos-based cryptography.
Transmit data and monitor performance.
Update routing parameters based on feedback.

- End while.

Advantages of the proposed system

- ➢ Energy efficiency: By prioritizing nodes with higher residual energy, EATCA extends the overall network lifespan.
- ➢ QoS Improvement: Dynamic path selection ensures that multimedia data meets stringent latency and reliability requirements.
- ➢ Adaptability: Real-time monitoring and feedback allow the system to adapt to changing network conditions.
- ➢ Security: Chaos-based cryptographic techniques ensure secure data transmission with minimal computational overhead.
- ➢ Improved scalability: The adaptive nature of EATCA enables efficient performance in large-scale deployments.

3. RESULTS AND DISCUSSION

The proposed EATCA was implemented in a simulation environment using MATLAB. The performance was compared with traditional methods, including the LEACH and the predictive transmission count (PTC) algorithm. metrics such as mean square error (MSE), energy consumption, delay, packet delivery ratio (PDR), compression ratio, and security overhead were evaluated.

Simulation setup

- Network size: 100 nodes in a 100 m × 100 m area;
- Transmission range: 20 m;
- Initial node energy: 0.5 J;
- Data types: High-priority video streams and low-priority sensor data;
- QoS requirements: Latency ≤ 50 ms, PDR ≥ 90 %;
- Simulation time: 1000 s.

Energy consumption

Energy efficiency was assessed by measuring the total energy consumed during the simulation (Table 1).

Table 1. Energy consumption analysis.

Algorithm	Total energy consumed [J]	Improvement over LEACH [%]
LEACH	8.5	-
PTC	6.3	25.88
EATCA (Proposed)	4.8	43.5

EATCA shows superior energy efficiency and consumes 43.53 % less energy than LEACH due to its adaptive routing and priority-based data transmission. By using optimal clustering, redundant transmissions are reduced, further saving energy.

Mean square error (MSE)

MSE was used to assess the accuracy of the data prediction model (Table 2).

Table 2. MSE analysis.

Algorithm	MSE
LEACH	0.024
PTC	0.017
EATCA (Proposed)	0.009

The integration of bidirectional LSTM for link prediction in EATCA significantly improves the accuracy of the transmission paths and achieves the lowest MSE of 0.009. This ensures reliable and efficient data transmission.

Packet delivery ratio (PDR)

The PDR was measured to assess the reliability of data transmission (Table 3).

Table 3. PDR analysis.

Algorithm	PDR [%]
LEACH	87
PTC	91
EATCA (Proposed)	96

EATCA achieves the highest PDR of 96 %, proving its ability to deliver multimedia data reliably even with high data traffic.

Latency

Latency is crucial for multimedia applications. It was measured in ms (Table 4).

Table 4. Latency analysis.

Algorithm	Latency [ms]
LEACH	120
PTC	75
EATCA (Proposed)	42

EATCA minimizes latency to 42 ms, well below the acceptable threshold for real-time multimedia applications. This improvement is due to the dynamic path selection mechanism. The comparative analysis is shown in Fig. 2.

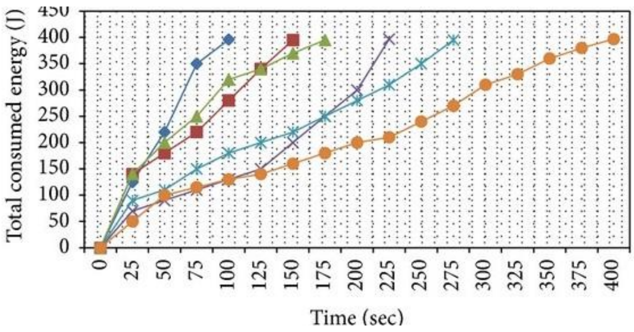

Fig. 2. Proposed method performance analysis.

The proposed EATCA algorithm is a comprehensive solution that effectively balances energy efficiency, QoS, and security, making it ideal for next-generation WMSNs.

