Science, Engineering and Technology Vol. 4, No. 1, pp. 80-93
www.setjournal.com *https://doi.org/10.54327/set2024/v4.i1.127*

Transforming Vehicular Networks: How 6G can Revolutionize Intelligent Transportation?

Amir Aghaei Anvigh[1], Yashar Khavan[2], Behrouz Pourghebleh[2]
[1]*IMT Atlantique, Department of Information and Communication Technologies, Nantes, France*
[2]*Department of Computer Engineering, Tabriz Branch, Islamic Azad University, Tabriz, Iran*

Abstract

Vehicular Ad-hoc Networks (VANETs) have enabled intelligent transportation systems by facilitating communication between vehicles and roadside infrastructure. However, the current 5G and 4G networks that support VANETs have certain limitations that hinder the full potential of VANET applications. These limitations include constraints in bandwidth, latency, connectivity, and security. The upcoming 6G network is expected to revolutionize VANETs by introducing several advancements. 6G will provide ultra-fast communication with significantly reduced latency, enabling real-time and high-bandwidth data exchange between vehicles. The network will also offer highly reliable and secure connectivity, ensuring the integrity and privacy of VANET communications. Precise localization and sensing capabilities will be enhanced in 6G-based VANETs, enabling accurate positioning of vehicles and improved situational awareness. This will facilitate collision avoidance, traffic management, and cooperative driving applications. Moreover, integrating edge computing in 6G networks will bring computing resources closer to the edge, lowering response times and facilitating faster decision-making in time-critical scenarios. This paper explores the key features and capabilities of 6G technology and how it can revolutionize intelligent transportation, addressing challenges and opportunities for adopting 6G in VANETs.

Keywords: *6G technology, Intelligent transportation, Vehicular networks, Ultra-high data rates.*

1. Introduction

Intelligent Transportation Systems (ITS) have emerged as a critical component in modernizing transportation networks, revolutionizing how people and goods move within cities and across regions [1]. The integration of communication technologies into vehicular networks has given rise to Vehicular Ad hoc Networks (VANETs), enabling vehicles to interact with each other, the infrastructure, and the environment [2]. This technological advancement has paved the way for enhanced safety, efficiency, and sustainability in transportation operations. The deployment of 5G technology marked a significant milestone in the evolution of VANETs, providing faster data rates, reduced latency, and improved connectivity [3, 4]. However, as the demands of intelligent transportation continue to grow, the limitations of 5G are becoming apparent, propelling researchers and industries to explore the transformative potential of 6G technology. The relentless pursuit of technological innovation has led to the development of 6G, the next generation of wireless communication [5]. Expected to build upon the foundation laid by its predecessors, 6G promises to deliver a leap forward in communication capabilities. Its ultra-high data rates, virtually zero latency, enhanced reliability, and energy efficiency are set to revolutionize Vehicular Networks and drive the intelligent transportation systems of the future. The prospect of 6G offers new possibilities for a wide array of applications

Corresponding author: *Behrouz Pourghebleh (behrouz.pourghebleh@gmail.com)*
Received: *12 February 2024*; Revised: *25 March 2024*; Accepted: *29 March 2024*; Published: *2 April 2024*

that have the potential to reshape the transportation landscape [6].

This paper examines how 6G technology can revolutionize intelligent transportation through its unique attributes and features. We will discuss key characteristics of 6G that position it as a strong contender for transforming VANETs, providing seamless Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) communication. Moreover, we will investigate the specific applications of 6G in intelligent transportation, ranging from cooperative collision avoidance to remote vehicle control and enhanced passenger experiences. Nevertheless, adopting 6G in Vehicular Networks is not without challenges. Infrastructure deployment and associated costs, spectrum allocation and regulation, interoperability, security, and privacy concerns present significant hurdles that need to be addressed for successful implementation. We will also discuss these challenges and identify potential solutions to ensure a smooth transition towards 6G-enabled intelligent transportation.

2. Backgrounds

Over the past two decades, the exponential growth in the number of vehicles has outpaced the improvements in transportation infrastructure, leading to significant traffic problems. As a result, the integration of ITS has become increasingly critical. ITS is designed to address transportation issues, improve roadway safety, and facilitate the development of intelligent roads. Through ITS, passengers and drivers receive useful real-time information about available seats and traffic flow, leading to improved security, comfort, and reduced commuting time [7]. The concept of VANETs has evolved with advancements in computation and communication technologies, giving rise to the Internet of Vehicles (IoV). IoV plays a pivotal role in ITS by connecting smart vehicles on the Internet, providing efficient collaboration and communication among vehicles, bicycles, pedestrians, and roadside infrastructures. As a result, a significant decrease in traffic accidents caused by unimpaired drivers is anticipated, contributing to enhanced traffic management and reducing collisions, traffic congestion, and air pollution.

The adoption of ITS is predicted to grow rapidly in the near future, driven by projects like CityVerve Manchester and ERTICO-ITS Europe, aimed at developing intelligent cities. IoV enables the connectivity of pedestrians, transportation infrastructures, and autonomous vehicles, facilitating the Vehicle-to-Everything (V2X) approach. Nevertheless, the proliferation of vehicular services and smart vehicles is anticipated to generate vast data volumes and substantial traffic on networks. Additionally, the complexity of IoV, coupled with low latency and high mobility requirements, may pose challenges in terms of cloud-based storage, management, and privacy. Maintaining consistency and interoperability among IoV systems from different vendors is crucial. To address these challenges, it is essential to establish decentralized, interoperable, flexible, scalable, and secure data exchange and storage mechanisms within the IoV ecosystem. Such measures are paramount to unlocking the full potential of ITS and realizing the benefits of the IoV in revolutionizing transportation systems.

5G has emerged as a significant enabler for enhancing ITS capabilities. 5G technology possesses four major properties, namely enhanced reliability and lower latency, wide connections and reduced power consumption, wide coverage, and higher capacity. These factors have made the Internet of Things (IoT) a potential ITS infrastructure. Compared to its predecessor, 4G, 5G offers not only faster speeds but also superior reliability and lower latency, which are essential prerequisites for ITS to advance towards intelligence. 5G facilitates the seamless integration of data management platforms, power grids, automation systems, sensor networks, and road networks. This integration is instrumental in realizing the concept of the Internet of Everything (IoE) for ITS. The introduction of 5G has accelerated the evolution of self-driving vehicles and revolutionized transportation industry technologies. With the standardization of 5G completed, commercial 5G networks were launched in 2019, further fueling the progress and deployment of ITS.

