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Energy efficient 5G RAN topologies for autonomous vehicles on highways: Research landscape and future prospects

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Abstract

This study explores energy-efficient 5G Radio Access Network (RAN) topologies tailored to support high-mobility autonomous vehicle (AV) operations on highways. A Systematic Literature Review (SLR) was conducted on 50 peer-reviewed articles published between 2019 and 2024. The review focused on identifying strategies for optimizing energy usage in 5G RAN deployments, particularly under high-speed vehicular conditions. The review identified four dominant approaches: dynamic gNodeB deployment, advanced sleep mode techniques, energy-aware routing, and heterogeneous network integration. Additionally, it highlighted key limitations in the literature, including minimal use of renewable energy models, lack of cross-layer coordination, and limited real-world implementation. To address the identified gaps, the study proposes a Dynamic Energy-Aware Framework integrating AI-based traffic prediction, adaptive resource control, and sustainability-aware design principles. The proposed framework offers practical insights for researchers, engineers, and policymakers aiming to develop scalable, energy-efficient, and resilient mobile network infrastructures aligned with net-zero emission goals and next-generation AV connectivity requirements.

Keywords: Autonomous vehicles, energy efficiency, high mobility, radio access network, topology optimization.

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1. Introduction

The fifth-generation (5G) wireless communication network has catalyzed breakthroughs in high-performance applications, notably in autonomous vehicle (AV) systems [1-3]. By enabling Ultra-Reliable Low-Latency Communication (URLLC), 5G facilitates real-time vehicle-to-everything (V2X) connectivity critical for ensuring safety, situational awareness, and operational efficiency in high-speed highway environments [4-8], which is essential for enhancing safety, situational awareness, and operational efficiency in AV mobility especially along high-speed highway corridors [9, 10] with the promise of ultra-reliable low-latency communication (URLLC) [11-13]. 5G enables real-time vehicle-to-everything (V2X) connectivity, crucial for safe and efficient AV operations on highways. This positions 5G RAN as a key enabler in the digital transformation of intelligent transportation infrastructures.

This capability positions 5G RAN as a critical enabler for the digital transformation of intelligent transportation infrastructure. However, supporting seamless AV mobility on highways requires dense deployments of 5G base stations, or gNodeBs (gNBs), leading to substantial energy consumption [14-16], introducing significant energy and environmental challenges [14]. Recent reports indicate that RAN components contribute over 50% of total energy usage in mobile networks, making them the largest source of operational expenditure and carbon emissions in telecom infrastructures. As global efforts intensify toward net-zero emissions, optimizing the energy efficiency of RAN deployments has become an urgent technical and environmental priority [17-20]. Optimizing energy usage within 5G infrastructures becomes both a technical and environmental imperative [21].

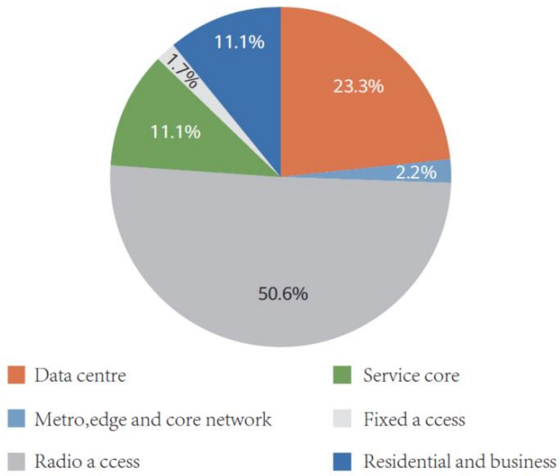

Figure 1.
Energy consumption of 5G network.

The deployment of 5G Radio Access Networks (RANs) poses significant energy challenges [22, 23], particularly due to the high power consumption of base stations, or gNodeBs (gNBs), which account for more than 50% of total network energy usage [24]. Highway-based AV deployment poses unique challenges for RAN topology design [25]. Unlike urban scenarios characterized by dense traffic but slower speeds, highways feature sparse user density combined with high-speed mobility (80–120 km/h), frequent handovers, and long coverage stretches [26-28]. These dynamics require not only robust radio coverage but also intelligent, energy-aware network behavior that can adapt in real-time [29-31]. Existing energy efficiency strategies in 5G networks include dynamic gNB activation [32-34], sleep mode scheduling [35, 36], energy-aware routing [37-39], and heterogeneous network (HetNet) integration [40-42]. While promising, many of these strategies have been designed for low-mobility or urban use cases and lack scalability or responsiveness to vehicular conditions on highways. Moreover, the literature predominantly focuses on simulation-based validations, with minimal experimentation under real-world conditions, such as irregular traffic patterns and fluctuating vehicular speeds. Integration with renewable energy sources and cross-layer coordination mechanisms also remains limited, leaving a gap between theoretical efficiency and deployable, sustainable solutions.

