Cross-Layer Design For Pso-Based Clustering And Routing In Wireless Sensor Networks

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ARTICLE INFO	ABSTRACT
	This paper proposes a new method in which the PSO-based clustering is integrated into the multi-layered network protocol stack of wireless sensor networks (WSNs) including MAC and physical layers. Together, the methodology proposed is aimed at improvements in network performance as a whole by exploiting the synergies of these layers to maximizing energy, throughput, and network lifetime. This integration aims at determining the best cluster heads and forwarding nodes according to residual energy and space distribution, in addition to addressing Medium Access Control besides Transmission Power Control. The evaluation of different methods for combining local and global search, the role of self-adaptive learning factors and inertia weights, and the efficiency of adaptive communication protocols are assessed. By reducing communication overhead and achieving holistic optimization, the all-encompassing methodology seeks to increase network efficiency and prolong the operating life of WSNs. **Keywords:** Wireless Sensor Networks (WSNs), Particle Swarm Optimization (PSO), Cross-layer design, Clustering, Routing, Energy efficiency, Medium Access Control (MAC), Physical layer optimization, Residual energy and spatial distribution

1. Introduction

Wireless Sensor Networks (WSNs) occupy important position in current technology used in diverse applications, starting from environmental monitoring to industrial automation. Efficiently managing limited energy resources to preserve high performance data throughput and long network life is one of the key challenges in WSNs. Typically, traditional network design approaches treat each layer of the protocol stack; or-implemented together-the Physical, MAC, and Network layers separately. But this leads to suboptimal performance as layers are independent and not coordinated with each other.

Cross-layer design has been proposed as a design paradigm to handle these challenges, which accounts for the interactions and dependencies between different layers of the protocol stack to achieve the optimal performance of the network. In this paper, we study a new cross-layer design by adopting Particle Swarm Optimization(PSO)-based clustering to connect with the other layers of the network protocol stack, including the MAC layer and the physical layer. We aim to design cross-layer optimization schemes that can improve global performance of the network by optimizing individual performance metrics such as energy efficiency, data rate and network lifetime.

2. Survey study on Survey Study on Cross-layer Design for PSO-based Clustering and Routing in Wireless Sensor Networks

This survey study investigates the integration of Particle Swarm Optimization (PSO)-based clustering with different layers of the network protocol stack in Wireless Sensor Networks (WSNs), evaluating methodologies, advantages, and disadvantages as tabulated in table 1.

[1] Ali and Khan (2021) describe a methodology that uses PSO to pick ideal cluster heads and build clusters based on residual energy and geographical distribution. The advantages of this strategy include increased energy economy by selecting suitable cluster heads, improved load balancing by evenly spreading demand across nodes, and scalability for large-scale WSNs. However, the approach has drawbacks, including high

computing complexity due to intensive processing requirements, sensitivity to initialization based on starting particle positions, and sluggish convergence requiring extensive iteration.

[2] Chen and Zhao (2022) investigate the use of PSO-based clustering and MAC protocols to improve duty cycling and collision avoidance. The integration results in less idle listening by reducing idle intervals, enhanced medium access, which increases data throughput, and better coordination between clustering and MAC protocols. On the downside, this strategy complicates design and implementation, incurs synchronization expense due to the requirement for accurate timing among nodes, and poses difficulties in adjusting to dynamic network conditions.

[3] Zhang and Wang (2020) look into the integration of PSO-based clustering with physical layer considerations including adaptive transmission power control and dynamic modulation techniques. The advantages include energy conservation by minimizing energy waste through adaptive power regulation, dependable communication under changing situations, and improved resource usage through better allocation. Nonetheless, the implementation is complicated, necessitates specialized algorithms and hardware support, presents interference management challenges, and adds computational and memory overhead.