The development and design of 6G communications began with the aim of catering to future communication needs. Unlike 5G, 6G networks will need to innovate significantly, enabling intelligence and aiming to achieve an impressive data rate of 1Tb/s. The potential of 6G goes beyond personalized communications, as it strives to implement the IoE paradigm fully, connecting various entities such as robots, devices, sensors, computing resources, wearables, and people. The fundamental potential architecture of 6G is an Integrated Space-Air-Ground-Underwater Network (ISAGUN) that supports instant and continuous hyper-connectivity. This network will enable communication across different domains to ensure comprehensive connectivity. An essential aspect of 6G is the integration of Artificial Intelligence (AI) as a fundamental function. Researchers view AI as a crucial component, as advanced machine learning technologies offer solutions for handling extremely complex scenarios efficiently.

In the pursuit of combining 6G with AI and other innovative technologies (6G+ABCDE), a concept called the "traffic brain" has been envisioned. This traffic brain, inspired by human brain functions, would possess long-term memory storage conversion and orientation capabilities, approaching human-like cognitive abilities. This revolution in technology may lead to computers exhibiting advanced thinking abilities, eliminating tedious and repetitive tasks, and transforming how we interact with technology. While this vision of the future might seem extraordinary and challenging to comprehend, it holds great potential for innovation revolution applied to 6G-AITS (6G-enabled Advanced Intelligent Transportation Systems). As research and development in 6G continue, the realization of this vision may pave the way for a groundbreaking era in communication and intelligent systems.

3. A Vision of the Future 6G Network

As we delve further into 6G development, it is essential to consider existing technologies and literature that provide insights into its potential performance, network structure, PHY (Physical Layer) technologies, and possible application opportunities. While 6G is still in the early stages of research, various predictions and expectations have been proposed based on advancements in the field.

3.1. Performance metrics and characteristics

6G necessitates advancements in various domains when compared to its predecessor, 5G. To begin with, 6G is expected to operate at higher frequencies, enabling transmission rates that are 100-1000 times faster than 5G. Consequently, users can experience data rates of up to 1 Tb/s [8]. Moreover, 6G is poised to revolutionize long-distance connectivity with an impressive latency of under 1 ms [9], outperforming 5G by tenfold. The density of the 6G network will significantly increase, boasting a capacity that might be 10-1000 times greater than that of 5G [10]. In terms of positioning accuracy, 6G will excel with 10 cm and 1 m precision for indoor and outdoor positioning, respectively, a tenfold improvement over 5G [11]. Additionally, 6G is projected to demonstrate enhanced energy efficiency, performing 10-100 percent better than 5G, while its spectrum performance is expected to be 5-10 percent superior to 5G [12]. Furthermore, 6G will impose more stringent demands on synchronization accuracy compared to 5G. Despite all-encompassing improvements, it is predicted that the cost of wireless connections in the 6G network will be minimal, amounting to less than 0.1 dollars/year [13]. This price point is exceptionally low, being 1000 times less than traditional 5G systems.

3.2. Space-air-ground-sea integrated network

It is widely agreed that the 6G network is an integrated system encompassing sea, ground, air, and space components, as illustrated in Figure 1. Positioned at the top layer of the Earth's network, the space network enhances the existing ground infrastructure [14]. This space network comprises three satellite types: Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Orbit (GSO) [15]. Satellite-based space communication networks (SCNs) play an increasingly vital role in various applications, including marine communications and emergency rescue operations [16]. Overcoming challenges in constructing IoT ecosystems in remote areas, SCNs offer a potential pathway to realize a global IoT [17]. Satellite-based IoT services have emerged, with LEO satellites being particularly suitable for their greater coverage, propagation delay, and power [18]. A growing number of satellites, including nanosatellites, will lead to greater accuracy and Quality of Experience (QoE) for ground users [19].

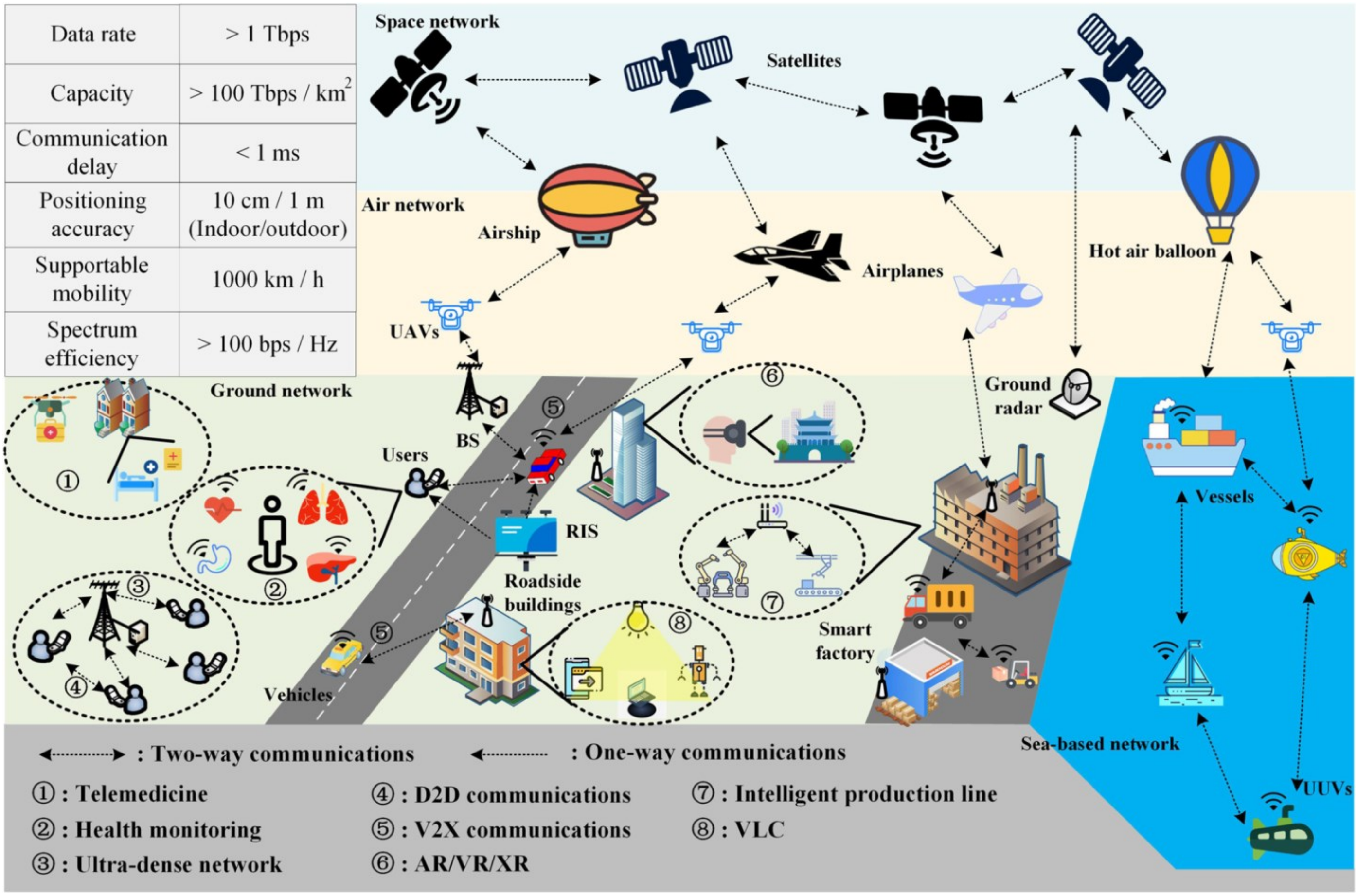

Figure 1. Space-air-ground-sea integrated network.

