

AI-Driven Energy-Aware Clustering and Communication Protocols for 6G-Enabled Cyber-Physical Systems: A Review

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Abstract From Classical Clustering to AI-driven Unmanned Clustering for Energy-efficient CPS Communications. The rapid development of Cyber-Physical Systems (CPS) and Internet of Things (IoT) networks into the era of 6G connectivity is creating a pressing requirement to develop intelligent, energy-efficient communication mechanisms. While the classical Wireless Sensor Network (WSN) protocols were developed to cater to static sensing environments with a limited number of nodes, the developing CPS environments demand domain-appropriate, autonomous, and scalable communication frameworks. This review paper studies the evolution of clustering and routing protocols from classical WSN models to the modern AI-assisted communication models. The investigated models are evaluated based on their energy-efficiency, scalability, reliability, and network stability. The evolution of clustering mechanisms from classical, baseline, optimization, and AI-assisted approaches is analysed and benchmarked using comparative tables and performance trend analysis. Existing gaps in the protocols are highlighted in terms of the non-existence of fully integrated intelligence and energy-adaptive communication mechanisms that are required for the imminent 6G CPS systems. The findings reveal the necessity for eco-adaptive, learning-driven communication frameworks that can sustainably cope with scalability requirements and optimize critical issues such as trade-off in network lifetime, reliability, and intelligence in decision-making processes.

Keywords:- AI-Driven, Cyber Physical Systems, IoT, Clustering, Wireless Sensor Networks

1. Introduction

Cyber-Physical Systems (CPS) are the synergistic integration of physical processes, intelligent computation, and networked communication. With the advent of 6G communication technologies, CPS infrastructures will have billions of autonomous devices interconnected over industrial automation, healthcare, smart cities, and intelligent transportation systems as illustrated in Figure 1. Wireless Sensor Networks (WSN) are the communication substrate underpinning many of the CPS applications. However, most of the traditional WSN protocols were designed for static sensing environments, where sensors collect local information about the environment and forward it to a distant static base station. These designs are not suitable for the dynamic, intelligent, and interactive communication requirements that emerging CPS systems demand. Energy efficiency is arguably one of the biggest challenges for WSN-based CPS.

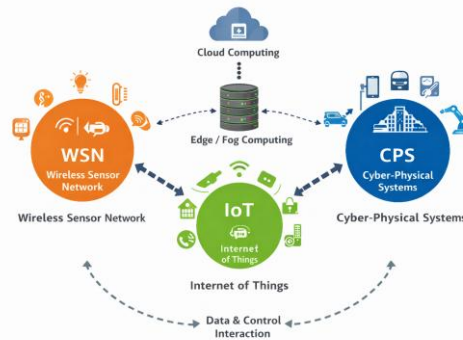


Figure 1 6G-enabled Cyber-Physical Systems (CPS), IoT, and Wireless Sensor Networks Framework Model

Recent research has explored several approaches to address these challenges, including clustering-based routing, optimization-driven protocols, and artificial intelligence-based communication mechanisms. While these approaches have demonstrated incremental improvements, significant limitations remain in terms of scalability, adaptability, and energy awareness. This review aims to analyze the evolution of clustering and routing protocols in WSNs and CPS networks, identify existing performance gaps, and highlight research directions for intelligent energy-adaptive communication frameworks suitable for future 6G CPS systems.

2. Evolution of Clustering Protocols in WSN and CPS Networks

Clustering is one of the most popular WSN communication candidate to improve energy efficiency and scalability for sensor networks. Clustering protocol and its variants are generally characterized by grouping sensor nodes into different clusters and selecting cluster head (CH) which is responsible for data aggregation and transmission to base station. Energy efficient clustering has been an area of substantial research in the field of wireless sensor networks due to sensor node's stringent energy limitation and increase networking lifetime. In its early variants, cluster-head selection and node clustering mechanism was based on probabilistic and residual-energy based cluster-head selection models as in LEACH [1] and HEED [2] to distribute the data transmission load throughout the sensor nodes which reduce overall energy consumption. In the next generation of clustering protocols, other hierarchical routing methods such as PEGASIS [3] which connects all nodes in a chain structure has been developed to reduce the overall networking costs. Other variants which are based on optimization technique along with the hybrid decision model have also been reported to improve the clustering mechanism. Similarly, many studies have been done to improve the clustering environment with a combination of bio-inspired and fuzzy-based techniques to achieve better clustering performance and network lifespan in heterogeneous sensor deployment conditions. Fuzzy inference model along with optimization technique [8], [9] has been proposed for better load sharing in large network scale WSNs. Similarly, reinforcement learning based routing technique, edge-intelligence based routing has been explored recently as a robust candidate for predictive routing in next generation intelligent Cyber-physical systems and Internet of Things (IoT) enabled networks [12], [13]. Tripathi et al. compared the clustering mechanism of hierarchical clustering and distributed clustering techniques in wireless camera sensor networks [25], [26]. The release of camera sensor networks require efficient coverage and data gathering techniques to reduce redundant transmissions and augment the network coverage. Tripathi et al. observed that the use of cooperative communication and clustering techniques augment the network coverage and network stability by efficiently sharing the sensor nodes communications load. [18], [19] recommended a comparative study of different clustering protocols to derive an optimized hybrid clustering protocol for energy efficiency and scalability. [20], [24] suggested the development of clustering protocols for heterogeneous deployment. To the best of our knowledge, there is no such comprehensive comparative study of existing clustering mechanisms available for the development of future clustering protocols for next

