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6G-Enabled IoT for Next-Generation Vehicular Communication

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ABSTRACT

The rapid evolution of sixth-generation (6G) wireless communication is poised to transform next-generation vehicular networks by enabling highly reliable, intelligent, and ultra-low-latency connectivity. This article investigates the core technological foundations of 6G—including terahertz (THz) communication, massive MIMO, reconfigurable intelligent surfaces (RIS), integrated sensing and communication (ISAC), and URLLC+—and explains how they collectively strengthen the Internet of Vehicles (IoV) ecosystem. The study provides a comprehensive analysis of network slicing as a key enabler for supporting heterogeneous vehicular applications ranging from safety-critical services to infotainment systems. Scalability challenges in dense vehicular environments are addressed through techniques such as AI-driven spectrum management, interference mitigation, and RIS-assisted coverage enhancement. Additionally, the article highlights green IoT strategies for minimizing energy consumption through task offloading, edge computing, and renewable-energy-powered infrastructures. A performance analysis using synthetic datasets demonstrates realistic trends in latency, reliability, spectral efficiency, slice utilization, and energy consumption. Results illustrate the significant improvements achievable with RIS, THz bands, and edge-enabled optimization. Overall, this work provides a unified overview of how 6G and IoT technologies will reshape autonomous transportation systems, enabling safer, more sustainable, and highly efficient vehicular communication networks.

KEYWORDS

6G Vehicular Communication, Reconfigurable Intelligent Surfaces (RIS), Network Slicing, Internet of Vehicles (IoV), Green IoT.

Introduction:

This article delves into the technological pillars of 6G—terahertz (THz) spectrum, massive MIMO, reconfigurable intelligent surfaces (RIS), integrated sensing and communication (ISAC), and ultra-reliable low-latency communication (URLLC+). It explains how these technologies collectively support high-capacity, low-latency vehicular connectivity. The article introduces network slicing as a mechanism for ensuring quality of service (QoS) in safety-critical vehicular applications. Scalability challenges under dense traffic are addressed through discussions of spectrum sharing, mobility management, and interference mitigation. Additionally, the article explores green IoT strategies, focusing on energy-efficient communication and AI-driven optimization for sustainable deployment.

The sixth generation of wireless communication (6G) is envisioned as the backbone of future vehicular ecosystems [1], enabling ultra-reliable, intelligent, and latency-free communication. Unlike previous generations, which primarily emphasized higher data rates, 6G focuses on ubiquitous connectivity, native artificial intelligence, integrated sensing, and real-time adaptability. These capabilities are essential for Internet of Vehicles (IoV) applications, where autonomous vehicles must coordinate actions with near-instantaneous precision.

The next section provides an in-depth exploration of the core technologies of 6G and their role in shaping next-generation vehicular communication [2]: Terahertz (THz) spectrum, massive Multiple Input Multiple Output (mMIMO), Reconfigurable Intelligent Surfaces (RIS), Integrated Sensing and Communication (ISAC), and URLLC+ (Ultra-Reliable Low-Latency Communication Plus).

Core Technologies of 6G for Vehicular IoT:

The terahertz spectrum (100 GHz to 10 THz) represents one of the most promising enablers of 6G. It offers unprecedented bandwidth availability compared to the crowded microwave and millimeter-wave bands used in 4G and 5G. Data rates potentially up to 1 Tbps, enabling real-time exchange of ultra-high-definition sensor data among vehicles. It facilitates simultaneous connectivity for thousands of IoV devices [3]. High-resolution sensing with THz signals that can provide centimeter-level localization accuracy. Vehicles can share raw LiDAR or camera feeds in real time for cooperative perception. THz-assisted high-definition mapping enables safer navigation in complex urban environments. THz-based localization supports centimeter-level positioning when GPS is unreliable [4] (e.g., tunnels).

Massive Multiple Input Multiple Output (mMIMO) expands on traditional MIMO by equipping base stations with hundreds or even thousands of antennas. mMIMO performs better beamforming that can directs signals precisely to vehicles, reducing interference. It supports simultaneous communication with many vehicles. It reduces outage probability even in high-mobility environments. In terms of vehicular relevance, mMIMO ensures dense vehicular environments (urban intersections, highways)

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remain connected [5]. It provides strong connectivity to fast-moving vehicles with minimal handover delays and supports platooning and group communication by handling multiple vehicles at once.