Moving to the air network, it exhibits inherent characteristics such as flexible mobility, adaptive altitude, and intelligent placement [20]. Comprising Unmanned Aerial Vehicles (UAVs), airships, air balloons, airplanes, high altitude platforms (HAPs), and other aircraft, the air network offers unique advantages. Firstly, the construction and deployment costs of Flying Base Stations (FBSs) are lower compared to ground base stations, with some UAVs even directly serving as BSs due to their abundant resources [21, 22]. Secondly, HAPs offer shorter time delays than space networks and broader coverage areas than ground networks [23]. Thirdly, low-cost UAVs are extensively utilized in network coverage and transportation due to their high mobility and hovering capabilities. Fourthly, FBSs can serve as relays for ground-to-satellite communications, enhancing the user experience for satellite services [24]. Additionally, UAVs can guide emergency vehicles in urban areas to select optimal routes [25].

When compared to space and air networks, the ground network constitutes the backbone of the 6G network. It will be an ultra-dense heterogeneous network comprising buildings, smart vehicles, intelligent devices, factories, and other ground facilities. All equipment and facilities within the ground network will communicate with each other. As depicted in Fig. 1, 6G will support future applications such as advanced medical treatment, ultra-dense communications, smart factories, and Device-to-Device (D2D) communications. To achieve technologies like holography and vehicular automatic driving and meet the Tb/s data transmission speed of 6G, the ground network will facilitate full-band communications, encompassing low frequency, microwave, millimeter wave, and terahertz bands.

Furthermore, given that the Earth's ocean area constitutes 71% of the total area, a sea-based network is vital for future oceanographic data collection and certain military activities. This sea-based network comprises vessels, Unmanned Underwater Vehicles (UUVs), underwater gliders, submarines, and more. While the current sea-based network faces challenges such as a complex environment, serious signal attenuation, real-time positioning issues, and limited computing resources, advancements in wireless communication methods under the sea, such as radio frequency, acoustic, and optical communications, enable high-speed data transmission between underwater devices and expand the scale of the sea-based network [26].

3.3. Ubiquitous AI in 6G

Ubiquitous AI in 6G refers to the pervasive integration of AI capabilities throughout the entire 6G network and its associated services. It entails embedding AI algorithms, machine learning models, and intelligent decision-making mechanisms at various levels, from edge devices and base stations to the core network and cloud infrastructure [27]. This ubiquitous AI presence in 6G empowers the network to analyze vast amounts of data, make intelligent decisions in real-time, and optimize its performance continuously [28]. The convergence of 6G and AI holds tremendous potential to revolutionize various industries, including intelligent transportation, healthcare, smart cities, industrial automation, and more [29]. In the context of intelligent transportation, ubiquitous AI in 6G can lead to several transformative applications. AI algorithms can analyze real-time traffic data, historical patterns, and other relevant information to optimize traffic signal timings, dynamically adjust traffic flow, and predict congestion [30]. This can lead to more efficient traffic management, reduced travel times, and improved overall transportation system performance. AI-powered analytics can optimize fleet operations by considering factors such as vehicle locations, traffic conditions, and delivery schedules. By making intelligent decisions regarding route planning, vehicle assignment, and maintenance schedules, fleet managers can enhance efficiency, reduce operational costs, and minimize carbon footprints.

Ubiquitous AI in 6G enables continuous monitoring and analysis of vehicle health data, identifying potential issues before they escalate. This predictive maintenance approach ensures timely repairs and reduces the risk of breakdowns, improving vehicle reliability and safety. In the realm of autonomous vehicles, AI plays a central role in perception, decision-making, and control. 6G's ubiquitous AI capabilities facilitate real-time communication and collaboration among autonomous vehicles, enabling them to share critical information, coordinate movements, and optimize traffic flow cooperatively. AI-driven personalization in vehicles can offer customized infotainment, comfort settings, and navigation preferences tailored to each passenger. With 6G's high data rates and low latency, AI can access cloud-based services seamlessly, enhancing the in-vehicle experience and making journeys more enjoyable and productive. Ubiquitous AI can power Advanced Driver Assistance Systems (ADASs) with real-time analysis of road conditions, vehicle dynamics, and potential hazards. By providing instant feedback and alerts to drivers, AI can significantly enhance road safety and reduce the risk of accidents. AI-powered surveillance systems can detect traffic violations, such as speeding or illegal parking, in real-time, enabling more efficient traffic enforcement and ensuring better compliance with traffic regulations. AI can optimize public transportation routes, schedules, and capacity planning based on passenger demand and real-time traffic conditions. This ensures more efficient and responsive public transit services, improving accessibility and rider satisfaction.

3.4. PHY techniques in 6G

In the context of 6G, several promising PHY techniques are being explored to meet the demanding requirements of ultra-high data rates, low latency, and massive connectivity. Terahertz (THz) Communication frequencies, ranging from 100 GHz to 10 THz, offer vast amounts of available bandwidth, enabling ultra-high data rates in 6G. However, THz communications face challenges due to high propagation losses and atmospheric absorption. Researchers are developing advanced antenna designs, beamforming techniques, and signal processing algorithms to mitigate these challenges and exploit the benefits of THz frequencies for future 6G networks.

Massive Multiple-Input Multiple-Output (MIMO) involves deploying a large number of antennas at base stations to serve multiple users simultaneously, dramatically increasing capacity and spectral efficiency. Cell-Free Massive MIMO goes a step further by pooling antennas from multiple base stations, creating a distributed MIMO system with improved coverage and interference management. These techniques promise significant gains in spectral efficiency and network performance. Intelligent Reflecting Surfaces (IRS), also known as reconfigurable intelligent surfaces or metasurfaces, consist of passive elements that can modify the phase and amplitude of incoming signals. By controlling the reflections of radio waves, IRS can optimize signal paths, enhance coverage, and improve signal quality, leading to increased network capacity and reduced interference.

