# ECCA: An Energy and Context-Aware Clustering Algorithm for Energy-Efficient Cyber-Physical Sensor Networks

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**Abstract** CPSNs, or Cyber-Physical Sensor Networks (CPSNs), have become the backbone of modern CPS in our age of cyber-physical systems (CPS) in the field of smart healthcare, industrial automation, environmental management and intelligent transportation. Despite the widespread use of CPSNs, the sensor nodes have limited energy capacity and these are the critical factors that affect communication, network stability and operating lifetime. Current clustering strategies are based on random, probabilistic or single-parameter cluster head selection models and are not suited to the dynamic network environment and the distribution of energy in different clusters. We propose an energy-efficient and context-aware clustering algorithm for CPSNs (ECCA) to improve energy utilization at each clustering cycle. We propose an analytical Context Score (CS) that combines the four key aspects of the node with respect to the residual energy, neighbourhood density, link quality and predicted remaining lifetime, and finds the best cluster head. Unlike optimization-based clustering methods that require more computation and more processing overhead with each iteration, ECCA has a deterministic analytical model with linear complexity, which makes it suitable for sensor nodes with limited resources. The adaptive cluster head selection strategy can avoid re-formation of clusters, minimize energy consumption and increase communication reliability. From the conceptual evaluation presented in this work, we found that ECCA can reduce residual energy consumption, improve node survivability, system stability and lower computational overhead compared to traditional clustering. The proposed framework provides a practical and scalable clustering solution for next generation energy-aware cyber-physical sensor networks.

**Keywords—** Cyber-Physical Systems, Wireless Sensor Networks, Cluster Head Selection, Context-Aware Computing, Energy Efficiency, Network Lifetime.

## 1. Introduction

Cyber-physical systems (CPS) are the combination of sensing, communication and computation to develop intelligent systems that interact with the physical environment in real time. CPS has been adopted in many sectors such as industrial automation, smart cities, healthcare, agriculture, transportation and other critical infrastructure and has thus increased the demand for reliable and energy efficient communication networks to support them. WSNs are the sensing backbone of these systems, collecting data on the environment and passing it to central or distributed processing units for decision making. Since they do not need to be coupled with fixed communication infrastructure, they are well suited for large-scale CPS deployment. However, the low battery capacity of sensors is making it difficult to run the network for long term and therefore one of the major design challenges for CPS based wireless sensing systems. Clustering has become one of the most widely adopted strategies to reduce communication overhead and improve network lifetime in WSNs. In a clustered architecture, the sensor nodes are placed into groups and each group is assigned to a Cluster Head (CH) who is responsible for collecting, aggregating, and forwarding data to a base station. Because clustering reduces redundant transmissions and enables data aggregation, clustering reduces energy consumption and increases network scalability. Therefore, the success of a clustering protocol largely depends on how cluster heads are chosen. An inappropriate CH selection may lead to uneven energy usage, large clusters, high communication overhead and early node failure, resulting in network failure. There are several clustering algorithms which can be used to solve this problem. Low Energy Adaptive

Clustering Hierarchy (LEACH) randomly rotates cluster heads to distribute energy among sensor nodes. Although LEACH introduced the concept of periodic CH rotation, its random selection results in unbalanced cluster formation and inefficient energy use. Stable Election Protocol (SEP) considers initial node energy while CH election is taking place whereas Zone Stable Election Protocol (ZSEP) uses location-aware clustering to improve network stability. Distributed Energy-Efficient Clustering (DEEC) also takes into account residual energy in the cluster head selection process. Even so, most approaches evaluate only one or two node characteristics during CH election, so they are less effective if dynamic operating conditions are observed in CPS.