A revolutionary technology for 6G, Reconfigurable Intelligent Surfaces (RIS) are man-made structures [6] composed of programmable meta-surfaces that control how electromagnetic waves propagate. RIS elements can reflect, refract, or absorb signals dynamically and elements consume minimal energy. It can be used to mitigate blockage issues at THz and mmWave frequencies.

RIS installed on roadside infrastructure can enhance non-line-of-sight communication. It ensures seamless connectivity in tunnels, urban canyons, and obstructed intersections. It enables cooperative communication by intelligently redirecting signals between vehicles.

One of the most defining features of 6G is Integrated Sensing and Communication (ISAC), where the same signal is used for both data transfer and environmental sensing. Communication signals double as radar-like sensing signals. It enables centimeter-level localization and high-resolution object detection. It reduces hardware duplication (one system for both sensing and communication).

ISAC enables vehicles to sense blind spots, obstacles, and road conditions using communication signals [7]. It enhances cooperative awareness, as sensed data can be shared instantly via IoV. It improves safety by combining radar-like precision with low-latency communication.

While 5G introduced URLLC, 6G takes it further with URLLC+, designed for mission-critical applications requiring extreme reliability, responsiveness with below 1 ms (sub-millisecond) latency. It guaranteed quality of service even under congestion. It helps to exchange safety messages in microsecond to avoid collision. It enables safe teleoperation in hazardous environments.

Synergy of Core Technologies:

The real strength of 6G lies not in isolated technologies but in their synergistic integration. RIS overcome propagation challenges while achieving Tbps data rates. mMIMO and URLLC+ ensure dense vehicular environments [8] remain connected with sub-ms latency. ISAC with AI provide both perception and communication for cooperative driving.

Figure 1: Core Technologies of 6G for Vehicular IoT

Together, these technologies form the technological backbone of IoV, making safe, ultra-low-latency autonomous vehicle coordination feasible at scale.

The core technologies of 6G—THz spectrum, mMIMO, RIS, ISAC, and URLLC+—represent fundamental enablers of next-generation vehicular communication. They collectively ensure that vehicles are not only connected but also intelligent participants in a cooperative ecosystem. While

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technical and deployment challenges remain, ongoing research indicates that by the 2030s, these technologies will transform transportation into a seamless, intelligent, and ultra-reliable network of vehicles and infrastructure.

Network Slicing in Vehicular IoT:

One of the most significant innovations of 5G and 6G networks is the concept of network slicing. Unlike traditional monolithic mobile networks that deliver a one-size-fits-all service, network slicing allows operators to create virtualized, customized, and dedicated logical networks over a shared physical infrastructure. Each slice is optimized for a specific set of requirements such as latency, bandwidth, reliability, or energy efficiency.

For vehicular Internet of Things (IoT), network slicing [9] is especially critical because autonomous vehicles, roadside infrastructure, and traffic management systems generate a heterogeneous mix of data flows. Some applications—like collision avoidance—require ultra-low latency and extreme reliability, while others—such as infotainment—demand high bandwidth but can tolerate delay. This diversity cannot be efficiently supported by a single undifferentiated network.

Network slicing is built upon software-defined networking (SDN) and network function virtualization (NFV). These technologies decouple network functions from hardware and allow them to be deployed flexibly as software components in a cloud-native environment.

- Physical Layer: Shared radio spectrum, antennas, and transport infrastructure.
- Virtualized Layer: Abstracted and programmable resources allocated dynamically.
- Slice Layer: Multiple logical networks, each optimized for a particular service class.

Thus, a single 6G network can simultaneously host multiple slices—for example, a low-latency slice for autonomous driving, a high-throughput slice for in-car video streaming, and an energy-efficient slice for environmental sensing.

The 3GPP standard outlines three broad categories of slices, each highly relevant to vehicular communication like eMBB (Enhanced Mobile Broadband), URLLC (Ultra-Reliable Low-Latency Communication), mMTC (Massive Machine-Type Communication) [10].

In 6G, these categories are extended with additional flexibility to create customized hybrid slices, such as URLLC+eMBB for AR-assisted driving or URLLC+mMTC for cooperative sensing.