Given this context, a deeper investigation into how gNB deployment density and vehicular speed influence energy consumption and network performance (handover success rate, latency, and throughput) is warranted [43]. Furthermore, integrating renewable energy models and cross-layer adaptive control remains underexplored in the literature.

To address these challenges, this study performs a systematic literature review (SLR) of 50 peer-reviewed articles published between 2019 and 2024, focusing on energy-efficient 5G RAN designs for highway-based AV scenarios. The study identifies core strategies, analyzes trade-offs, highlights limitations, and introduces a conceptual framework integrating AI-driven traffic prediction, adaptive resource management, and sustainability-aware decision-making. Ultimately, this study proposes a conceptual framework for dynamic, energy-aware RAN design tailored to AV highway scenarios. This framework integrates AI-based traffic forecasting, adaptive gNB control, cross-layer optimization, and hybrid energy management. By offering both theoretical synthesis and practical direction, this work aims to support researchers, engineers, and policymakers in advancing toward more sustainable and future-proof mobile communication infrastructures.

2. Purpose of the Study

The purpose of this study is to systematically investigate and synthesize state-of-the-art strategies for enhancing energy efficiency in 5G Radio Access Network (RAN) topologies, with a dedicated focus on high-mobility environments such as autonomous vehicle (AV) operations on highways. As 5G networks increasingly underpin ultra-reliable low-latency communication (URLLC) for intelligent transportation systems, the challenge of escalating energy consumption primarily from dense and persistent gNodeB (gNB) deployments poses a significant barrier to sustainable network design [44]. This study responds to that challenge by conducting a rigorous Systematic Literature Review (SLR) covering peer-reviewed works published between 2019 and 2024.

It aims to critically examine the impact of gNB density, vehicular speed, and network dynamics on energy consumption, handover performance, and latency. The analysis prioritizes techniques including dynamic base station activation, advanced sleep mode scheduling, energy-aware routing, and heterogeneous network (HetNet) architectures all assessed in the context of high-speed vehicular mobility [45].

Beyond the synthesis of existing approaches, this study seeks to identify key limitations in the current research landscape, such as the lack of real-world testbed validation, insufficient integration of renewable energy models, and minimal adoption of cross-layer optimization strategies. These gaps highlight the need for a more holistic, predictive, and adaptive design paradigm.

To address this need, the study introduces a conceptual framework for Dynamic Energy-Aware 5G RAN design. This framework integrates AI-driven traffic prediction, real-time resource orchestration, and sustainability-aware decision-making to enable context-responsive and energy-resilient network operations. The ultimate goal is to support not only the performance demands of AV systems but also the broader imperative of reducing the carbon footprint of next-generation mobile infrastructures. In aligning with global net-zero objectives, the study aspires to inform future research directions, guide policymaking in green ICT development, and offer a scalable blueprint for sustainable RAN deployment in high-mobility scenarios.

3. Related Works

Numerous studies have addressed the issue of energy efficiency in 5G Radio Access Networks (RAN), particularly focusing on infrastructure-level optimizations to reduce power consumption in dense deployments. Existing literature highlights that gNodeBs (gNBs), which are the primary energy consumers in 5G networks, are often over-provisioned to ensure Quality of Service (QoS) in peak traffic scenarios, leading to inefficiencies during off-peak periods [46].

Recent research efforts have proposed various energy-saving mechanisms, including dynamic base station activation, intelligent sleep mode control, and energy-aware routing. For example, Shen et al. [47] and Pan et al. [48] introduced load-based sleep control strategies that dynamically activate gNBs in response to traffic demands, while Velez et al. [49] and Ahmad et al. [50] emphasized migration-aware resource control within Multi-access Edge Computing (MEC) environments. These strategies show promise in reducing static energy consumption, but their performance under high-mobility conditions, such as on highways with autonomous vehicles (AVs), remains underexplored. In addition, sleep mode techniques have been extensively reviewed by Del-Valle-Soto et al. [51], Renga et al. [52], and Salahdine et al. [53], who categorize various sleep configurations, including micro-sleep, long sleep, and adaptive wake-up mechanisms. However, many of these models assume relatively stable traffic conditions, which may not align with the dynamic and unpredictable nature of vehicular networks. Studies on energy-aware routing, such as those by Modi and Bhattacharya [54], propose selecting transmission paths based on green metrics like link quality, interference, and node load. While these approaches are effective in minimizing transmission energy in mesh or D2D-enabled topologies, their scalability and responsiveness in high-speed AV environments are still limited.