Non-Orthogonal Multiple Access (NOMA) is a multi-user communication technique that allows multiple devices to share the same time-frequency resources. It assigns different power levels and decoding priorities to each user, enabling simultaneous data transmission. NOMA improves spectral efficiency and accommodates a large number of connected devices, making it suitable for 6G's mMTC requirements. Orbital Angular Momentum (OAM) multiplexing exploits the spatial domain by using unique phase patterns in radio waves to create multiple data-carrying channels within the same frequency band. This spatial multiplexing technique can significantly increase data capacity, making it attractive for future 6G networks. Full-duplex communication allows devices to transmit and receive data simultaneously on the same frequency band. In 6G, full-duplex techniques promise higher spectral efficiency and reduced latency by eliminating the need for time-division duplexing.

6G is expected to leverage multi-band communication, utilizing different frequency bands for different purposes to achieve better coverage and capacity. Spectrum-sharing techniques, such as dynamic spectrum access and spectrum pooling, will enable efficient utilization of available frequency resources and facilitate coexistence with other communication systems. Hybrid beamforming combines analog and digital beamforming to optimize the trade-off between complexity and performance. By using fewer RF chains and digital processing, hybrid beamforming reduces hardware complexity while still providing directional beamforming benefits, making it suitable for massive MIMO and mmWave communications in 6G.

3.5. Existing literature on 6G

Currently, researchers are primarily focusing on the vision and prospects of 6G. A review of existing literature reveals some key areas of interest and progress in 6G research. Several studies [12, 13, 31-33] propose that the 6G network will be a 3D integrated network incorporating space, air, ground, and sea components. They present various 6G performance indicators by comparing them with those of 4G and 5G networks. Researchers of [10, 11, 34] are exploring potential communication technologies for 6G. To meet the high communication rates and ultra-dense communication requirements of 6G, new technologies will be introduced, and existing ones will be upgraded. Researchers [35-37] discuss the development of 6G networking and edge computing technologies. These technologies are crucial for enabling efficient and seamless communication in the next-generation network. Blockchain Applications: The characteristics of privacy and secure information sharing in blockchain technology make it promising for 6G applications. Researchers of [38, 39] highlighted the potential and development of blockchain technology in 6G networks. AI and machine learning technologies are expected to play a significant role in 6G. Studies [27, 40, 41] emphasize the intelligence of future 6G networks and explore the possibilities of applying machine learning technologies in 6G. Apart from the overall outlook of 6G, some papers focus on specific layers of the 6G network.

Research [42-44] discussed the necessity of satellite communication in the future and introduced relevant satellite communication technologies. UAVs, HAPs, and other aircraft are crucial components of the 6G air network. They not only provide services for the ground network but also act as relay nodes to assist satellite communication [45, 46]. Communication in remote and maritime areas has been a challenging issue, and 6G is expected to address this problem and achieve true global interconnection [47, 48]. As the backbone of the 6G network, the ground network has various application scenarios. For instance, studies [49, 50] explore the applications of 6G in the IIoT scenario, while others [51, 52] discuss relevant technologies in 6G vehicular networks. In summary, current research on 6G is centered around its vision and potential, encompassing areas such as network architecture, communication technologies, edge computing, blockchain applications, AI integration, and improvements in specific components like space, air, sea, and ground networks. As researchers delve deeper into these aspects, 6G is poised to revolutionize communication and networking on a global scale.

4. Key Features of 6G for VANETs

The key features of 6G technology hold immense promise for transforming VANETs and revolutionizing the landscape of intelligent transportation, as outlined in Table 1. With its ultra-high data rates, anticipated to reach terabits per second (Tbps), 6G can facilitate seamless communication between vehicles and infrastructure, supporting bandwidth-intensive applications and services. Moreover, its virtually zero latency, reduced to mere microseconds, ensures real-time responsiveness critical for safety-critical applications like cooperative collision avoidance. This low latency capability can significantly enhance safety and system efficiency, allowing vehicles to exchange critical information swiftly and prevent accidents. Additionally, 6G's enhanced reliability and network availability, achieved through advanced error correction and redundancy techniques, ensure robust and dependable connections in challenging vehicular environments, reducing the risk of communication failures.

The massive machine-type communications (mMTC) capability of 6G is a boon for VANETs, as it can accommodate the proliferation of IoT devices within intelligent transportation systems. By enabling seamless connections with various sensors and roadside units, mMTC facilitates comprehensive data sharing and intelligent decision-making, paving the way for more efficient and adaptive vehicular networks. Moreover, 6G's focus on energy efficiency is vital for battery-powered vehicles in VANETs. With advanced energy-saving mechanisms, 6G optimizes data transmission and reception while minimizing power consumption, enhancing the sustainability and longevity of vehicular operations. Security and privacy are paramount in the context of vehicular communication, and 6G addresses these concerns through advanced security mechanisms, such as quantum-resistant cryptography and blockchain technologies. These mechanisms safeguard communication channels from cyber threats and protect sensitive vehicle and user data. Furthermore, 6G's integration of AI brings intelligence and autonomy to VANETs. AI-driven algorithms optimize network resources, predict traffic patterns, manage communication links, and detect anomalies, ensuring more intelligent and proactive vehicular networks.

The transformative potential of 6G technology goes beyond just enhancing the technical capabilities of VANETs. It opens up new possibilities for a wide array of applications that have the potential to redefine the entire intelligent transportation ecosystem. One such application is cooperative collision avoidance, where vehicles equipped with 6G communication can exchange real-time information, such as speed, position, and direction, to avoid potential collisions and enhance road safety.

Table 1. 6G features for VANETs.

Feature	Description
Ultra-High Data Rates	Terabits per second (Tbps) data transmission speeds enable bandwidth-intensive applications.
Virtually Zero Latency	Communication delays are reduced to microseconds, which is critical for real-time safety applications.
Enhanced Reliability	Advanced error correction and redundancy techniques ensure robust and dependable connections.
Massive Machine-Type Communications (mMTC)	Supports a massive number of connected devices, facilitating IoT integration in VANETs.
Energy Efficiency	Advanced energy-saving mechanisms optimize power consumption for battery-powered vehicles.
Enhanced Security and Privacy	Incorporates quantum-resistant cryptography and blockchain technologies for secure communication.
Integration of AI	AI-driven algorithms optimize resources, predict traffic patterns, and detect anomalies.

The virtually zero latency of 6G ensures that critical collision avoidance messages are delivered without delay, enabling swift responses in emergencies. Another area where 6G can make a significant impact is in traffic management and optimization. With its ultra-high data rates, 6G enables the seamless exchange of traffic data between vehicles and infrastructure, facilitating dynamic traffic flow management. AI-driven algorithms can analyze real-time data to predict traffic patterns, optimize signal timings, and suggest alternative routes, reducing congestion and travel time for commuters.