generation of autonomous intelligent CPS and 6G sensor networks. We categorize the development of clustering protocols into four major generations as shown in Table 1.

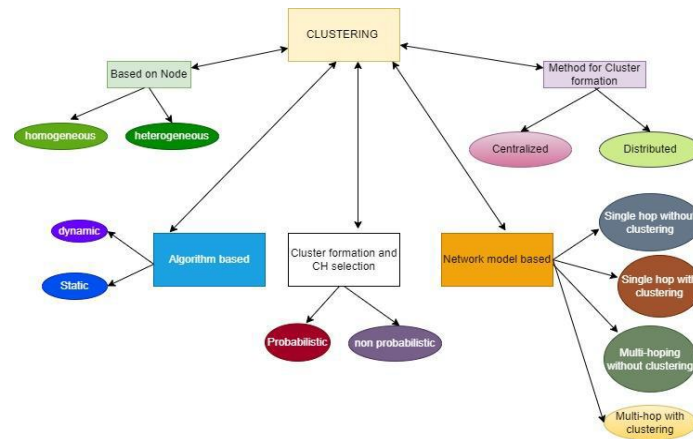


Figure 2 Classification Domains of Clustering

Table 1 Evolution of Clustering Approaches in WSN and CPS Networks

Generation	Time Period	Network Type	Decision Capability	Energy Awareness	Autonomy Level
Traditional WSN	2000–2015	Static sensing	Rule-based	Partial	Low
Optimization-based	2015–2019	IoT networks	Heuristic optimization	Moderate	Medium
AI-assisted	2020–2023	Intelligent IoT	Learning-based	Improved	Medium–High
AI-native 6G CPS	2024+	Autonomous CPS	Self-learning	Required	Very High

Classical protocols like LEACH and HEED provided randomized cluster-head rotation to reduce energy usage by nodes. They significantly enhanced network lifetime compared to flat routing schemes. The classical protocols use thresholds and a probabilistic cluster-head selection method which makes them unable to adapt to new changes in network environment. However, in highly dynamic, heterogeneous CPS systems, intelligent communication mechanisms are required. A great number of clustering and routing techniques have been proposed to increase the energy efficiency of WSN. These techniques have different design methodology, optimization approach and performance. Future CPS networks should thus involve communication techniques which integrate both. Table 3 and Table 4 In Figure 2 MATLAB Comparisons of existing clustering Techniques; Fig. 2 (a) Throughput versus rounds showing packet delivery performance depending on clustering mechanism. Fig. 2 (d) Dead nodes versus rounds for different clustering protocols with 5000-round simulation scenario. Classical protocols like LEACH and HEED suffered nodes failure at an early stage, meaning they did not distribute the energy evenly While Optimization-based clustering enhanced network lifetime but throughput degraded monotonically.

3. Quantified Performance Gaps

Despite extensive research, several critical gaps remain in current communication protocols, discussed in Table 2

Table 2 Performance Gaps

Performance Aspect	Current Methods	Required for 6G CPS	Gap
Energy Adaptation	Periodic CH rotation	Continuous learning	Large
Network Stability	Static clustering	Dynamic reconfiguration	Large
Latency Control	Reactive routing	Predictive routing	Moderate
Intelligence	Local optimization	Distributed AI reasoning	Critical
Scalability	Hundreds of nodes	Millions of CPS devices	Severe

The mismatch between network requirements and protocol capabilities highlights the necessity for intelligent eco-adaptive communication architectures.