Heterogeneous Network (HetNet) architectures have also gained attention as a means of enhancing energy efficiency through macro-small cell coordination. Works by Fall et al. [55] explore dynamic task offloading and relay-based communication, showing energy gains through reduced handover frequency and localized processing. Nevertheless, most of these studies are either simulation-based or applied to static or low-mobility scenarios, and do not address the specific constraints of high-speed mobility along highways.

Moreover, while the integration of renewable energy into RAN infrastructure is widely discussed Enayati et al. [56] few studies provide practical models for real-time energy switching or hybrid power management in mobile, vehicular contexts.

Some works have also considered the integration of renewable energy sources into 5G RAN. For instance, Tan and Uprasen [57] presented solar-powered gNB prototypes, and Divya et al. [58] highlighted the potential of hybrid energy switching in microcell environments. Nevertheless, there is a lack of real-time control systems capable of switching power sources dynamically in response to network load and environmental factors, especially for distributed deployments along highways.

Only a few studies have implemented practical testbeds for 5 G-based AV communication. For instance, Mikami et al. [59] deployed a field trial along a toll highway to assess handover performance and energy metrics under high-speed mobility. Similarly, Hamidi-Sepehr et al. [60] examined multi-cell coordination in a real-world 5 G-V2X environment. Despite these efforts, comprehensive evaluations of energy-aware RAN topologies in such settings remain scarce.

Despite these valuable contributions, the majority of studies suffer from three key limitations:

1. Scenario mismatch – Many proposed solutions are evaluated in static, low-mobility environments rather than high-speed vehicular scenarios.
2. Layer isolation – Most strategies optimize a single layer without coordinating across protocol stacks.

3. Lack of predictive intelligence – Few studies incorporate AI-based traffic prediction or adaptive decision-making to anticipate network changes proactively.

This literature gap underscores the need for a more holistic, cross-layer framework that integrates mobility prediction, real-time energy management, and sustainability-aware optimization tailored for highway-based AV communications. This study aims to address these shortcomings by synthesizing current approaches and proposing a comprehensive conceptual framework for dynamic, energy-efficient RAN operation.

4. Methodology

This study adopts a structured Systematic Literature Review (SLR) approach to identify, classify, and analyze existing research on energy-efficient 5G RAN topologies that support high-mobility scenarios, particularly autonomous vehicle (AV) communication on highways.

The Methodology is Designed to Ensure Transparency, Replicability, and Comprehensive Coverage of Relevant Literature in Alignment with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Guidelines.

4.1. Research Framework

The methodological process is structured into the following four stages:

4.1.1. Formulation of Research Questions

The review is guided by three primary research questions (RQs):

RQ1: What strategies have been proposed to enhance energy efficiency in 5G RAN for highway-based AV scenarios?

RQ2: How do gNB density and vehicular speed affect energy usage, latency, and handover performance?

RQ3: What are the existing limitations and future opportunities for sustainable and adaptive 5G RAN deployment?

4.1.2. Systematic Search Strategy

A systematic search was conducted across six reputable academic databases: IEEE Xplore, Scopus, Web of Science, ScienceDirect, and SpringerLink. The search covered publications from 2019 to 2024 to capture post-5G Release 15 developments. The following Boolean keyword combinations were used: ("5G RAN" OR "gNodeB" OR "Radio Access Network") AND ("energy efficiency" OR "green communication") AND ("autonomous vehicle" OR "high mobility") AND ("topology" OR "deployment" OR "architecture").

The temporal distribution of publications reflects the research community's growing interest in energy-efficient 5G RAN topologies, particularly for autonomous vehicle applications. As shown in Figure 2, the number of relevant publications surged significantly starting from 2017, peaking in 2024.