The integration of 6G with autonomous vehicles holds the potential for remote vehicle control. Through the combination of low latency and high data rates, 6G allows for real-time remote monitoring and control of autonomous vehicles, enabling remote assistance and intervention when needed. This capability not only enhances safety but also opens up new possibilities for autonomous mobility services, such as remotely operated shared autonomous vehicles. Furthermore, the ultra-high data rates and low latency of 6G enable enhanced infotainment and passenger experiences in vehicles. Passengers can enjoy high-quality multimedia services, augmented reality experiences, and seamless connectivity while on the move. Such entertainment options can transform the travel experience, making journeys more enjoyable and productive for passengers. The 6G technology's potential extends beyond the vehicle-to-vehicle and vehicle-to-infrastructure communication. It also enables efficient vehicle-to-network communication, where vehicles can connect to a wider array of cloud-based services, such as real-time traffic updates, weather information, and navigation assistance. This integration with cloud services enhances the overall intelligence and efficiency of VANETs, making them a crucial component of smart city ecosystems.

As the deployment of 6G technology progresses, the research community and industries will continue to explore new applications and possibilities for VANETs. However, alongside these exciting opportunities, some challenges need to be addressed. These include infrastructure deployment and cost, spectrum allocation and regulation, interoperability, and standardization, as well as security and privacy concerns. Overcoming these challenges will be crucial in realizing the full potential of 6G technology in transforming VANETs and redefining the future of intelligent transportation. The successful integration of 6G into VANETs will pave the way for safer, more efficient, and connected transportation systems, ultimately revolutionizing the way we move and experience mobility in the years to come.

5. 6G Applications in Intelligent Transportation

6G technology offers a wide range of transformative applications in the field of intelligent transportation, as summarized in Table 2. With its ultra-high data rates and virtually zero latency, 6G enables real-time V2V communication, allowing for cooperative collision avoidance systems that can predict and prevent potential accidents. Additionally, the advanced communication capabilities of 6G facilitate efficient traffic management and optimization through seamless V2I communication, leading to reduced congestion and improved traffic flow. Furthermore, 6G's low latency and high data rates enable remote vehicle control, enhancing the safety of autonomous vehicles and enabling remote assistance in challenging situations.

In the context of passenger experiences, 6G opens the door to enhanced infotainment services, providing passengers with high-quality multimedia and augmented reality experiences during travel. Moreover, 6G fosters intelligent public transportation systems by enabling real-time communication and coordination among vehicles and transit infrastructure, improving the efficiency and reliability of public transit services. The technology's potential extends to logistics and freight management, where 6G-powered communication allows for real-time monitoring of vehicles and cargo, optimizing supply chains and streamlining freight transportation. As urban air mobility gains prominence, 6G's capabilities become crucial for enabling safe and efficient communication between aerial vehicles, ground infrastructure, and air traffic control in the realm of future air transportation. Overall, 6G technology holds the promise of revolutionizing intelligent transportation, ushering in a new era of connected, efficient, and sustainable mobility solutions.

Table 2. 6G applications in intelligent transportation.

Application	Description
Cooperative Collision Avoidance	Real-time V2V communication to predict and prevent potential accidents.
Traffic Management and Optimization	Efficient traffic flow management, signal optimization, and route suggestions for reduced congestion.
Remote Vehicle Control	Real-time remote monitoring and control of autonomous vehicles for enhanced safety and remote assistance.
Enhanced Infotainment and Passenger Experience	High-quality multimedia services and augmented reality experiences for passengers during travel.
V2I Communication	Seamless communication between vehicles and smart infrastructure for improved traffic control and information.
Remote Diagnostics and Maintenance	Real-time vehicle health monitoring and predictive maintenance for optimized fleet efficiency.
Intelligent Public Transportation	Real-time communication and coordination among vehicles and transit infrastructure for efficient public transit.
Smart Logistics and Freight Management	Real-time monitoring and coordination of vehicles and cargo for optimized supply chain and freight operations.
Urban Air Mobility (UAM)	Efficient communication between aerial vehicles, ground infrastructure, and air traffic control for safe UAM.
Smart Charging Solutions	Efficient communication between electric vehicles and charging infrastructure for optimized energy usage.
Collaborative Perception for Autonomous Vehicles	Sharing sensor data between vehicles to enhance situational awareness for autonomous driving.
Integration with Smart City Initiatives	Data-driven decision-making for optimized traffic management and seamless integration with smart city services.

In addition to the aforementioned applications, 6G technology brings about remarkable advancements in remote diagnostics and maintenance for vehicles. Through its mMTC capability, 6G allows seamless connectivity between vehicles and diagnostic sensors, facilitating real-time monitoring of vehicle health. This enables predictive maintenance, as vehicles can transmit data on their condition and performance to maintenance centers, ensuring timely repairs and proactive measures to prevent breakdowns. As a result, vehicle downtime is minimized, and fleet efficiency is optimized, leading to cost savings and improved overall transportation operations. The integration of 6G in intelligent transportation systems also plays a pivotal role in enabling more sustainable and eco-friendly practices. The high data rates and low latency enable efficient communication between electric vehicles and charging infrastructure, facilitating smart charging solutions. By dynamically coordinating charging schedules based on electricity demand, grid capacity, and vehicle availability, 6G-powered intelligent charging systems can optimize energy usage, reduce peak loads, and promote the adoption of electric vehicles.

Moreover, 6G technology empowers vehicles with advanced sensing capabilities, enabling them to communicate data from various onboard sensors, such as LiDAR, cameras, and radar, to other vehicles and infrastructure. This collaborative perception capability enhances situational awareness for autonomous vehicles, enabling them to navigate complex traffic scenarios, adverse weather conditions, and challenging environments better. As the world increasingly embraces smart city initiatives, 6G plays a critical role in shaping the future of urban transportation. Its integration with smart city infrastructure allows for data-driven decision-making, enabling optimized traffic management, dynamic routing, and efficient allocation of resources. Additionally, 6G supports the seamless integration of intelligent transportation systems with other essential services, such as public safety, healthcare, and emergency response, creating a holistic smart city ecosystem that fosters safety, sustainability, and quality of life for its residents.

6. Challenges and Considerations

The deployment of 6G technology in intelligent transportation presents numerous challenges and considerations that must be carefully addressed to ensure its successful implementation. One of the primary challenges is the significant infrastructure investment required for 6G network deployment, which includes installing new base stations and communication nodes to support ultra-high data rates and low latency. The associated costs and complexities of upgrading existing infrastructure and ensuring widespread coverage pose considerable financial and logistical challenges. Additionally, spectrum allocation and regulation issues must be resolved to ensure sufficient spectrum resources for 6G communication in intelligent transportation without interference. Coordinating spectrum usage among different stakeholders and industries is crucial to avoid fragmentation and optimize spectrum efficiency. Interoperability and standardization are equally critical considerations, as diverse stakeholders may develop proprietary solutions, potentially leading to compatibility issues and hindering seamless communication between vehicles, infrastructure, and smart city systems. Establishing common standards and protocols will be essential to promote interoperability and create a unified framework for 6G communication in intelligent transportation.