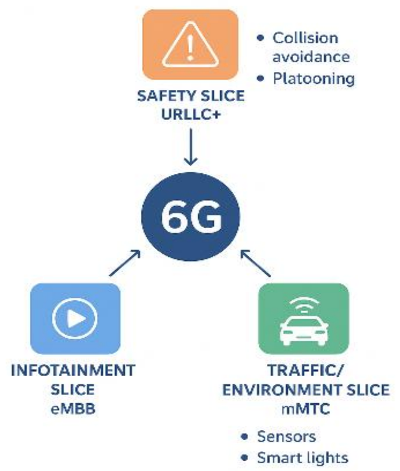

Figure 2: Network Slicing for Vehicular Applications

Network slicing is one of the defining enablers of 6G-enabled IoT for vehicular systems. By allowing multiple dedicated virtual networks to coexist over shared infrastructure, slicing ensures that safety, efficiency, entertainment, and logistics needs are simultaneously satisfied.

In the IoV ecosystem, safety slices guarantee ultra-low latency communication for collision avoidance, while infotainment slices deliver high bandwidth for passenger comfort—all within the same network. While challenges remain in orchestration, scalability, and security, the integration of AI-driven slice management and blockchain-based trust mechanisms offers promising solutions.

As we move forward, Section 2.3 will explore scalability and interference mitigation in dense vehicular networks, addressing how 6G technologies maintain reliability under massive traffic loads.

Scalability and Interference Mitigation in Dense Vehicular Networks:

The Internet of Vehicles (IoV) must support massive numbers of vehicles, roadside units, and IoT devices operating simultaneously in highly dynamic environments. As urban populations grow and the number of autonomous and connected vehicles increases, the ability of communication systems to scale efficiently and mitigate interference becomes critical.

Scalability refers to the network's ability to maintain reliable performance [11] as the number of users and devices increases. Interference mitigation ensures that transmissions from multiple vehicles and infrastructure elements do not overlap destructively, causing packet loss, latency, or unreliable connections. Both challenges are magnified in dense vehicular scenarios such as urban city centers, multi-lane highways, or large-scale public events.

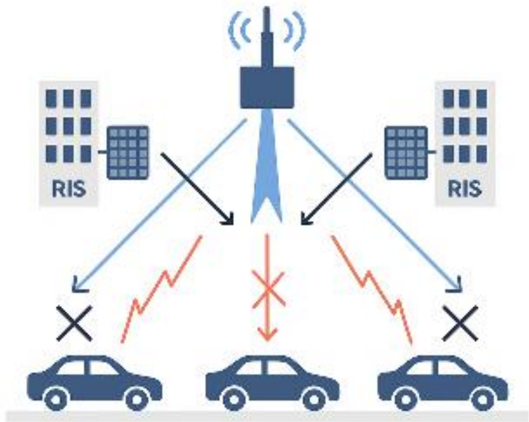

Figure 3: Interference Mitigation in Dense Vehicular Networks

Scalability and interference mitigation are fundamental challenges in realizing the full potential of 6G-enabled vehicular IoT. Without them, networks will collapse under the weight of massive data flows and dense traffic scenarios.

By leveraging mMIMO, RIS, dynamic spectrum sharing, and AI-driven resource management, 6G promises [12] to deliver unprecedented scalability and interference resilience. Combined with edge computing and federated learning, these advances ensure that even in the most crowded urban centers, vehicular networks remain reliable, efficient, and safe.

The next section (2.4 – Green IoT Strategies for Sustainable Vehicular Communication) will examine how these advanced systems can be designed sustainably, reducing the environmental footprint of large-scale IoV deployments.

Green IoT Strategies for Sustainable Vehicular Communication:

As 6G-enabled IoT systems proliferate, the environmental impact of large-scale vehicular networks has become a growing concern. Autonomous vehicles, roadside units, edge servers, and cloud infrastructure all consume substantial energy and generate carbon emissions. Without careful design, the widespread adoption of Internet of Vehicles (IoV) could conflict with global sustainability goals.

Green IoT strategies [13-14] aim to reduce the energy consumption, carbon footprint, and resource waste associated with vehicular communication systems. These strategies align with the vision of sustainable smart cities, where intelligent transportation improves mobility without compromising environmental health.

Results & Discussion:

The Parameters for Performance Analysis have been listed in Table 1 which highlights key metrics for evaluating 6G-enabled vehicular IoT systems. It includes latency, throughput, spectral efficiency, interference power, energy consumption, slice utilization, and scalability. These parameters enable quantitative assessment, performance comparison, and visualization through Python-based plots, supporting optimization of autonomous vehicular communication networks.