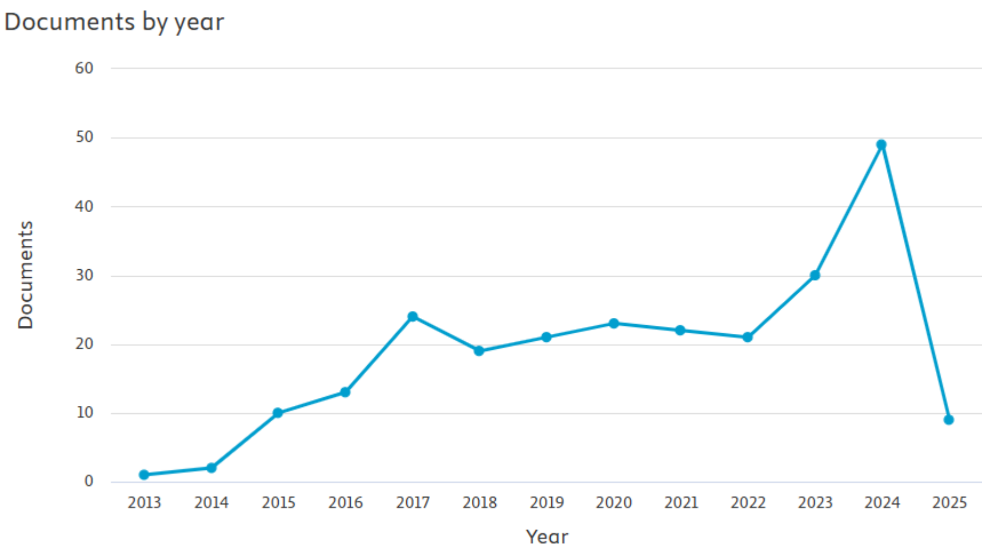

Figure 2.
Number of publications by year (2013–2025), showing increasing interest in energy-efficient 5G RAN for AV systems.

4.1.3. Inclusion and Exclusion Criteria

To ensure the quality and relevance of the literature, the following criteria were applied:

a. Inclusion Criteria:
   - Studies focusing on energy-efficient 5G RAN designs.
   - High-mobility use cases, particularly highway-based AV scenarios.
   - Analysis of gNB density, handover frequency, or power-saving mechanisms.
   - Peer-reviewed journal or conference publications.

b. Exclusion Criteria:

- Articles addressing non-5G networks (e.g., LTE-only).
- Non-peer-reviewed materials such as editorials or opinion pieces.
- Studies lacking quantitative evaluation or real-world applicability.

4.1.4. Selection and Screening Process

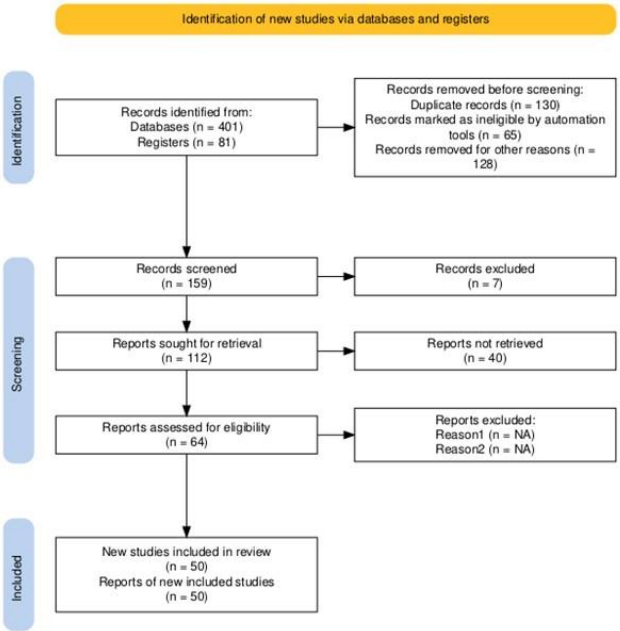

Figure 3.
PRISMA flow diagram.

Initially, 482 records were identified. After removing 86 duplicates, the remaining 396 articles were screened by title and abstract, resulting in 152 eligible for full-text review.

Upon applying the inclusion criteria, 50 studies were retained for qualitative synthesis. The entire screening process is illustrated in Figure 2.

4.1.5. Data Extraction and Analysis

Key information was extracted from each study, including:

- Publication year and source
- RAN architecture/topology under study
- Energy-saving strategy employed
- Simulation or testbed tools
- Evaluation metrics (e.g., latency, throughput, energy gain)
- Scenario context (urban, highway, or mixed)

To facilitate thematic analysis, a coding scheme was applied to group strategies into four categories:

1. Dynamic gNB Deployment
2. Sleep Mode Optimization
3. Energy-Aware Routing
4. Heterogeneous Network (HetNet) Integration

The geographical distribution of the 50 reviewed studies indicates significant global participation in this research domain. As illustrated in Figure 4, China, India, and the United Kingdom emerge as leading contributors, reflecting both technological advancement and policy focus on sustainable network development.

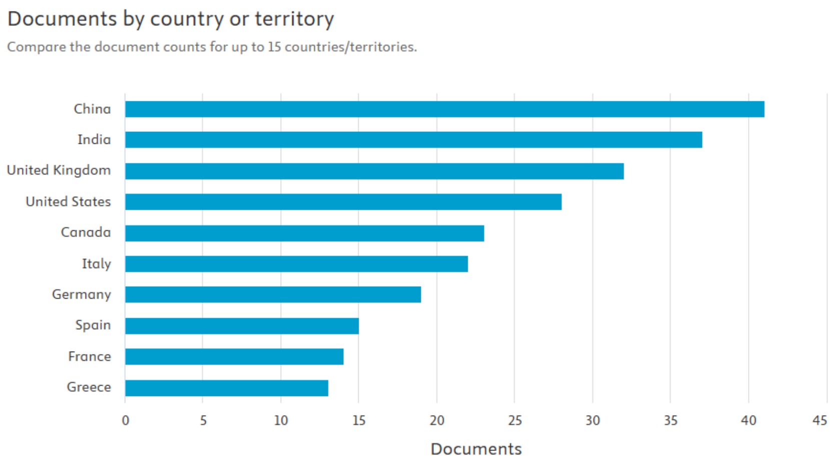

Figure 4.
Distribution of reviewed documents by country or territory (2019–2024).