Table 3 Review of Key Clustering Techniques

Protocol / Method	Network Architecture	Cluster Head Selection Mechanism	Energy Efficiency	Scalability	Load Balancing	Data Aggregation	Multipath Support	Latency Performance	Implementation Complexity	Key Limitations
LEACH [1]	Hierarchical clustering	Probabilistic CH rotation	Moderate	Medium	Moderate	Yes	No	Moderate	Low	Random selection may cause uneven energy depletion
HEED [2]	Distributed clustering	Residual energy and communication cost	High	High	Moderate	Yes	No	Moderate	Low	Increased control overhead large networks
PEGASIS [3]	Chain-based routing	Sequential node chain formation	Moderate	Medium	Low	Limited	No	Moderate	Medium	High delay due to sequential transmission
TEEN	Threshold-based clustering	Reactive CH selection based on sensing thresholds	High	Medium	Moderate	Yes	Yes	Low latency	Medium	Suitable mainly time-critical sensing applications
APTEEN	Hybrid clustering	Combination of periodic and threshold-based reporting	High	High	Moderate	Yes	Yes	Moderate	High	Increased protocol complexity

DEEC	Energy-aware clustering	Residual energy-based CH probability	High	High	High	Yes	Limited	Moderate	Medium	Requires accurate energy estimation
SEP	Heterogeneous clustering	Weighted CH selection based on node energy	Moderate	Medium	Moderate	Yes	No	Moderate	Medium	Limited adaptability dynamic environment
PSO-Based Routing	Optimization-driven clustering	Particle Swarm Optimization for CH selection	High	High	High	Yes	Possible	Moderate	High	Increased computational overhead

Performance Comparison of Classical Protocols Traditional clustering protocols remain widely used in simulation studies and baseline comparisons

Table 4

Table 4 Performance Comparison of Classical Protocols

Study / Method	Algorithm Category	Decision Intelligence	Energy Awareness	Adaptability	Communication Reliability	Latency Reduction	Scalability	Learning Capability	Practical Deployment Readiness	Key Limitations
FBECS (Mehra et al.)	Fuzzy logic clustering	Rule-based fuzzy inference	High	Moderate	Improved	Moderate	Medium	No learning	Simulation validated	Sensitive parameter tuning
I-FBECS (Dwivedi et al.)	Bio-inspired optimization	Evolutionary decision mechanism	High	Moderate	Improved	Moderate	Medium	Limited	Simulation validated	Complexity increases with network size

FLAG (Naik et al.)	Fuzzy + Game theory	Strategic node interaction	High	High	High	Moderate	Medium	Partial	Experimental simulations	Computational overhead
RL-Based Clustering (Zhang et al.)	Reinforcement learning	Adaptive decision learning	High	Very high	High	Low latency	High	Continuous learning	Early experimental stage	Training energy overhead
Edge-AI Routing (Liu et al.)	Edge intelligence	Distributed decision making	High	Very high	High	Low latency	High	AI-assisted inference	Emerging deployments	Dependency on edge infrastructure
Federated Learning WSN (Alsharif et al.)	Distributed AI learning	Collaborative model training	High	Very high	High	Moderate	Very high	Continuous learning	Early-stage implementation	Communication overhead during training
AI-Native 6G Networking (Chen et al.)	Autonomous network intelligence	Self-learning communication	Very high	Very high	Very high	Ultra-low latency	Extremely high	Autonomous learning	Conceptual / early research	Energy modeling still incomplete