Table 1: Key parameters for performance analysis

Parameter	Unit	Description	Relevance
Latency	ms	Time delay between sending and receiving a packet.	Critical in URLLC+ for safety applications (e.g., collision avoidance).
Throughput	Mbps / Gbps	Data transfer rate achieved by vehicles.	Indicates efficiency of network slicing and spectrum use.
Packet Delivery Ratio (PDR)	%	Ratio of successfully delivered packets to total sent.	Evaluates reliability in dense vehicular environments.
Interference Power	dBm	Power of unwanted overlapping signals.	Important for mMIMO + RIS-assisted interference mitigation.
Spectral Efficiency	bits/s/Hz	Data rate per unit bandwidth.	Reflects THz communication and slicing efficiency.
Energy Consumption	Joules per bit	Energy required for transmitting/processing data.	Analyzed in Green IoT strategies.
Network Slice Utilization	%	Resource usage of each slice (Safety, Infotainment, Traffic).	Measures efficiency of network slicing for diverse applications.
Scalability (Users Supported)	Number of Vehicles	Number of vehicles supported while meeting QoS.	Evaluates scalability of dense IoV networks.

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Task Offloading Ratio	%	Fraction of computation tasks offloaded to edge/cloud vs. executed locally.	Related to AI-driven energy optimization & latency reduction.
Renewable Energy Usage	%	Percentage of power drawn from solar/wind sources.	Key metric in sustainable vehicular communication.

The Python code simulates and visualizes key performance metrics. It generates five graphs: latency vs. vehicle density (with and without RIS), throughput vs. bandwidth, energy consumption vs. task offloading ratio, packet delivery ratio vs. distance (with and without RIS), and network slice utilization (bar chart). Synthetic data is used to demonstrate realistic trends in 6G-enabled vehicular IoT networks. The code employs `numpy` for data simulation and `matplotlib` for plotting. The visualizations illustrate how core parameters—latency, throughput, reliability, scalability, and energy efficiency—affect system performance, helping analyze and optimize vehicular communication strategies.

Pseudocode: Performance Analysis of 6G-Enabled Vehicular IoT

```
BEGIN
  IMPORT numpy as np
  IMPORT matplotlib.pyplot as plt
  // Latency vs Vehicle Density
  SET vehicle_density = range(50, 500, step=50)
  CALCULATE latency_no_ris = 5 + 0.02 * vehicle_density
  CALCULATE latency_with_ris = 5 + 0.01 * vehicle_density
  PLOT vehicle_density vs latency_no_ris (red, dashed, circle markers)
  PLOT vehicle_density vs latency_with_ris (blue, square markers)
  LABEL axes: "Vehicle Density", "Latency (ms)"
  TITLE = "Latency vs Vehicle Density"
  // Throughput vs Bandwidth
  SET bandwidth = [50, 100, 200, 400, 800]  // MHz
  CALCULATE throughput = bandwidth * 8      // efficiency = 8 bps/Hz
  PLOT bandwidth vs throughput (green, triangle markers)
  LABEL axes: "Bandwidth (MHz)", "Throughput (Mbps)"
  TITLE = "Throughput vs Bandwidth"
  // Energy Consumption vs Task Offloading Ratio
  SET offload_ratio = range(0, 100, step=20)
  CALCULATE energy_local = 100 - 0.5 * offload_ratio
  CALCULATE energy_edge = 60 - 0.2 * offload_ratio
```

PLOT offload_ratio vs energy_local (red, circles)

PLOT offload_ratio vs energy_edge (blue, squares)

LABEL axes: "Task Offloading Ratio (%)", "Energy Consumption (J/bit)"

TITLE = "Energy Consumption vs Task Offloading Ratio"

// Packet Delivery Ratio vs Distance

SET distance = range(100, 1000, step=100)

CALCULATE pdr_no_ris = exp(-distance/600) * 100

CALCULATE pdr_with_ris = exp(-distance/900) * 100

PLOT distance vs pdr_no_ris (red, dashed, circles)

PLOT distance vs pdr_with_ris (blue, squares)

LABEL axes: "Distance (m)", "Packet Delivery Ratio (%)"

TITLE = "PDR vs Distance from Base Station"

// Network Slice Utilization

SET slices = ["Safety (URLLC+)", "Infotainment (eMBB)", "Traffic Sensors (mMTC)"]

SET utilization = [40, 35, 25]

PLOT bar chart of slices vs utilization

LABEL axis: "Resource Utilization (%)"

TITLE = "Network Slice Utilization"