4.2. Quality Assessment

Each selected study was assessed based on its methodological rigor, clarity of scope, relevance to AV scenarios, and innovation in energy-saving approaches. Only articles meeting a minimum quality threshold were included in the final synthesis to ensure the reliability of insights derived from the review.

4.3. Synthesis and Analysis Techniques

The extracted data were analyzed using two complementary approaches:

- Descriptive Synthesis
  Mapping frequency of strategies, energy metrics used, and scenario types covered (e.g., AV, UAV, urban).
- Interpretive Synthesis
  Exploring relationships and trade-offs between gNB density, vehicle speed, energy usage, and network performance.

Where applicable, existing models were reanalyzed to produce comparative insights and identify optimal deployment thresholds under mobility constraints.

4.4. Review Consistency Assurance

To ensure methodological rigor, the inclusion and exclusion process followed a clearly defined protocol based on PRISMA guidelines. Although conducted by a single reviewer, the selection criteria were applied consistently, and borderline cases were re-evaluated to avoid selection bias.

5. Results and Discussion

This section presents the synthesized findings from the 50 selected studies and discusses their implications within the context of energy-efficient 5G RAN design for high-mobility autonomous vehicle (AV) environments. The results are categorized into four primary strategies frequently employed in the literature, followed by a critical evaluation of their effectiveness, limitations, and potential integration into future network frameworks.

5.1. Categorization of Energy-Saving Strategies

Based on thematic synthesis, the reviewed studies predominantly adopt the following categories of strategies:

- Dynamic gNB Deployment
  Several studies, Ranaweera et al. [61] demonstrated that selectively activating gNodeBs based on real-time traffic demand significantly reduces energy consumption without compromising service continuity. This approach is particularly effective in highway scenarios where traffic density varies across time and location.
- Advanced Sleep Mode Techniques
  Works by Pedhadiya et al. [62] and Ha et al. [63] such as micro-sleep and queue-threshold-based long sleep modes. These techniques enable idle base stations to enter low-power states, resulting in measurable energy savings during off-peak periods.
- Energy-Aware Routing
  Studies like those by Nithya et al. [64] and Riasudheen et al. [65] introduced routing protocols that optimize path selection based on energy costs and link quality. Although more commonly applied in device-to-device (D2D) or relay-assisted topologies, this strategy offers potential for RAN-level optimization under vehicular conditions.
- Heterogeneous Network (HetNet) Integration
  Integration of macro and small cells for task offloading and handover minimization was reported in studies such as Alqasir [66] and Ullah et al. [67]. The inclusion of Device-to-Device communication and relay nodes contributed to localized processing and reduced overall transmission energy.

Table 1.
Comparative Overview of Energy-Efficient Strategies for 5G RAN in AV Scenarios.

Strategy	Key Mechanisms	Relative Energy Impact	Relevance to AV Scenarios
Dynamic gNB Deployment	Real-time activation/deactivation of gNBs based on traffic load and location	High (30–50% potential energy savings)	High – enables flexible coverage along highways with variable traffic
Advanced Sleep Mode Techniques	Micro/long sleep modes, queue-threshold triggers, predictive sleep scheduling	Moderate to High	Medium – effective during off-peak hours but limited in ultra-dynamic flow
Energy-Aware Routing	Path selection based on energy metrics, interference, and load balancing	Moderate	Medium – useful for edge-based relaying or vehicular mesh networks
HetNet Integration	Small cell offloading, relay-aided communication, D2D collaboration	High (especially in dense deployments)	High – supports handover minimization and local offloading in mobility zones

Table 1 provides a comparative overview of the four strategies, summarizing their key mechanisms, relative energy impact, and relevance to AV scenarios.

5.2. Quantitative Insights and Trade-off Analysis

Several studies presented mathematical models to quantify the trade-off between gNB density, energy consumption, and latency.