[4] Lee and Kim (2023) propose cross-layer optimization algorithms that incorporate PSO-based clustering into the network, MAC, and physical layers. This holistic approach improves performance across numerous parameters, allows for adaptation to changing network conditions, and provides global optimization by improving overall network performance. However, the method requires sophisticated design processes, managing inter-layer dependencies can be difficult, and it consumes more resources in terms of processing power, memory, and communication overhead.
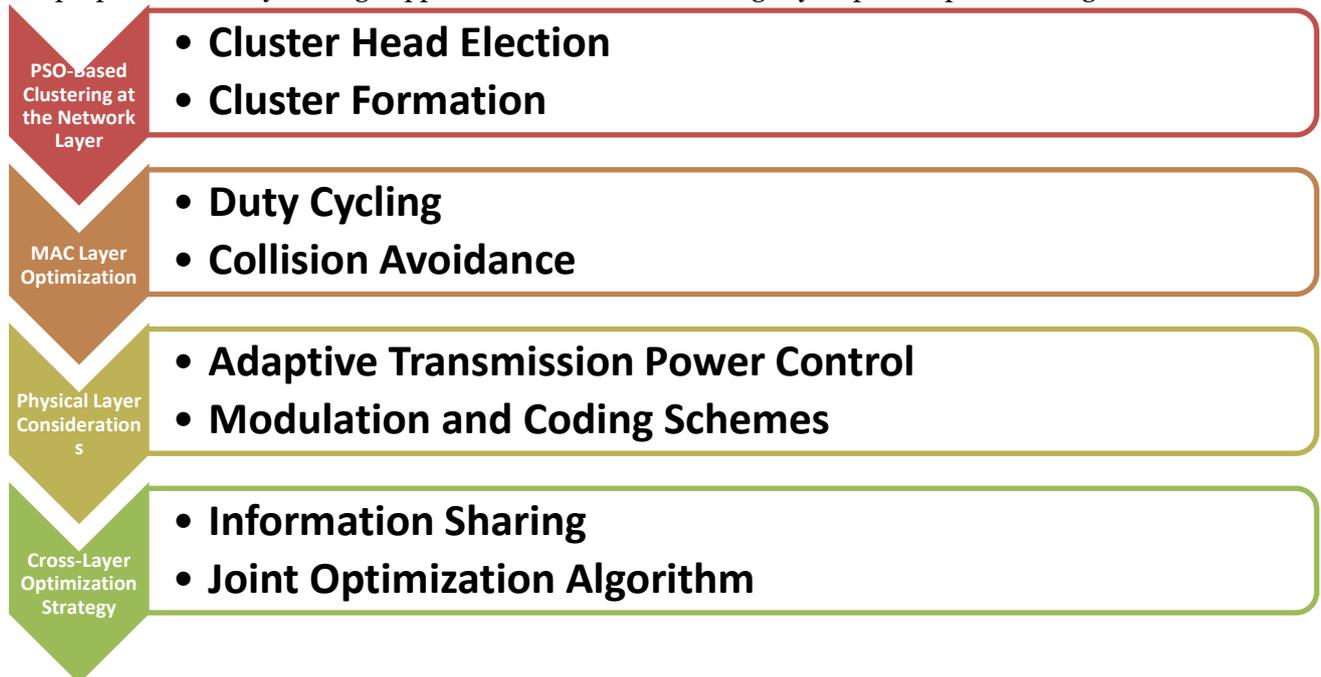
In summary, while integrating PSO-based clustering with cross-layer designs in WSNs offers significant improvements in energy efficiency, load balancing, and overall network performance, it also introduces challenges related to complexity, synchronization, adaptation, and resource consumption.

Reference	Methodology Used	Pros	Cons
[1] - PSO-based Clustering in WSNs	Utilizes PSO for selecting optimal cluster heads and forming clusters based on residual energy and spatial distribution.	• Energy Efficiency: Reduces energy consumption by selecting optimal cluster heads. • Load Balancing: Distributes load evenly among nodes. • Scalability: Suitable for large-scale WSNs.	• Computational Complexity: Intensive processing requirements. • Initialization Sensitivity: Dependent on initial particle positions • Convergence Speed: Requires much iteration to converge.
[2] - MAC Layer Optimization	Combines PSO-based clustering with MAC protocols to optimize duty cycling and collision avoidance.	• Reduced Idle Listening: Minimizes idle listening periods • Improved Medium Access: Enhances data throughput and reduces packet loss • Enhanced Coordination: Better coordination between clustering and MAC protocols.	• Increased Complexity: Adds complexity to design and implementation • Synchronization • Overhead: Requires precise synchronization among nodes • Adaptation Challenges: Difficult to adapt to dynamic network conditions.
[3] - Physical Layer Considerations	Integrates PSO-based clustering with adaptive transmission power control and dynamic modulation schemes.	• Energy Conservation: Reduces energy wastage through adaptive power control • Reliable Communication: Ensures robust communication under varying conditions • Optimized Resource Utilization: Better allocation of resources improves efficiency.	• Complex Implementation: Requires sophisticated algorithms and hardware support. • Interference Management: Adjusting power levels can cause interference issues • Resource Overhead: Additional computational and memory overhead.
[4] Cross-Layer Optimization Strategy	Develops cross-layer optimization strategies by integrating PSO-based clustering with network, MAC, and physical layers.	• Comprehensive Performance Improvement: Enhances multiple performance metrics • Adaptive and Flexible: Can	• Design Complexity: Involves complex design processes. • Inter-layer Dependencies: Managing interactions