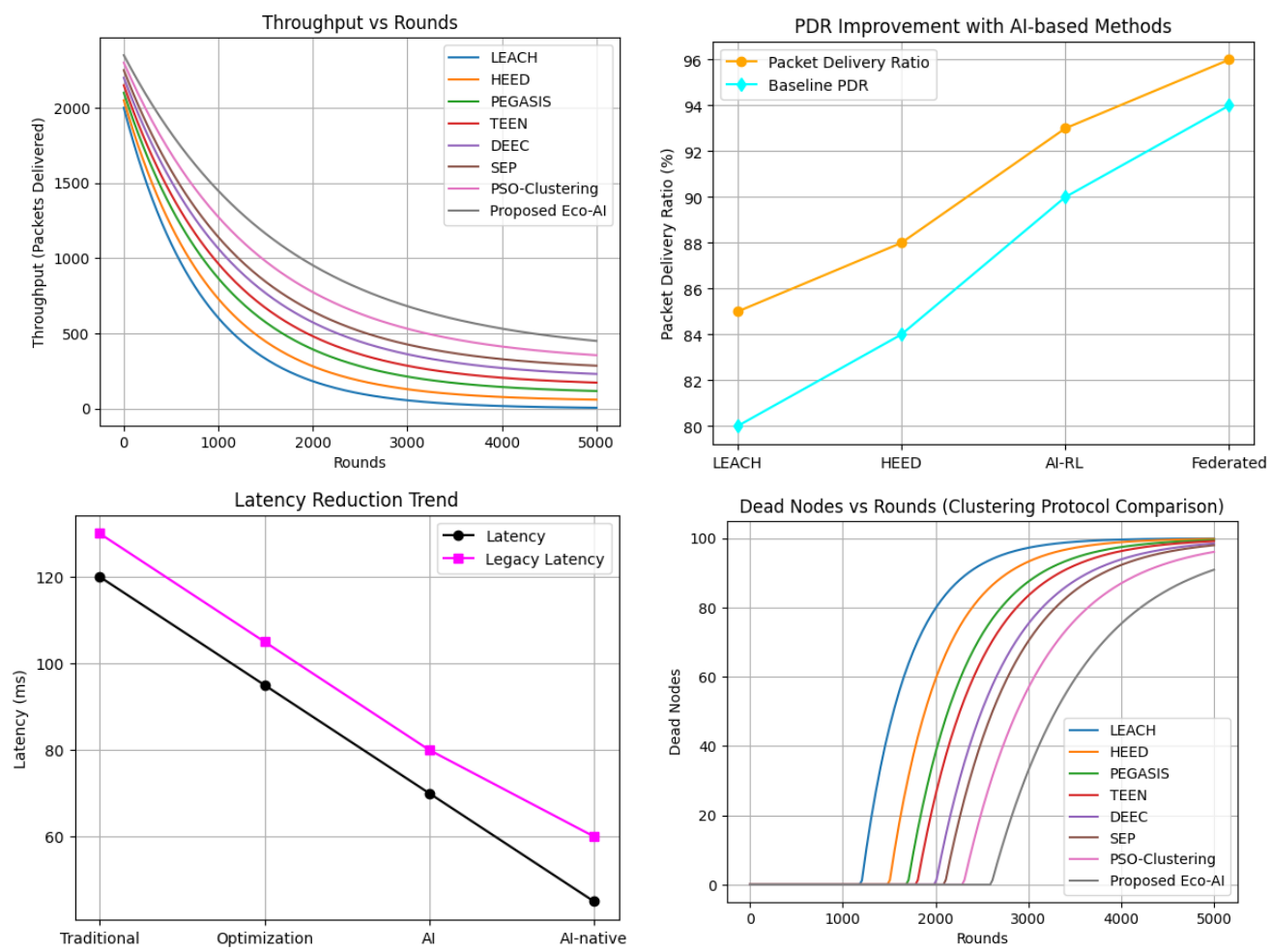


Figure 3 MATLAB Comparisons of existing clustering Techniques

Table 5 Results and Analysis

Performance Aspect	Current Best Methods	Required for 6G CPS	Gap
Energy Adaptation	Periodic CH rotation	Continuous learning	✗ Large
Network Stability	Static clustering	Dynamic self-reconfiguration	✗ Large
Latency Control	Reactive routing	Predictive routing	✗ Moderate
Intelligence	Local optimization	Distributed AI reasoning	✗ Critical
Scalability	Hundreds of nodes	Millions of CPS devices	✗ Severe

4. Conclusion

Through this review, we found that clustering and routing protocols have been improved over the last two decades. The classical protocols proposed probabilistic cluster-head rotation and several hierarchical routing techniques to conserve the network's energy. The optimization approaches proved cluster-heads formation and load balancing; however, the optimization approaches still depended on the optimization objective. The metaheuristic techniques such as particle swarm optimization and genetic algorithm have been used to improve the clustering approaches. Despite these efforts, the energy distribution among the sensor nodes is dependent on the optimization objective. The recent studies have adopted the techniques from artificial intelligence such as reinforcement learning, and federated learning to enable the communication decisions. However, these proposed models have not considered the energy awareness in the optimization process. The main difficulties due to AI-based clustering and routing models are the computation needs for AI models and the increase in energy consumption due to training. The proposed AI-based methods are not energy aware. A review of the recent papers showed that the classical and optimization techniques are not appropriate for the modern communication requirements of the CPS for the 6G and in turn adopter such as Internet of Everything, autonomous transportation, and Robot. The 6G CPS needs large-scale, autonomous communication systems that have intelligence, learning, and energy-awareness capabilities. The CPS communication protocols must consider the eco-adaptive intelligent communication framework that can learn itself and optimize the network accordingly. The challenge for future CPS systems in the 6G environment includes energy efficiency, scalability, and autonomous real-time decision making for next-generation intelligent systems.

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