Another pressing concern is the security and privacy of 6G-enabled transportation systems. As intelligent transportation relies heavily on connected technologies and data exchange, ensuring robust cybersecurity mechanisms is imperative to protect against cyber threats and unauthorized access. Equally important is safeguarding user and vehicle data privacy to gain public trust and acceptance. Public perception and acceptance are essential for the successful adoption of 6G in intelligent transportation. Addressing concerns related to data privacy, job displacement due to automation, and the safety of autonomous technologies through effective communication and education initiatives is vital in fostering public confidence and support.

Furthermore, energy consumption and sustainability are significant considerations, given the potential increase in energy demand from more data-intensive 6G networks. Balancing the need for high performance with energy conservation measures is crucial for the long-term sustainability of 6G-enabled intelligent transportation systems, especially for battery-powered vehicles and remote infrastructure locations. Integrating 6G with legacy transportation systems and infrastructure poses compatibility challenges, as older systems may not support the capabilities of 6G. Ensuring smooth integration and optimizing the performance of legacy systems are necessary to maximize the benefits of 6G in intelligent transportation.

Finally, network resilience and redundancy are paramount in intelligent transportation systems, where communication failures can have severe consequences. Implementing fail-safe mechanisms, redundant communication paths, and robust network design is essential to maintain reliable communication in critical situations or adverse environmental conditions. Addressing these challenges and considerations requires collaboration among stakeholders, regulatory bodies, and industry players to pave the way for a seamless and successful integration of 6G technology into intelligent transportation, unlocking its full potential in shaping a safer, more efficient, and connected future of mobility.

7. Opportunities and Future Directions

6G technology opens up new possibilities for the widespread adoption and advancement of autonomous vehicles. The ultra-high data rates and low latency of 6G enable seamless communication between autonomous vehicles, infrastructure, and cloud-based services, enhancing their perception and decision-making capabilities. With 6G, autonomous vehicles can navigate complex traffic scenarios, adverse weather conditions, and challenging environments more efficiently, making self-driving cars safer and more reliable. This paves the way for a future where autonomous vehicles become an integral part of intelligent transportation systems, transforming mobility and urban planning.

6G technology facilitates the integration of intelligent transportation systems with broader smart city initiatives. The efficient communication between vehicles, infrastructure, and smart city systems allows for data-driven decision-making, optimizing traffic management, energy usage, and resource allocation. Seamless integration with other smart city services, such as public safety, healthcare, and emergency response, can lead to more sustainable and resilient urban environments. This collaboration fosters the development of comprehensive smart city ecosystems, enhancing the quality of life for citizens and improving urban mobility.

6G's capabilities drive the emergence of innovative mobility services beyond conventional transportation modes. The technology's high data rates and low latency enable real-time coordination between different modes of transportation, including ridesharing, bike-sharing, and micro-mobility services. By integrating these services into a seamless multi-modal transportation network, 6G facilitates efficient and personalized mobility solutions, reducing congestion and promoting eco-friendly transportation choices. With its cooperative collision avoidance and real-time communication capabilities, 6G can significantly enhance road safety. Vehicles equipped with 6G can communicate with each other and infrastructure elements to detect potential hazards, share real-time traffic information, and prevent accidents. This cooperative safety approach, combined with advancements in V2X communication, can revolutionize road safety and drastically reduce the number of accidents and fatalities.

6G technology's ability to handle vast amounts of data in real-time opens up opportunities for sophisticated transportation analytics. AI-driven algorithms can analyze massive data streams from vehicles, sensors, and infrastructure to gain insights into traffic patterns, demand forecasting, and transportation behavior. These analytics can inform decision-makers, urban planners, and policymakers, enabling them to make data-driven, efficient, and sustainable transportation policies and infrastructure investments. 6G's mMTC capability facilitates seamless connectivity between vehicles and cargo, enabling real-time tracking and monitoring of goods in transit. This connected freight management enhances supply chain efficiency, reduces delivery times, and optimizes logistics operations. It also enables better resource allocation, minimizing wastage and environmental impact and fostering a more sustainable approach to freight transportation.

6G can synergize with other emerging technologies, such as edge computing, artificial intelligence, and blockchain. Edge computing, coupled with 6G's low latency, enables real-time data processing at the network edge, reducing data transmission delays and enhancing system responsiveness. AI can be harnessed to optimize transportation operations, improve traffic flow, and predict transportation demand, while blockchain can enhance data security and trust in vehicular communication. 6G's high data rates and low latency enable real-time traffic data collection and analysis. By utilizing AI-driven algorithms and machine learning, 6G can predict traffic patterns and congestion in advance, allowing for more proactive traffic management. Dynamic traffic rerouting and signal optimization can be implemented in real-time, reducing traffic jams and improving overall transportation efficiency.

6G can revolutionize parking systems by enabling real-time availability updates and seamless payment transactions. With 6G-enabled sensors and communication, drivers can quickly locate and reserve parking spots, reducing the time spent searching for parking spaces and alleviating traffic congestion in urban areas. The high data rates and low latency of 6G can enhance Augmented Reality (AR) navigation experiences. Through AR overlays on windshields or head-up displays, drivers can receive real-time navigation guidance, traffic alerts, and points of interest information, leading to safer and more immersive navigation experiences.

6G can be leveraged for environmental monitoring in intelligent transportation systems. Sensors embedded in vehicles and infrastructure can collect data on air quality, noise levels, and emissions, contributing to smarter urban planning and more sustainable transportation policies. 6G's efficient communication capabilities enable on-demand mobility services, such as ride-hailing and micro-transit solutions, to become more seamless and responsive. Passengers can request transportation services in real-time, and autonomous vehicles or drones can quickly respond to these requests, optimizing transportation availability and accessibility.

With 6G's high data rates and low latency, emergency responders can access real-time information and video feeds from accident sites, enabling faster response times and more effective incident management. Additionally, public safety agencies can leverage 6G for improved coordination and communication during emergencies and disasters. The widespread adoption of 6G in intelligent transportation has the potential to create significant social and economic impacts. The transformation of mobility services, increased accessibility to transportation options, and improved traffic management can lead to enhanced quality of life, reduced transportation costs, and increased productivity for individuals and businesses alike.

8. Conclusion

Several key technologies will play a crucial role in realizing the potential of 6G-enabled VANETs. These technologies include terahertz communication, which allows for higher-frequency transmissions and increased bandwidth; optical wireless communication, which provides high-capacity and secure data transfer through optical links; reconfigurable intelligent surfaces, which manipulate wireless signals to improve coverage and capacity; and edge computing, which enables distributed processing and data storage near the network edge. Despite the promising potential of 6G-based VANETs, several open challenges need to be addressed. These challenges include developing efficient resource management strategies, ensuring robust security mechanisms to protect against cyber-attacks, integrating heterogeneous communication technologies, and addressing spectrum allocation and interference management issues.

Competing Interests Statement

The authors declare no competing interests.