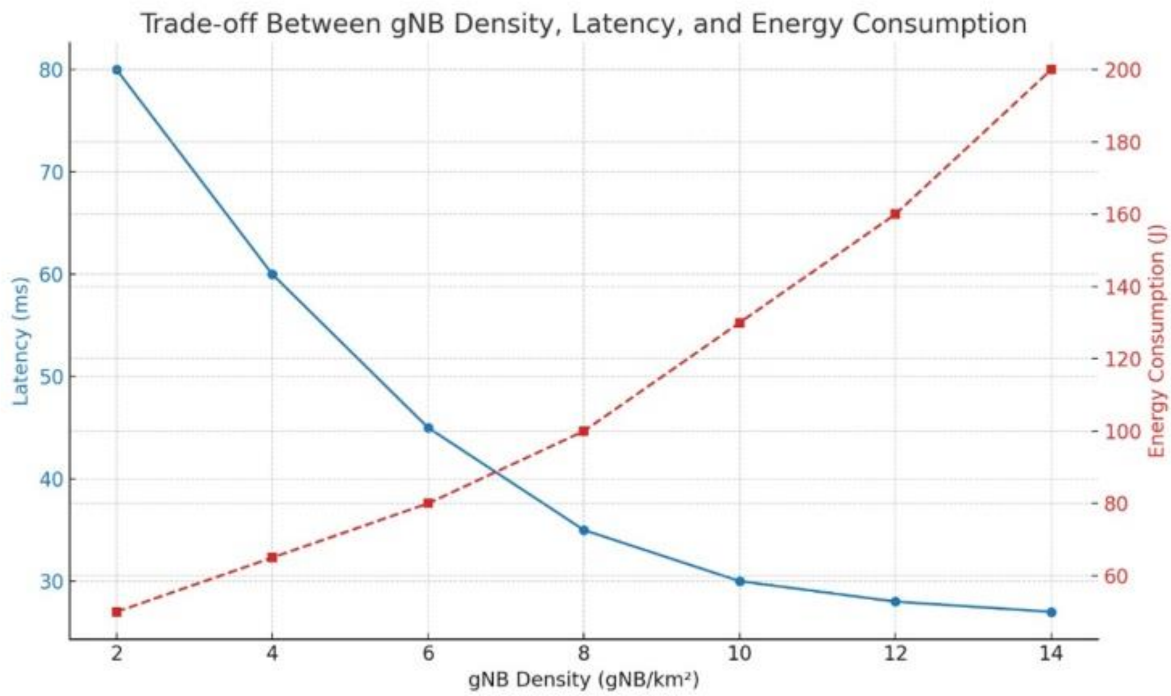

Figure 5.
Trade-off curve between gNB density, latency, and energy usage.

The findings indicate:

- Increasing gNB density generally improves latency due to shorter propagation distances, but results in exponentially higher energy consumption, particularly beyond 10 gNB/km².
- High-speed mobility (e.g., 100–120 km/h) significantly increases handover frequency, which contributes to signalingoverhead and additional power usage.

- Optimal deployment zones exist (typically between 6–10 gNB/km²) where latency improvements remain substantial, yet energy costs are manageable.

Figure 5 illustrates the trade-off curve between gNB density, latency, and energy usage. It emphasizes the importance of intelligent deployment planning to avoid diminishing returns in performance while maintaining energy efficiency.

5.3. Limitations of Existing Approaches

Despite promising advancements, current strategies present several limitations:

- A majority of solutions remain simulation-based, lacking real-world testbed validation.
- Renewable energy integration is often conceptual, with minimal implementation of real-time hybrid power models.
- Most existing works adopt a single-layer optimization approach (e.g., PHY or MAC), neglecting cross-layer coordination critical for dynamic high-mobility environments.

Table 2.
Key limitations in existing studies and their implications for future 5G RAN design.

Identified Limitation	Description	Implications for Future Designs
Lack of Real-World Validation	Most studies rely on simulations without deployment in actual highway environments	Necessitates field-based testbeds and large-scale pilot implementations
Limited Renewable Energy Integration	Few works implement hybrid or green power models for gNB operations	Urgent need to integrate solar/wind/grid switching for sustainable operation
Single-Layer Optimization Approach	Focus is mainly on the physical or MAC layer without cross-layer coordination	Requires holistic, multi-layer optimization for latency-energy trade-off
Absence of Predictive Traffic Modeling	Static traffic assumptions fail to capture dynamic vehicular behavior	Integration of AI-driven prediction for proactive network resource management
Minimal Focus on High-Mobility Specific Topologies	Existing models are often optimized for urban or static users	Development of topology designs tailored for vehicular speed and handover rates
Inconsistent Evaluation Metrics	Heterogeneous performance indicators used across studies	Standardization of energy efficiency and latency benchmarks is needed

Table 2 summarizes key limitations extracted from the literature and their implications for future system designs.