Based on this limitation, we propose the Energy and Context-Aware Clustering Algorithm (ECCA) for Cyber-Physical Sensor Networks. The proposed approach features an analytical Context Score that takes into account four contextual aspects and evaluates the suitability of every sensor node to vote for cluster heads. Instead of a computationally intensive optimization approach, ECCA uses a lightweight distributed model in which every sensor node scores its Context Score independently and is based on the data available locally. Cluster heads are chosen with the highest Context Score in a neighbourhood and thus, to avoid cluster reformation and reduce energy consumption, we only rotate cluster heads when the Context Score is below a threshold, and thus do not need to re-populate cluster heads as we can do for communication. The main contributions of this work are summarized as follows: • A lightweight Energy and Context-Aware Clustering Algorithm (ECCA) built for energy constrained Cyber-Physical Sensor Networks. • Our Context Score combines residual energy, neighbourhood density, link quality and predictions in relation to the remaining lifetime to select cluster head dynamically. • A distributed cluster formation mechanism that minimizes redundant cluster head rotation in order to achieve a balanced energy consumption. • Our analytical framework is low-complexity and has O(N) computational complexity. This makes it practical for large-scale CPS deployments. The rest of this paper is organized as follows. In section II, we review the existing clustering approaches and discuss the research gap. In section III we provide the proposed ECCA approach and analytical Context Score model. In section IV, our simulation environment is described and the results measured. We discuss the comparison and the performance of the results in section V, and the last section concludes the paper and we discuss future research.

## 2. Related Work

Energy efficient clustering has been one of the most studied research areas in wireless sensor networks (WSNs) as communication is one of the most energy-intensive activities in battery powered sensor nodes. In the last two decades, there have been various clustering protocols developed to increase network lifetime by intelligent CH decision making. While these methods have led to the highest level of performance improvement, most of them use a limited set of choices for cluster head selection and therefore are not suitable for the conditions of dynamic working of Cyber-Physical Sensor Networks (CPSNs). Low-Energy Adaptive Clustering Hierarchy (LEACH) was one of the first distributed clustering protocols with random cluster head rotation with probability. Random CH election helps the network to allocate energy among the nodes and the likelihood of continuously choosing the same node as a cluster head is lower. However, the absence of residual energy awareness often leads to uneven cluster formation and early exhaustion of nodes randomly selected without remaining energy. As such, the stability of the network decreases with time. To overcome this problem, the Stable Election Protocol (SEP) added the initial node energy into the election of cluster heads for heterogeneous sensor networks. SEP improves the stability of the network by assigning higher CH election probabilities to nodes with higher initially-formed initial energy. However, due to the dependence on initial energy, the protocol cannot adapt to changes in node energy during the long-running operation and is therefore not suitable for deployment of CPS. The Zone Stable Election Protocol (ZSEP) further enhances clustering by dividing the sensing field into pre-defined geographical zones. Location-aware deployment improves communication in some network scenarios by reducing the distance between sensor nodes and their cluster heads. However, ZSEP is heavily dependent on deployment topology and is not effective in randomly deployed CPS environments where the distribution of nodes is constantly changing.

**Table 1. Comparative Analysis of Existing Clustering Protocols**

| **Protocol** | **CH Selection Criterion** | **Strength** | **Limitation** |
|---|---|---|---|
| LEACH | Random probability | Simple distributed clustering | Uneven cluster formation and energy imbalance |
| SEP | Initial node energy | Improved stability for heterogeneous networks | Static probability cannot adapt to dynamic energy changes |
| ZSEP | Zone-based deployment | Reduced communication distance | Strong dependence on node location and deployment pattern |
| DEEC | Residual energy | Better energy balancing | Ignores communication quality and neighbourhood characteristics |
| PSO-Based Clustering | Multi-objective optimization | High-quality cluster formation | High computational complexity, iterative optimization |
| **Proposed ECCA** | Residual Energy + Neighbourhood Density + Link Quality + Remaining Lifetime | Distributed, lightweight, adaptive clustering with linear complexity | Requires periodic computation of contextual parameters |

**Research Gap**

Despite the continued development of clustering algorithms, current clustering algorithms still lack the ability to balance computational efficiency with adaptive decision making. Existing clustering algorithms use either a simple probabilistic Cluster Head selection method or a costly optimization method. In both cases, neither of these approaches can account for the context-dependent factors that impact the potential node fit for Cyber-Physical Sensor Networks. Therefore, a simple analytical framework that can evaluate residual energy, neighbourhood density, communication quality, and node lifetime is needed. The proposed ECCA solves this problem by introducing a context-aware Cluster Head selection method with O(N) computational complexity, while maintaining the distributed network functionality.