Data and Materials Accessibility

No additional data or materials were utilized for the research described in the article.

References

[1] J. N. Njoku, C. I. Nwakanma, G. C. Amaizu, and D. S. Kim, "Prospects and challenges of Metaverse application in data-driven intelligent transportation systems," *IET Intelligent Transport Systems,* vol. 17, no. 1, pp. 1-21, 2023.

[2] B. Pourghebleh and N. Jafari Navimipour, "Towards efficient data collection mechanisms in the vehicular ad hoc networks," *International Journal of Communication Systems,* vol. 32, no. 5, p. e3893, 2019.

[3] A. Kaul and I. Altaf, "Vanet-TSMA: A traffic safety management approach for smart road transportation in vehicular ad hoc networks," *International Journal of Communication Systems,* vol. 35, no. 9, p. e5132, 2022.

[4] H. Guo, X. Zhou, J. Liu, and Y. Zhang, "Vehicular intelligence in 6G: Networking, communications, and computing," *Vehicular Communications,* vol. 33, p. 100399, 2022.

[5] B. Cao, Z. Sun, J. Zhang, and Y. Gu, "Resource allocation in 5G IoV architecture based on SDN and fog-cloud computing," *IEEE Transactions on Intelligent Transportation Systems,* vol. 22, no. 6, pp. 3832-3840, 2021.

[6] P. M. Shakeel, S. Baskar, H. Fouad, G. Manogaran, V. Saravanan, and Q. Xin, "Creating collision-free communication in IoT with 6G using multiple machine access learning collision avoidance protocol," *Mobile Networks and Applications,* vol. 26, pp. 969-980, 2021.

[7] S. Saeidi, S. Enjedani, E. Alvandi Behineh, K. Tehranian, and S. Jazayerifar, "Factors Affecting Public Transportation Use during Pandemic: An Integrated Approach of Technology Acceptance Model and Theory of Planned Behavior," *Tehnički glasnik,* vol. 18, pp. 1-12, 09/01 2023, doi: 10.31803/tg-20230601145322.

[8] K. B. Letaief, W. Chen, Y. Shi, J. Zhang, and Y.-J. A. Zhang, "The roadmap to 6G: AI empowered wireless networks," *IEEE communications magazine,* vol. 57, no. 8, pp. 84-90, 2019.

[9] M. Z. Chowdhury, M. T. Hossan, and Y. M. Jang, "Interference management based on RT/nRT traffic classification for FFR-aided small cell/macrocell heterogeneous networks," *IEEE Access,* vol. 6, pp. 31340-31358, 2018.

[10] P. Yang, Y. Xiao, M. Xiao, and S. Li, "6G wireless communications: Vision and potential techniques," *IEEE network,* vol. 33, no. 4, pp. 70-75, 2019.

[11] M. Z. Chowdhury, M. Shahjalal, S. Ahmed, and Y. M. Jang, "6G wireless communication systems: Applications, requirements, technologies, challenges, and research directions," *IEEE Open Journal of the Communications Society,* vol. 1, pp. 957-975, 2020.

[12] Z. Zhang *et al.*, "6G wireless networks: Vision, requirements, architecture, and key technologies," *IEEE*

vehicular technology magazine, vol. 14, no. 3, pp. 28-41, 2019.

[13] S. Zhang, C. Xiang, and S. Xu, "6G: Connecting everything by 1000 times price reduction," *IEEE Open Journal of Vehicular Technology,* vol. 1, pp. 107-115, 2020.

[14] B. Mao, F. Tang, Y. Kawamoto, and N. Kato, "Optimizing computation offloading in satellite-UAV-served 6G IoT: A deep learning approach," *IEEE Network,* vol. 35, no. 4, pp. 102-108, 2021.

[15] J. Liu, Y. Shi, Z. M. Fadlullah, and N. Kato, "Space-air-ground integrated network: A survey," *IEEE Communications Surveys & Tutorials,* vol. 20, no. 4, pp. 2714-2741, 2018.

[16] C.-Q. Dai, L. Guo, S. Fu, and Q. Chen, "Contact plan design with directional space-time graph in two-layer space communication networks," *IEEE Internet of Things Journal,* vol. 6, no. 6, pp. 10862-10874, 2019.

[17] M. De Sanctis, E. Cianca, G. Araniti, I. Bisio, and R. Prasad, "Satellite communications supporting internet of remote things," *IEEE Internet of Things Journal,* vol. 3, no. 1, pp. 113-123, 2015.

[18] L. Wang, S. Liu, W. Wang, and Z. Fan, "Dynamic uplink transmission scheduling for satellite Internet of Things applications," *China Communications,* vol. 17, no. 10, pp. 241-248, 2020.

[19] A. Freimann, T. Petermann, and K. Schilling, "Interference-free contact plan design for wireless communication in space-terrestrial networks," in *2019 IEEE International Conference on Space Mission Challenges for Information Technology (SMC-IT)*, 2019: IEEE, pp. 55-61.

[20] D. Mishra and E. Natalizio, "A survey on cellular-connected UAVs: Design challenges, enabling 5G/B5G innovations, and experimental advancements," *Computer Networks,* vol. 182, p. 107451, 2020.

[21] S.-F. Chou, A.-C. Pang, and Y.-J. Yu, "Energy-aware 3D unmanned aerial vehicle deployment for network throughput optimization," *IEEE Transactions on Wireless Communications,* vol. 19, no. 1, pp. 563-578, 2019.

[22] S. A. Hadiwardoyo *et al.*, "Optimizing UAV-to-car communications in 3D environments through dynamic UAV positioning," in *2019 IEEE/ACM 23rd International Symposium on Distributed Simulation and Real Time Applications (DS-RT)*, 2019: IEEE, pp. 1-8.

[23] J. Liu, X. Du, J. Cui, M. Pan, and D. Wei, "Task-oriented intelligent networking architecture for the space–air–ground–aqua integrated network," *IEEE Internet of Things Journal,* vol. 7, no. 6, pp. 5345-5358, 2020.

[24] X. Huang, J. A. Zhang, R. P. Liu, Y. J. Guo, and L. Hanzo, "Airplane-aided integrated networking for 6G wireless: Will it work?," *IEEE Vehicular Technology Magazine,* vol. 14, no. 3, pp. 84-91, 2019.

[25] O. S. Oubbati, A. Lakas, P. Lorenz, M. Atiquzzaman, and A. Jamalipour, "Leveraging communicating UAVs for emergency vehicle guidance in urban areas," *IEEE Transactions on Emerging Topics in Computing,* vol. 9, no. 2, pp. 1070-1082, 2019.

[26] T. Huang, W. Yang, J. Wu, J. Ma, X. Zhang, and D. Zhang, "A survey on green 6G network: Architecture and technologies," *IEEE access,* vol. 7, pp. 175758-175768, 2019.