5.4. Implications for High-Mobility AV Scenarios

The findings underscore the necessity for context-aware, adaptive frameworks that can:

- Dynamically reconfigure base station activity based on predicted traffic flow.
- Coordinate across network layers to balance latency, coverage, and energy consumption.
- Integrate renewable energy awareness into the decision-making process.

In high-mobility scenarios such as toll roads and highways, predictive AI-based control and real-time sensing mechanisms are crucial for maintaining both service continuity and sustainability.

5.5. Comparison with Previous Review Studies

Compared to prior reviews, which often focus broadly on green communication or urban network optimization [68-70], this study distinguishes itself by specifically addressing the intersection of energy efficiency and vehicular mobility. The proposed analysis contributes to narrowing the gap between theoretical modeling and practical, deployment-ready solutions for AV-specific 5G networks.

6. Proposed Framework

To address the identified limitations in existing research and to support energy-efficient 5G RAN deployments in high-mobility autonomous vehicle (AV) environments, this study proposes a Dynamic Energy-Aware 5G RAN Framework. The framework integrates predictive intelligence, adaptive network control, and cross-layer coordination to ensure optimal energy utilization without compromising service continuity.

6.1. Framework Overview

The proposed framework is designed to be modular, scalable, and compatible with emerging technologies such as edge computing and cooperative vehicle-to-everything (C-V2X) communication. It consists of three core functional layers:

1. Sensing and Prediction Layer
   This layer continuously monitors network and environmental parameters, including:

- Vehicular density and mobility patterns
- Channel state information
- Real-time traffic demand

AI-based models such as mobility forecasting and demand prediction (e.g., reinforcement learning, federated learning) are utilized to proactively anticipate changes in network load and mobility behavior.

6.2. Dynamic Resource Management Layer

Based on predictive insights, this layer orchestrates network resources through:

- Adaptive gNB Activation: Enables just-in-time switching of gNBs between active, sleep, and idle states.
- Intelligent Sleep Mode Scheduler: Dynamically adjusts sleep-wake cycles using queue thresholds, timers, and traffic patterns.
- Energy-Aware Routing Engine: Selects transmission paths based on energy cost, link quality, and interference metrics.

6.3. Cross-Layer Decision and Optimization Layer

This strategic layer integrates feedback from physical, MAC, and network layers to balance multiple objectives, including:

- Latency minimization
- Energy efficiency
- Service reliability

To overcome the limitations identified in existing approaches and to support sustainable, high-performance RAN deployment in highway-based AV scenarios, this study proposes a Dynamic Energy-Aware Framework. The framework is modular, scalable, and integrates AI-driven sensing, resource adaptation, and cross-layer optimization, as illustrated in Figure 6.

