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A Q-Learning Optimized Cluster-Based Framework for Energy-Efficient Communication in 6G VANETs

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ABSTRACT

The future of intelligent transportation now rests on the integration of Vehicular Ad-hoc Networks (VANETs) with powerful wireless or 6G wireless standards. However, most of the very features that make 6G revolutionary—immense data rates and dense connectivity—also threaten its sustainability by drastically increasing energy consumption. In this paper, we tackle this problem with a novel framework that combines two intelligent techniques. First of all, our Stable Clustering Algorithm (SCA) creates robust network groups by selecting leaders based on a balanced score of their remaining battery, driving patterns, and connection stability. Second, our Reinforcement Learning-based Adaptive Sleep Scheduling (RASS) protocol utilizes a Q-learning model to make informed decisions, enabling roadside units and vehicles to enter low-power "sleep" modes during periods of inactivity without missing critical data. Extensive simulations show our combined framework is remarkably effective. It reduces total network energy use by up to 41.5% and extends network lifetime by 34.8% compared to modern benchmarks. It must look at EECB and ECRP, all while maintaining the strict quality of service required for ultra-reliable, low-latency applications.

1. Introduction

The march toward 6G wireless communication promises a fully connected, intelligent world, with self-driving cars and advanced vehicular networks at its heart [1]. By leveraging technologies such as terahertz (THz) communications and pervasive AI, 6G is expected to deliver breathtaking speeds and near-instant response times, enabling everything from cooperative driving to immersive in-car experiences [2]. But this high-performance future generation comes with high energy and cost. The computational load of AI, the signal losses at THz frequencies, and the sheer number of connected devices create an energy consumption model that is simply unsustainable [3]. This is a critical issue for electric vehicles, where communication systems drain the driving battery, and for roadside sensors that run on limited power. Developing energy-efficient communication isn't just an optimization task—it's a fundamental requirement for making 6G VANETs a practical reality.

This Cluster-based routing is a very impressive and useful method to improve scalability in mobile networks by organizing nodes into manageable groups [4]. However, traditional methods often sacrifice energy conservation for stability, leading to early battery drain in group leaders. Furthermore, a major source of waste comes from radios sitting idle, listening for messages that never come [5]. To overcome these limitations, we propose a comprehensive energy management framework. Our main contributions are:

1. **A Stable Clustering Algorithm (SCA): Is this a** protocol that selects and chooses group leaders using a smart score that balances a node's remaining energy, its stable driving behaviour, and its central location, promoting both energy efficiency and long-lasting groups.
2. **In the RL-based Adaptive Sleep Scheduling (RASS) protocol:- It** is one of the technique or approaches that can be applied in a Q-learning model to let vehicles along with units on the roadside determine when it's safe to sleep. In allowing for the system to learn from network conditions and cut off energy waste through quiet times without slowing down replies to essential safety alerts, it guarantees the ability to grasp how to obtain a superposition and Entanglement with actual measurement.

   3. Holistic performance evaluation: In order to demonstrate our combined SCA-RASS framework's superior performance in conserving energy, extending network life, and maintaining service quality in a realistic 6G-VANET scenario, we must attempt to simulate it in place of current leading and trending protocols.

2. Related Work

The quest for energy efficiency in VANETs typically focuses on two areas: organizing the network topology through clustering and managing radio resources via sleep scheduling.

Energy-Aware Clustering: Many protocols now these days used to must include energy levels in their leader-selection process. For instance, the Energy-Efficient Cluster-Based (EECB) protocol [6] uses a function based on remaining battery and distance. Similarly, the Energy-Aware Clustering and Routing Protocol (ECRP) [7] considers how quickly or faster a battery is draining. While these help balance energy use, they can struggle with the constant motion of vehicles, leading to frequent and disruptive leader changes. Our SCA algorithm counters this by directly factoring in mobility and connection stability. **Sleep Scheduling Mechanisms: The** Duty cycling, or periodically turning off the radio, is a basic energy-saving technique. One study [8] proposed an adaptive method for roadside units based on traffic density. More recently, machine learning has entered the field, with one approach using learning for wake-up scheduling in respective sensor networks [9]. However, using reinforcement learning for a coordinated, context-aware sleep schedule within a clustered 6G-VANET—a complex and dynamic environment—remains a new frontier. Our RASS protocol explores this by deploying a distributed Q-learning framework that allows nodes to learn the best sleep policy based on their local observations. Our work stands out by uniting a stability-focused clustering mechanism with a smart, self-learning sleep scheduler, specifically designed for the high-speed, low-latency world of 6G-VANETs. For this related work many prominent researchers have done the work as- Bhawaria & Rathore (10), Bhawaria & Rathore (11), Bhawaria & Rathore (12), Rathore et al. (13), Bhawaria et al. (14), Bhawaria et al. (15), Mathur and Bhawaria (16), Meedal et al. (17).