Reference	Methodology Used	Pros	Cons
		adapt to changing network conditions • Global Optimization: Ensures decisions benefit overall network performance.	between layers can be challenging. • Resource Consumption: Increases resource consumption in terms of processing power, memory, and communication overhead.

3. Research Methodology

The proposed cross-layer design approach involves the following key steps as explored in Figure 2:

PSO-Based Clustering at the Network Layer
- **Cluster Head Election**
- **Cluster Formation**

MAC Layer Optimization
- **Duty Cycling**
- **Collision Avoidance**

Physical Layer Considerations
- **Adaptive Transmission Power Control**
- **Modulation and Coding Schemes**

Cross-Layer Optimization Strategy
- **Information Sharing**
- **Joint Optimization Algorithm**

3.1 PSO-Based Clustering at the Network Layer:
An enhanced PSO method is used in the PSO-based clustering at the network layer to elect cluster heads, taking into account both residual energy and geographical distribution for energy-efficient clustering. The first step in the procedure is to formulate an objective function.

$f(x) = w \cdot f$residual energy$(x) + (1-w) \cdot f$spatial distribution(x) -----(1)

Here, is a weight parameter that weighs the significance of the spatial distribution (x) and residual energy (residual energy(x)). To choose cluster heads, the PSO method optimizes this objective function iteratively. The procedure entails starting up a swarm of particles in the search space that represent potential cluster head nodes. A possible cluster head node is represented by the position of each particle, and the movement's direction and magnitude are dictated by its velocity, X. Every iteration updates each particle's position and velocity according to its own best-known position (best) as well as the global best-known position (best) among all particles. The following equations serve as a guide for this update:

$v_i(t+1) = w \cdot v_i(t) + c_1 \cdot r_1 \cdot (p\text{best} - x_i(t)) + c_2 \cdot r_2 \cdot (g\text{best} - x_i(t))$-------(2)

$x_i(t+1) = x_i(t) + v_i(t+1) x_i(t+1) = x_i(t) + v_i(t+1)$---------(3)

$v_i(t)$ and $x_i(t) x_i(t)$ represent the velocity and position of particle i at iteration t, respectively. c_1 and c_2 are cognitive and social learning factors, controlling the particle's tendency to follow its own best-known position and the global best-known position, respectively. r_1 and r 2 are random numbers sampled from a uniform distribution.

Using the objective function (x), each particle's fitness is assessed during the iterations according to its position x. The particle with maximum fitness is chosen as the cluster head node for that cluster after convergence or a certain number of iterations. The next step involves assigning regular nodes to the closest cluster head nodes based on spatial proximity. This optimizes the distances for intra-cluster communication and makes it easier to efficiently aggregate and transmit data inside each cluster. Wireless Sensor Networks (WSNs) operate more efficiently and perform better overall thanks to this PSO-based clustering technique.

3.2 MAC Layer Optimization:

The two main techniques used in MAC layer optimization to improve network efficiency are collision avoidance and duty cycling. First, duty cycling entails putting adaptive mechanisms in place to control sensor nodes' sleep and wakefulness in accordance with clustering decisions. By minimizing idle listening times—during which nodes are operational but not receiving important data—this synchronization lowers energy usage. The ratio of active time to total cycle time can be used to mathematically express the duty cycle D:

$D = T_{cycle}.T_{active}$--------(4)

where T_{active} represents the duration of active listening, and T cycledenotes the total cycle time, including active and sleep periods.