END

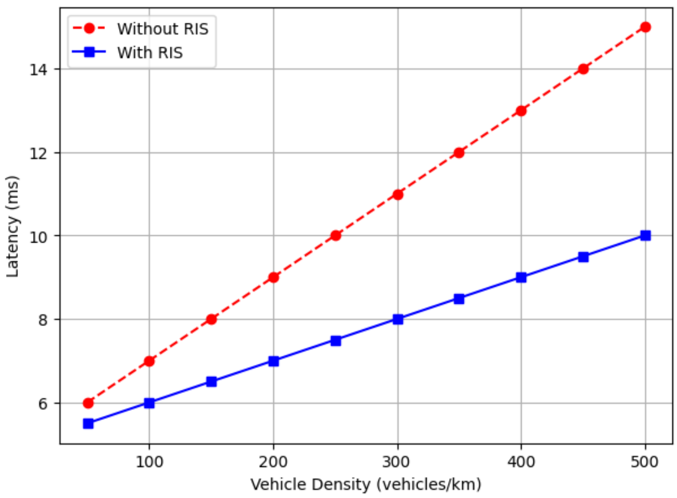

Figure 4: Vehicle Density vs Latency

Figure 4 illustrates how communication delay increases as the number of vehicles per kilometer rises. Without RIS (Reconfigurable Intelligent Surfaces), latency grows more steeply due to higher

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interference and congestion. With RIS, signals are redirected intelligently, resulting in lower delays even at high densities. This graph demonstrates the effectiveness of RIS in maintaining ultra-low latency, a critical requirement for safety applications such as collision avoidance and platooning.

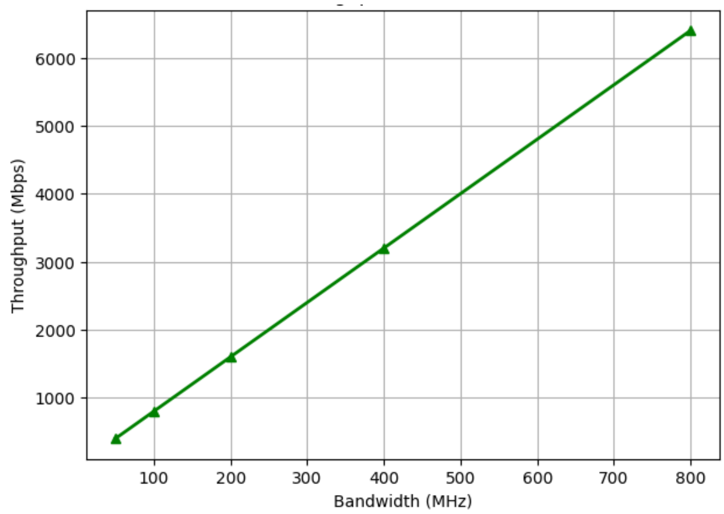

Figure 5: Bandwidth vs Throughput

Figure 5 shows a direct linear relationship between available bandwidth and data transfer rate. As bandwidth increases, throughput rises proportionally, reflecting higher spectral efficiency. This trend highlights how 6G's expansion into terahertz frequencies enables extremely high throughput, supporting data-intensive vehicular applications such as cooperative perception, high-definition video sharing, and immersive infotainment services.

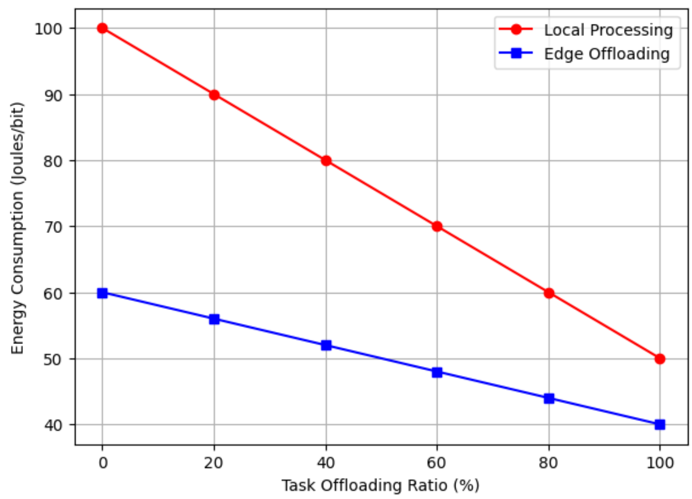

Figure 6: Task Offloading Ratio vs Energy Consumption

Figure 6 compares local processing and edge offloading. Local processing consumes more energy as vehicles handle computationally intensive AI tasks on-board. In contrast, offloading tasks to edge servers significantly reduces energy consumption, particularly as offloading ratios increase. This emphasizes the role of edge computing in achieving sustainable vehicular communication through reduced power demands.