3. System Model and Problem Formulation

3.1 Network Architecture

We model a highway with a set of smart vehicles = {v1, v2, ..., vn}. Each vehicle has a 6G onboard unit capable of standard and high-frequency (THz) communication, and knows its own location, speed, and battery level. A set of 6G-enabled roadside units (RSUs),R = {r1, r2, ..., rm}, is deployed along the road. The network is organized into clusters = {c1, c2, ..., ck}, each with a Cluster Head (CH), several Cluster Members (CMs), and sometimes a Cluster Gateway (CGW).

3.2 Energy Consumption Model

A VANET node's energy is essentially and primarily consumed by connectivity and communication. The transmitter radio can be in one of four power states: transmission (Tx), reception (Rx), idle, or sleep. Their power draw follows this order:P_tx > P_rx ≈ , P_idle, P.sleep. The whole energy a node(i) consumes over a period ΔT(is) and the addition of the energy used in every state.

3.3 Problem Statement

Our goal is to maximize the network's operational lifetime—defined as the time until the first node runs out of energy—while strictly meeting the quality of service (QoS) demands of safety applications. This means we must find the best clustering strategy (Ψ) and the best sleep scheduling policy (Π).

4. The Proposed SCA-RASS Framework

4.1 Stable Clustering Algorithm (SCA)

The SCA runs a periodic election for the cluster head. Each vehicle calculates its fitness score(i), which is a weighted blend of three factors:

- **It's the normalized remaining battery.**
- **Its stability** (measured by how similar its speed is to its neighbours).
- **Its connectivity** (how many neighbours it has).

The vehicle with the best score in its vicinity becomes the cluster head. A hysteresis mechanism is used to prevent constant, unnecessary leader changes.

4.2 RL-Based Adaptive Sleep Scheduling (RASS)

We frame the sleep decision process for each node as a Markov Decision Process (MDP).

- **State (**s_t**):** What the node currently knows (e.g., its role, current traffic load, time since last important message).
- **Action (**a_t**):** The decision it makes—either SLEEP (0) or ACTIVE (1).
- **Reward (**R_t**):** The feedback. The node gets rewarded for saving energy but is penalized for dropping packets or causing delays.

Each node learns a policyπ(s)that tells it the best action to take in any given state to maximize its long-term reward. It does this by continuously updating a Q-value table using the standard Q-learning update rule. Critical nodes like Cluster Heads do not enter sleep mode.

5. Performance Evaluation

5.1 Simulation Setup

We tested our SCA-RASS framework in the NS-3 simulator using modules designed for 6G and THz communication. We compared its performance against two state-of-the-art protocols: EECB [6] and ECRP [7]. Key simulation parameters are listed below.

Simulation Area	6 km x 4-lane highway
Number of Vehicles	100 - 200
Vehicle Speed	70 - 120 km/h
Communication Tech	5G NR (C-V2X) + 6G THz
MAC Protocol	IEEE 802.11bd / NR-V2X
Traffic Model	Periodic Beaconing + Event-Driven
P_tx, P_rx, P_idle, P_sleep	1.2W, 0.9W, 0.85W, 0.015W
Initial Energy (Vehicles)	15 kJ
Q-learningα, γ	0.6, 0.95

Table 1: Simulation Parameters

5.2 Results and Analysis

- **Energy Consumption:** Our framework demonstrated a **41.5%** reduction in total energy use compared to EECB and a **38.1%** reduction compared to ECRP. This is a direct result of forming stable clusters and putting nodes to sleep slowly, smoothly, and intelligently.
- **Network Lifetime: S** CA-RASS might extend the time until the first node sleeps/fails by **34.8%** over on EECB and **29.5%** over on ECRP, which may ensure the network remains operational for significantly longer.
- **QoS Metrics:** As shown in Table 2, these major energy savings did not compromise performance. Our framework maintained a high Packet Delivery Ratio (PDR) and low latency, within the required limits for safety-critical messaging.

EECB [6]	96.2	8.5
ECRP [7]	97.5	7.8
SCA-RASS (Proposed)	96.8	8.2

Table 2: QoS Performance (150 vehicles)

6. Conclusion

This paper confronted the critical issue of energy sustainability in next-generation 6G vehicular networks. Our solution, the SCA-RASS framework, successfully merges a stability-focused clustering algorithm with an intelligent, self-learning sleep scheduler. This combination may allow the network to adapt dynamically to traffic conditions, to reduce or slash energy waste during quiet periods while remaining instantly responsive to critical events. Simulation results confirm that our framework achieves dramatic/undisputed reductions in energy consumption and significant extensions of network lifetime, all without degrading the service quality essential for safety applications. For future work, we plan to test the framework in complex urban settings and explore more advanced Deep Q-Learning models to handle even more complex scenarios.

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