[27] H. Yang, A. Alphones, Z. Xiong, D. Niyato, J. Zhao, and K. Wu, "Artificial-intelligence-enabled intelligent 6G networks," *IEEE Network,* vol. 34, no. 6, pp. 272-280, 2020.

[28] S. Dang, O. Amin, B. Shihada, and M.-S. Alouini, "What should 6G be?," *Nature Electronics,* vol. 3, no. 1, pp. 20-29, 2020.

[29] J. Du, C. Jiang, J. Wang, Y. Ren, and M. Debbah, "Machine learning for 6G wireless networks: Carrying forward enhanced bandwidth, massive access, and ultrareliable/low-latency service," *IEEE Vehicular Technology Magazine,* vol. 15, no. 4, pp. 122-134, 2020.

[30] H. Kim, J. Ben-Othman, L. Mokdad, J. Son, and C. Li, "Research challenges and security threats to AI-driven 5G virtual emotion applications using autonomous vehicles, drones, and smart devices," *IEEE network,* vol. 34, no. 6, pp. 288-294, 2020.

[31] I. F. Akyildiz, A. Kak, and S. Nie, "6G and beyond: The future of wireless communications systems," *IEEE access,* vol. 8, pp. 133995-134030, 2020.

[32] S. Chen, Y.-C. Liang, S. Sun, S. Kang, W. Cheng, and M. Peng, "Vision, requirements, and technology trend of 6G: How to tackle the challenges of system coverage, capacity, user data-rate and movement speed," *IEEE Wireless Communications,* vol. 27, no. 2, pp. 218-228, 2020.

[33] G. Liu *et al.*, "Vision, requirements and network architecture of 6G mobile network beyond 2030," *China Communications,* vol. 17, no. 9, pp. 92-104, 2020.

[34] K. Rikkinen, P. Kyosti, M. E. Leinonen, M. Berg, and A. Parssinen, "THz radio communication: Link budget analysis toward 6G," *IEEE Communications Magazine,* vol. 58, no. 11, pp. 22-27, 2020.

[35] X. Tang *et al.*, "Computing power network: The architecture of convergence of computing and networking towards 6G requirement," *China communications,* vol. 18, no. 2, pp. 175-185, 2021.

[36] J. Mei, X. Wang, and K. Zheng, "An intelligent self-sustained RAN slicing framework for diverse service provisioning in 5G-beyond and 6G networks,"

Intelligent and Converged Networks, vol. 1, no. 3, pp. 281-294, 2020.

[37] S. U. Jamil, M. A. Khan, and S. ur Rehman, "Intelligent task off-loading and resource allocation for 6G smart city environment," in *2020 IEEE 45th Conference on Local Computer Networks (LCN)*, 2020: IEEE, pp. 441-444.

[38] T. Nguyen, N. Tran, L. Loven, J. Partala, M.-T. Kechadi, and S. Pirttikangas, "Privacy-aware blockchain innovation for 6G: Challenges and opportunities," *2020 2nd 6G Wireless Summit (6G SUMMIT),* pp. 1-5, 2020.

[39] R. Sekaran, R. Patan, A. Raveendran, F. Al-Turjman, M. Ramachandran, and L. Mostarda, "Survival study on blockchain based 6G-enabled mobile edge computation for IoT automation," *IEEE access,* vol. 8, pp. 143453-143463, 2020.

[40] M. J. Piran and D. Y. Suh, "Learning-driven wireless communications, towards 6G," in *2019 International Conference on Computing, Electronics & Communications Engineering (iCCECE)*, 2019: IEEE, pp. 219-224.

[41] Y. Liu, X. Yuan, Z. Xiong, J. Kang, X. Wang, and D. Niyato, "Federated learning for 6G communications: Challenges, methods, and future directions," *China Communications,* vol. 17, no. 9, pp. 105-118, 2020.

[42] S. Chen, S. Sun, and S. Kang, "System integration of terrestrial mobile communication and satellite communication—the trends, challenges and key technologies in B5G and 6G," *China communications,* vol. 17, no. 12, pp. 156-171, 2020.

[43] X. Fang, W. Feng, T. Wei, Y. Chen, N. Ge, and C.-X. Wang, "5G embraces satellites for 6G ubiquitous IoT: Basic models for integrated satellite terrestrial networks," *IEEE Internet of Things Journal,* vol. 8, no. 18, pp. 14399-14417, 2021.

[44] S. Fu, J. Gao, and L. Zhao, "Collaborative multi-resource allocation in terrestrial-satellite network towards 6G," *IEEE Transactions on Wireless Communications,* vol. 20, no. 11, pp. 7057-7071, 2021.

[45] H. Hashida, Y. Kawamoto, and N. Kato, "Intelligent reflecting surface placement optimization in air-ground communication networks toward 6G," *IEEE Wireless Communications,* vol. 27, no. 6, pp. 146-151, 2020.

[46] S. Han *et al.*, "Artificial-intelligence-enabled air interface for 6G: Solutions, challenges, and standardization impacts," *IEEE Communications Magazine,* vol. 58, no. 10, pp. 73-79, 2020.

[47] Y. Liu, C.-X. Wang, H. Chang, Y. He, and J. Bian, "A novel non-stationary 6G UAV channel model for maritime communications," *IEEE Journal on Selected Areas in Communications,* vol. 39, no. 10, pp. 2992-3005, 2021.

[48] Y. Wang, W. Feng, J. Wang, and T. Q. Quek, "Hybrid satellite-UAV-terrestrial networks for 6G ubiquitous coverage: A maritime communications perspective," *IEEE Journal on Selected Areas in Communications,* vol. 39, no. 11, pp. 3475-3490, 2021.

[49] G. Han, J. Tu, L. Liu, M. Martinez-Garcia, and Y. Peng, "Anomaly detection based on multidimensional data processing for protecting vital devices in 6G-enabled massive IIoT," *IEEE Internet of Things Journal,* vol. 8, no. 7, pp. 5219-5229, 2021.

[50] D. Kutuzov, A. Osovsky, O. Stukach, and D. Starov, "Modeling of IIoT traffic processing by intra-chip NoC routers of 5G/6G networks," in *2021 international siberian conference on control and communications (SIBCON)*, 2021: IEEE, pp. 1-5.

[51] F. Tang, Y. Kawamoto, N. Kato, and J. Liu, "Future intelligent and secure vehicular network toward 6G: Machine-learning approaches," *Proceedings of the IEEE,* vol. 108, no. 2, pp. 292-307, 2019.

[52] K. Gao, C. Xu, P. Zhang, J. Qin, L. Zhong, and G.-M. Muntean, "GCH-MV: Game-enhanced compensation handover scheme for multipath TCP in 6G software defined vehicular networks," *IEEE Transactions on Vehicular Technology,* vol. 69, no. 12, pp. 16142-16154, 2020.