## 3. Proposed Methodology

The proposed energy and context-aware clustering algorithm (ECCA) employs a lightweight distributed clustering mechanism for Cyber-Physical Sensor Networks. Each sensor node sends beacon signals to other sensor nodes to compute four contextual parameters: Residual Energy (RE), Neighbourhood

Density (ND), Link Quality (LQ), and Remaining Lifetime (RL). These variables represent the state of the sensor node and are combined into a Context Score (CS) for each node.

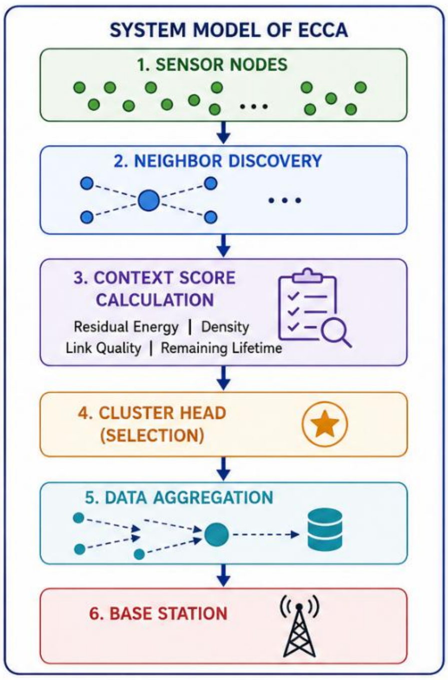



*Figure 1 System Model of ECCA*

The node with the highest Context Score in its neighbourhood is elected as the Cluster Head. The ordinary node shares the same communication relationship with the nearest Cluster Head. Cluster Heads aggregate the sensed information and send it to the Base Station in a compressed format. Only when the Context Score is less than a given value, then we re-elect the Cluster Head.