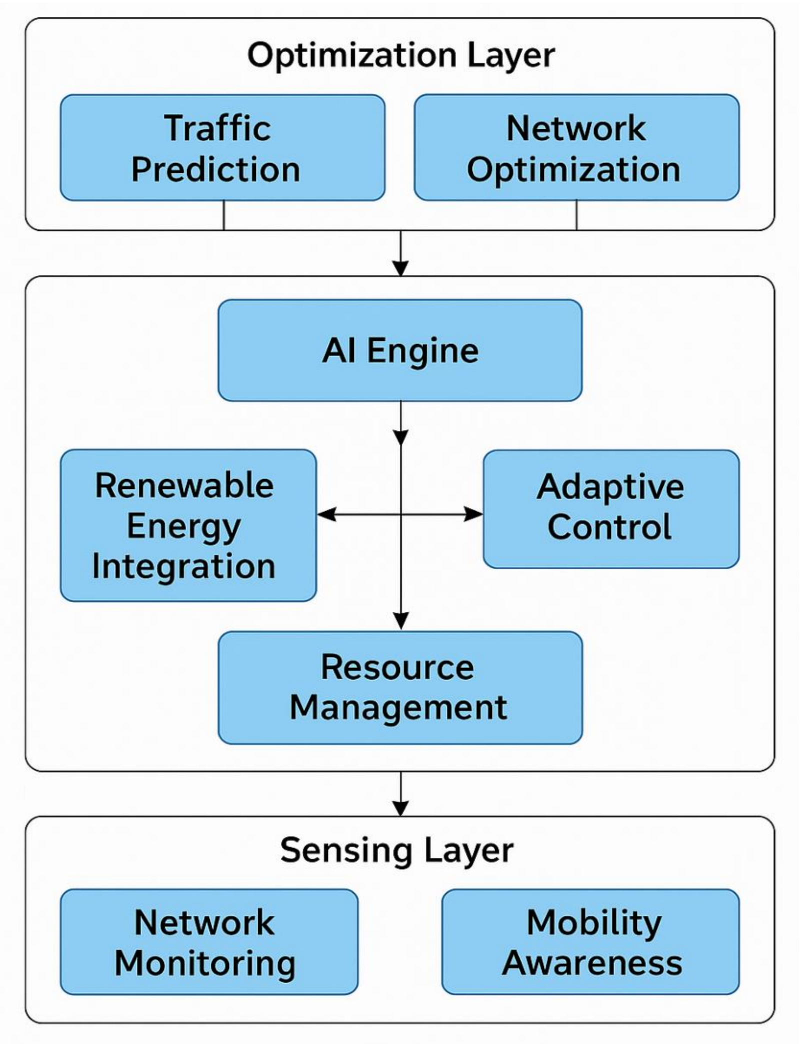

Figure 6.
Proposed Dynamic Energy-Aware 5G RAN Framework integrating sensing, resource management, and optimization layers.

The framework enables AI-driven adaptation, renewable-aware control, and low-latency operation under high-mobility vehicular scenarios. Optimization algorithms such as multi-objective genetic programming or deep Q-networks can be employed to continuously refine network parameters in response to dynamic vehicular mobility.

6.4. Integration of Renewable Energy Models

The framework incorporates a Renewable-Aware Controller, which monitors solar or wind energy availability and enables hybrid power switching for gNBs. This allows base stations to prioritize sustainable energy sources based on forecasted availability and load requirements, thereby reducing carbon footprints and supporting net-zero objectives.

6.5. Models System Adaptability and Scalability

The modular architecture of the framework ensures compatibility with diverse deployment scenarios and geographical conditions. It can be scaled vertically (from local segments to highway-wide networks) and horizontally (across 5G and beyond networks such as 6G). Moreover, its adaptability allows seamless integration with third-party traffic platforms, vehicular datasets (e.g., OpenV2X, SUMO), and testbed environments.

6.6. Summary of Core Features

Table 3 summarizes the key features of the proposed framework and their corresponding contributions to energy efficiency and AV performance.

Table 3.
Summarizes The Key Features of the Proposed Framework.

Feature	Functionality	Contribution
AI-Based Mobility Prediction	Anticipates traffic density and vehicle speed variations	Enables proactive gNB control
Adaptive gNB Control	Dynamically activates/sleeps gNBs	Reduces energy consumption
Energy-Aware Routing	Selects low-cost paths based on green metrics	Minimizes transmission overhead
Cross-Layer Optimization	Integrates PHY–MAC–NET decisions	Balances latency and energy
Renewable Energy Integration	Supports solar/wind/grid hybrid power models	Promotes sustainability

7. Conclusion and Future Work

This study conducted a comprehensive Systematic Literature Review (SLR) to examine energy-efficient design strategies for 5G Radio Access Network (RAN) topologies in high-mobility scenarios, particularly those supporting autonomous vehicles (AVs) on highways. The review synthesized findings from 50 peer-reviewed studies published between 2019 and 2024, offering critical insights into current trends, gaps, and emerging solutions.

Four major energy-saving strategies were identified and categorized: dynamic gNB deployment, advanced sleep mode techniques, energy-aware routing, and heterogeneous network (HetNet) integration. Quantitative analysis revealed significant trade-offs between gNB density, latency, and energy consumption, underscoring the need for intelligent and adaptive network configurations tailored to the demands of high-speed vehicular environments.

To address the shortcomings observed in existing literature such as limited real-world validation, lack of renewable energy integration, and the absence of cross-layer optimization, this paper proposes a Dynamic Energy-Aware 5G RAN Framework. The framework incorporates AI-based mobility prediction, adaptive base station control, energy-aware routing, and sustainable power management. It provides a flexible and scalable approach for designing next-generation mobile infrastructures that align with both performance and sustainability goals.

7.1. Future Work

Future research should aim to operationalize the proposed framework through real-world deployments and advanced simulation environments. Specific areas for further investigation include:

- Development of testbeds for AV communication along highways to validate adaptive deployment and energy-saving mechanisms.
- Integration of open-source vehicular datasets (e.g., SUMO, OpenV2X) into real-time optimization models.
- Implementation of AI-driven sleep mode control using reinforcement or federated learning techniques for dynamic and secure adaptation.
- Evaluation of hybrid renewable energy models, allowing for real-time switching between solar, wind, and grid power based on traffic load and energy availability.
- Design of cross-layer coordination algorithms that can balance energy consumption, latency, and Quality of Service (QoS) under fluctuating mobility and network conditions.

By bridging the divide between theoretical models and deployable solutions, this study contributes to the foundational knowledge required to design intelligent, sustainable, and resilient mobile communication infrastructures for the future of autonomous transportation systems.

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