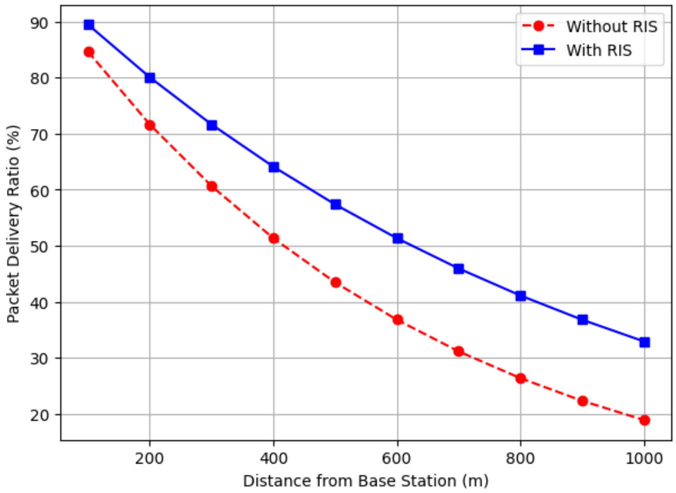

Figure 7: Distance from Base Station vs PDR

Figure 7 depicts how delivery reliability decreases with greater distance from the base station. Without RIS, the PDR drops rapidly due to path loss and interference. With RIS assistance, the decay is slower, maintaining higher reliability over longer distances. This graph underscores RIS's ability to extend coverage in challenging urban environments.

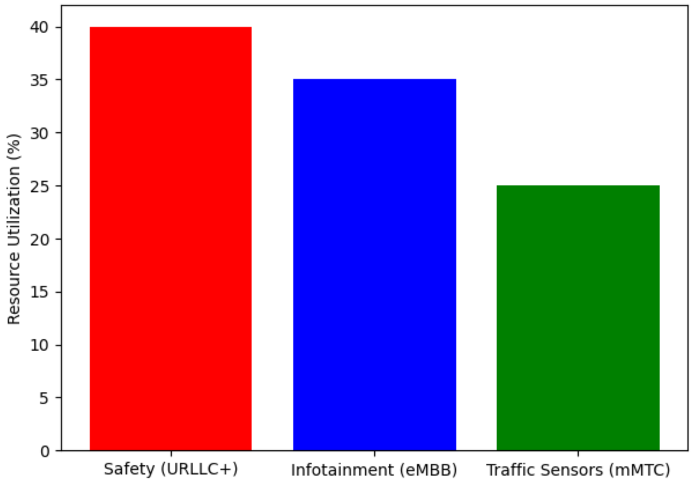

Figure 8: Network Slice Utilization in Vehicular IoT

Figure 8 presents how network resources are distributed across safety, infotainment, and traffic monitoring slices. Safety slices consume the largest portion, followed by infotainment and sensor slices. This demonstrates the importance of network slicing in managing diverse vehicular applications with differing quality-of-service requirements.

Conclusion:

This article demonstrates that 6G-enabled IoT represents a major technological leap toward fully autonomous, intelligent, and sustainable vehicular communication networks. The integration of THz bands, massive MIMO, RIS, ISAC, and URLLC+ establishes a communication environment that can support extreme reliability, ultra-low latency, and Tbps-level throughput, all of which are essential for next-generation IoV applications. Network slicing further enhances system flexibility by allowing customized virtual networks to coexist on shared infrastructure, ensuring that safety-critical, infotainment, and sensor-driven workloads receive appropriate resources without conflict. The analysis of scalability and interference mitigation highlights the importance of RIS-assisted propagation control, AI-based spectrum optimization, and dynamic resource allocation for handling dense traffic environments. Green IoT strategies—including task offloading and renewable-energy-assisted communication—underscore the need for energy-efficient design as vehicular networks continue to expand. The simulated performance metrics validate the effectiveness of these technologies, showing substantial improvements in latency, reliability, efficiency, and sustainability. In conclusion, 6G-enabled vehicular IoT will serve as the backbone of future intelligent transportation, supporting cooperative driving, autonomous mobility, and smart city integration. Continued research will further refine these technologies to ensure global scalability, security, and environmental compatibility.

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