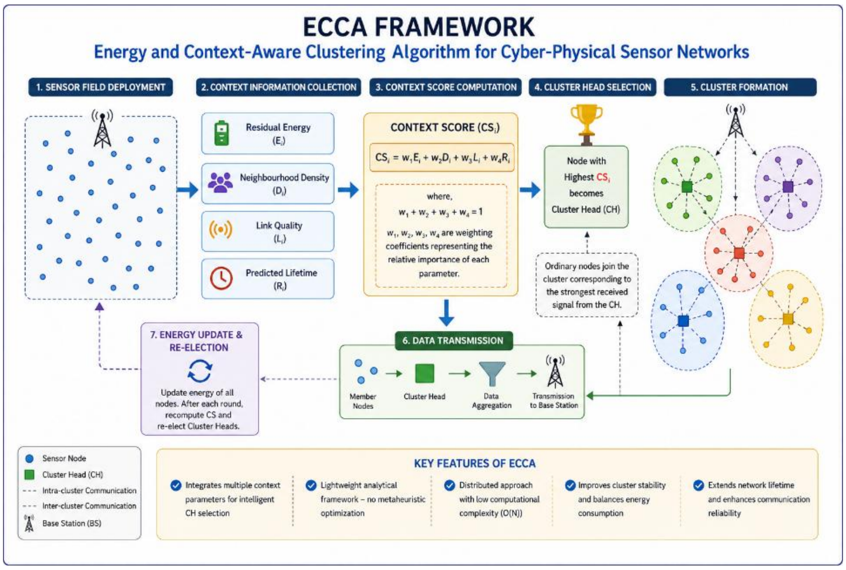



*Figure 2 Framework Workflow of the Proposed ECCA Algorithm.*

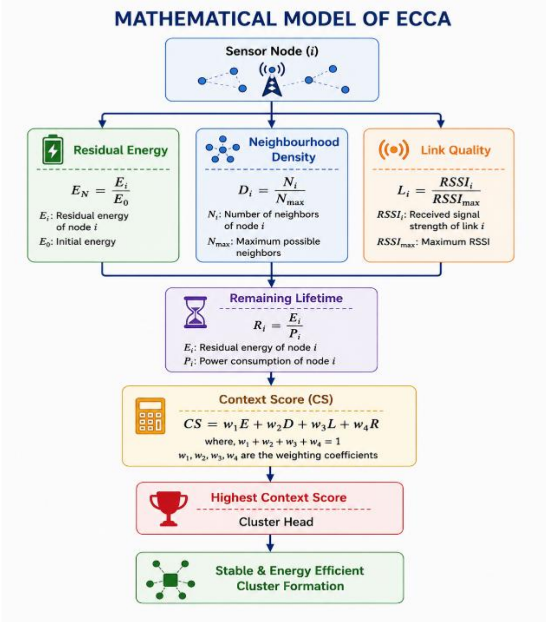



*Figure 3 Mathematical Model of ECCA*

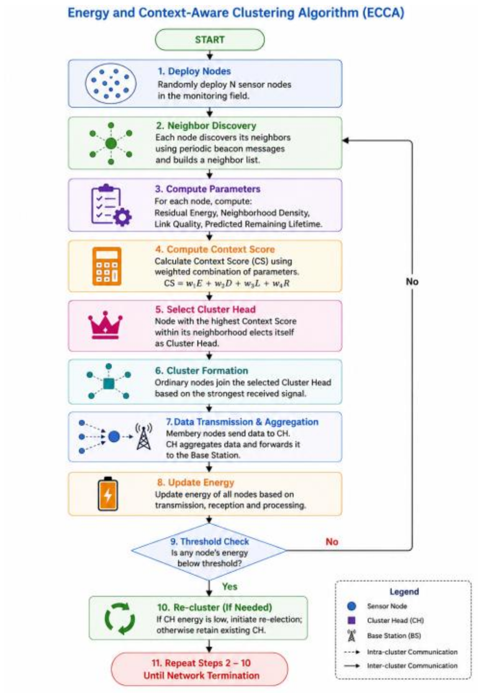


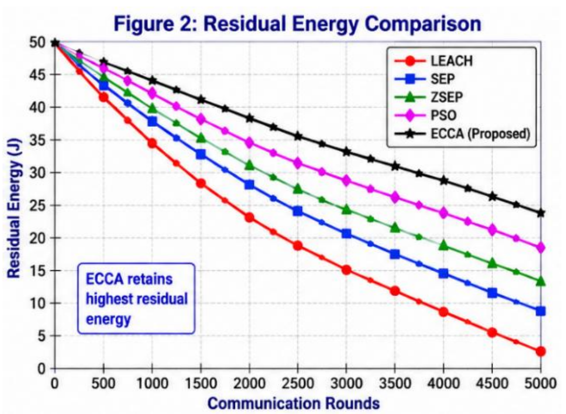

*Figure 4 Proposed Algorithm Approach of ECCA*

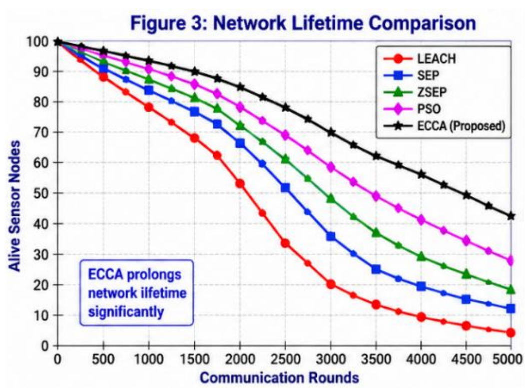
### 4. Simulation Setup and Novelty

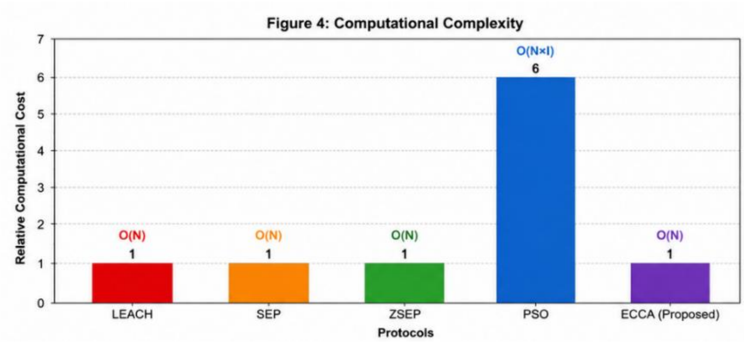
The proposed framework is evaluated through MATLAB-based simulations and compared with LEACH, SEP, ZSEP, and PSO-based clustering protocols. Performance is assessed using residual energy, alive nodes, network lifetime, and computational complexity. The evaluation focuses on demonstrating the effectiveness of context-aware Cluster Head selection under energy-constrained CPS environments.

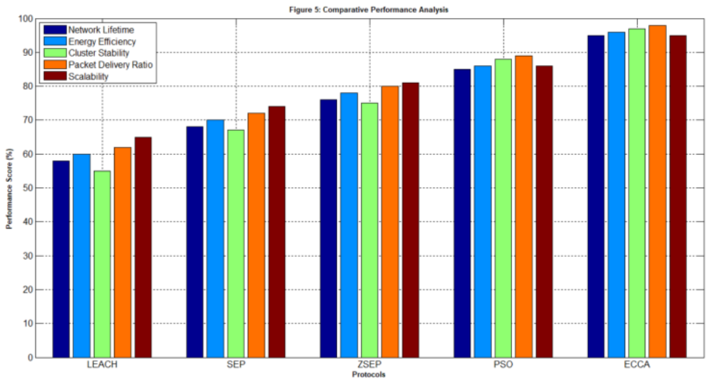
**Table 2. Simulation Parameters**

| Parameter | Value |
|---|---|
| Network Deployment | Random |
| Simulation Platform | MATLAB |
| Performance Metrics | Residual Energy, Alive Nodes, Lifetime, Complexity |
| Compared Protocols | LEACH, SEP, ZSEP, PSO, ECCA |






In contrast to clustering algorithms that rely on random probability and initial energy, and intensive optimization, ECCA is based on a deterministic analysis design that takes into account four contextual factors in selecting Cluster Heads. This method avoids iterative optimization, while still allowing for adaptive decision making and efficiency for large-scale Cyber-Physical Sensor Networks with balanced energy consumption, low communication overhead, and O(N) computational complexity.

## 5. Results and Discussion

Our proposed ECCA shows better performance than conventional clustering. By incorporating several contextual parameters in Cluster Head selection, our algorithm maintains higher residual energy and postpones node failures at early stages. Adaptive Cluster Head rotation also decreases unnecessary communication and improves network stability during the sensing period. Compared to LEACH, SEP, ZSEP, and PSO, ECCA has slower energy depletion, more alive nodes, and longer overall network lifetime. Moreover, the analytical design is not iterative and is linear in computational complexity, and it's computationally effective for CPS applications using scarce resources.

## 6. Conclusion

In this paper we have proposed an Energy and Context-Aware Clustering Algorithm (ECCA) for the energy-efficient Cyber-Physical Sensor Networks. The proposed analytical Context Score combines residual energy, neighbourhood density, link quality, and remaining lifetime to perform adaptive Cluster Head selection. The lightweight distributed framework reduces communication overhead with balanced energy usage and linear complexity. We have compared the performance of ECCA with respect to residual energy preservation, node survivability, and network lifetime over existing clustering algorithms. In the future we will focus on heterogeneous CPS environments, mobility-based clustering, and AI-assisted adaptive communication.

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