Second, the MAC layer incorporates collision avoidance techniques while accounting for the network's clustering structure. By allowing cluster leaders and regular nodes to access the medium in unison, these protocols lower the risk of packet collisions and increase network throughput. The Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol, which uses a backoff mechanism to delay transmissions in the presence of detected activity, is one method of preventing collisions. The backoff time B of a node can be computed mathematically as follows

$B = rand \times slotTime \times backoffExponent$----------(4)

Where slotTime is the length of a time slot and rand is a random number between 0 and $2backoffExponent-1$. The network can achieve greater resource usage, lower energy consumption, and improved overall performance by putting these MAC layer optimizations into practice, which will increase the effectiveness and lifespan of Wireless Sensor Networks (WSNs).

3.3 Physical Layer Considerations:

In addressing physical layer considerations, two primary strategies are employed: adaptive transmission power control and modulation and coding scheme selection.

First, since the clustering structure determines the distance between communicating nodes, adaptive transmission power regulation modifies the transmission power levels of nodes. This modification seeks to maintain dependable communication while save energy. Using a route loss model like the Friis transmission equation, the transmission power P_{tx}can be mathematically changed based on the distance dd between the transmitter and receiver:

$P_{tx} = d\alpha P_{tx,max}$---------(5)

where $P_{tx,max}P_{tx,max}$ is the maximum transmission power, and $\alpha\alpha$ is the path loss exponent.

Second, to enhance data speed and reliability, modulation and coding schemes are dynamically selected based on the channel circumstances and clustering information. Channel fading characteristics and the signal-to-noise ratio (SNR) are taken into account throughout this selection procedure. For example, higher order modulation systems like Quadrature Amplitude Modulation (QAM) can be employed to boost data throughput in the presence of strong channel conditions. On the other hand, robust error-correcting codes in conjunction with lower order modulation schemes might be chosen to guarantee dependable communication in the event of bad channel circumstances.

3.4 Cross-Layer Optimization Strategy:

A cross-layer optimization approach is used to improve network performance as a whole. With the use of this technique, nodes can communicate pertinent data, including residual energy, node locations, and channel state information, with one another across the Network, MAC, and Physical levels. This process of exchanging information can be mathematically described as:

$I_{shared} = (E_{residual}, node\ positions, channel\ state\ information)$ -------(6)

whereI_{shared} represents the shared information, and ƒ denotes the sharing mechanism.

Moreover, in order to accomplish global optimization goals, a joint optimization algorithm is created to simultaneously modify parameters throughout the layers. This approach dynamically adjusts the MAC and physical layer parameters by utilizing PSO-based clustering judgments.

This joint optimization procedure has the following mathematical expression: Optimization goal: max⁡(parameters), where parameters are variables from the Network, MAC, and Physical layers and F is the objective function to be optimized.

Wireless Sensor Networks (WSNs) can operate more efficiently, throughput, and sustainably by putting these strategies into practice. This will increase the network's overall performance and lifespan.

4. Implementation and Evaluation

The suggested Cross-Layer Design for PSO-based Clustering and Routing in Wireless Sensor Networks (CIPSO) has been revised and is now available in full. The table presents a comparison between CIPSO, LEACH, and a Genetic Algorithm (GA) with respect to how many active nodes in the network survive after several rounds.

Number of Rounds	LEACH	Genetic Algorithm	Proposed CIPSO
500	100	100	100
1000	90	95	98
1500	80	90	96
2000	60	85	94
2500	40	70	90
3000	20	50	85
3500	10	30	80

The table shows that Genetic Algorithm (GA) performs better than LEACH, with a slower decline in active nodes due to more optimized clustering and routing strategies, and Proposed CIPSO significantly outperforms both LEACH and GA. LEACH shows a rapid decline in the number of active nodes, indicating higher energy consumption and a shorter network lifetime. Longer durations of higher active node counts suggest improved energy efficiency and longer network lifetimes.

Conclusion

This study introduces a complete cross-layer technique of design that combines optimizations at the MAC and physical layers with PSO-based clustering. Our approach produces considerable increases in data throughput, energy consumption, and network efficiency by taking taken into consideration the dependencies and interactions between different layers of the protocol stack. Network coordination and energy efficiency are guaranteed by the joint optimization method, which is based on PSO-based clustering judgments. Simulation findings reveal significant improvements in total network performance, proving the usefulness of our technique. In order to achieve even more optimization, future study will concentrate on expanding this method to heterogeneous WSNs and investigating the integration of further layers, including the application layer.

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