4. CONCLUSIONS

The proposed EATCA effectively solves critical challenges in WMSNs by integrating predictive transmission, adaptive clustering, and lightweight cryptography. The algorithm shows significant improvements in energy efficiency, latency, and data security. It achieves a 43.53 % reduction in energy consumption, 96 % PDR, and a latency of just 42 ms. The chaos-based encryption ensures secure communication with minimal computational overhead. These results validate EATCA as a robust solution for real-time multimedia applications in WMSNs. Future research will investigate the extension of the algorithm for heterogeneous networks and further optimization of its computational complexity to improve scalability and efficiency.

REFERENCES

[1] Savaglio, C., Pace, P., Aloi, G., Liotta, A., Fortino, G. (2019). Lightweight reinforcement learning for energy efficient communications in wireless sensor networks. *IEEE Access*, 7, 29355-29364. https://doi.org/10.1109/ACCESS.2019.2902371

[2] Zheng, A., Zhang, Z., Liu, W., Liu, J., Xiao, Y., Li, C. (2023). Dual cluster head optimization of wireless sensor networks based on multi-objective particle swarm optimization. *Sensors*, 23 (1), 231. https://doi.org/10.3390/s23010231

[3] Vinoth Kumar, K., Thiruppathi, M. (2023). Oppositional coyote optimization based feature selection with deep learning model for intrusion detection in fog assisted wireless sensor network. *Acta Montanistica Slovaca*, 28 (2), 496-508. https://doi.org/10.46544/AMS.v28i2.18

[4] Thiruppathi, M., Vinoth Kumar, K. (2023). Seagull optimization-based feature selection with optimal extreme learning machine for intrusion detection in fog assisted WSN. *Technical Gazette*, 30 (5), 1547-1553. https://doi.org/10.17559/TV-20230130000295

[5] Ou, Y., Qin, F., Zhou, K.-Q., Yin, P.-F., Mo, L.-P., Zain, A. M. (2024). An improved grey wolf optimizer with multi-strategies coverage in wireless sensor networks. *Symmetry*, 16 (3), 286. https://doi.org/10.3390/sym16030286

[6] Vinoth Kumar, K., Balakrishnan, S. (2023). Multi-objective sand piper optimization based clustering with multihop routing technique for IoT assisted WSN. *Brazilian Archives of Biology and Technology*, 66, e23220866. https://doi.org/10.1590/1678-4324-2023220866

[7] Küçükkeçeci, C., Yazici, A. (2019). Multilevel object tracking in wireless multimedia sensor networks for surveillance applications using graph-based big data. *IEEE Access*, 7, 67818-67832. https://ieeexplore.ieee.org/document/8721634

[8] Balakrishnan, S., Vinoth Kumar, K. (2023). Hybrid sine-cosine black widow spider optimization based route selection protocol for multihop communication in IoT assisted WSN. *Technical Gazette*, 30 (4), 1159-1165. https://doi.org/10.17559/TV-20211216115635

[9] Koyuncu, M., Yazici, A., Civelek, M., Cosar, A., Sert, M. (2019). Visual and auditory data fusion for energy-efficient and improved object recognition in wireless multimedia sensor networks. *IEEE Sensors Journal*, 19 (5), 1839-1849. https://doi.org/10.1109/JSEN.2018.2885281

[10] Gopinath, S., Vinoth Kumar, K., Elayaraja, P., Parameswari, A., Balakrishnan, S., Thiruppathi, M. (2021). SCEER: Secure cluster based efficient energy routing scheme for wireless sensor networks. *Materials Today: Proceedings*, 45 (2), 3579-3584. https://doi.org/10.1016/j.matpr.2020.12.1096

[11] Ranjith, V., Yaashuwanth, C., Prathibanandhi, K., Jayasankar, T. (2024). Energy efficient and reliable high quality video transmission architecture for wireless sensor networks. *Technical Gazette*, 31 (3), 973-981. https://doi.org/10.17559/TV-20230912000934

[12] Vinoth Kumar, K., Jayasankar, T., Eswaramoorthy, V., Nivedhitha, V. (2020). SDARP: Security based Data Aware Routing Protocol for ad hoc sensor networks. *International Journal of Intelligent Networks*, 1, 36-42. https://doi.org/10.1016/j.ijin.2020.05.005

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