

6G Technologies for Vehicular Ad Hoc Networks: A Survey of Enablers, Architectures, and Open Challenges

Dharm Raj

Department of Computer Science & Engineering, Sharda School of Computing
Science & Engineering,
Sharda University, Greater Noida, India
dharmraj4u@gmail.com

Abstract. Vehicular ad hoc networks (VANETs) are evolving from best-effort safety-message broadcasting toward a data-intensive substrate for cooperative automated driving, remote driving, and immersive in-vehicle services. These applications demand sub-millisecond latency, reliability beyond $1 - 10^{-7}$, centimetre-level positioning, and multi-Gbps throughput under extreme mobility, which exceeds what DSRC, LTE-V2X, and 5G NR-V2X can jointly guarantee. This survey reviews the sixth-generation (6G) technologies most relevant to VANETs: terahertz and sub-THz communications, reconfigurable intelligent surfaces, integrated sensing and communication, native artificial intelligence, edge and fog computing with digital twins, integrated space-air-ground networks, and next-generation security and privacy mechanisms. For each enabler we summarise the operating principle, its specific benefit for vehicular links, representative research results, and the vehicular-specific obstacles that remain. We then propose a layered reference architecture for 6G-enabled VANETs, compare the enablers against key performance indicators, and identify open research directions, including mobility-aware beam management at THz, real-time RIS control, trustworthy and explainable AI, and standardisation of IMT-2030 V2X.

Keywords: 6G · VANET · V2X · Terahertz · Reconfigurable intelligent surface · Integrated sensing and communication · Edge intelligence · Non-terrestrial networks

1 Introduction

Vehicular ad hoc networks (VANETs) enable vehicles to exchange information with one another (V2V), with roadside infrastructure (V2I), with pedestrians (V2P), and with the network (V2N), collectively termed vehicle-to-everything (V2X) communication [3, 14, 27]. First-generation VANETs relied on IEEE 802.11p-based Dedicated Short-Range Communications (DSRC), designed primarily for periodic broadcast of cooperative awareness messages with latency budgets of about 100 ms [15]. Cellular V2X followed: LTE-V2X (3GPP Release 14) introduced the PC5 sidelink, and 5G NR-V2X (Release 16 onward)

added unicast and groupcast sidelink modes, flexible numerologies, and support for advanced use cases such as vehicle platooning, extended sensors, and remote driving [6, 11].

Even so, the trajectory of automated mobility points beyond the capability envelope of 5G. Fully cooperative Level-5 driving, real-time sharing of raw LiDAR and camera data, high-definition (HD) map streaming, and tele-operated driving require simultaneous ultra-high throughput, ultra-low latency, extreme reliability, and precise positioning under high relative speeds and rapidly changing topology [22, 34]. 3GPP has quantified some of these needs: advanced V2X scenarios call for end-to-end latencies as low as 3 ms, reliability up to 99.999%, and data rates up to 1 Gbps for sensor sharing [11].

Sixth-generation (6G) systems, framed by ITU-R as IMT-2030 [35], target peak rates of the order of 1 Tbps, air-interface latency of 0.1 ms, connection densities up to 10^7 devices/km², and new capabilities including native AI and integrated sensing [12, 16, 31]. These targets align closely with the requirements of next-generation VANETs, motivating a focused survey.

Contributions. Although broad 6G surveys exist [7, 31, 35] and V2X-focused works have appeared [22, 34], a compact review that links each 6G enabler to concrete VANET challenges is still useful for researchers entering the area. This paper (i) summarises the evolution of VANET technologies and the requirements that motivate 6G; (ii) surveys seven families of 6G enablers from a vehicular perspective; (iii) proposes a layered reference architecture for 6G-enabled VANETs; (iv) compares enablers against key performance indicators (KPIs); and (v) outlines open challenges and research directions.

The remainder of the paper is organised as follows. Section 2 reviews VANET evolution and requirements. Section 3 surveys the 6G enablers. Section 4 presents the reference architecture and comparative analysis. Section 5 discusses open challenges, and Section 6 concludes.

2 VANET Evolution and 6G-Era Requirements

2.1 From DSRC to NR-V2X

Table 1 summarises the generations of vehicular communication. DSRC offers decentralised, infrastructure-free operation but suffers from contention-based channel access that degrades in dense traffic [15]; simulation studies of V2V protocols confirm that routing and MAC performance vary strongly with node density and road conditions, particularly in emerging-economy traffic scenarios [25]. LTE-V2X improved range and reliability through semi-persistent scheduling on the PC5 interface, while NR-V2X introduced HARQ feedback on the sidelink, millimetre-wave (mmWave) support in FR2, and quality-of-service (QoS) differentiation [11]. However, mmWave beam alignment under high mobility, blockage by large vehicles, and limited edge processing still constrain NR-V2X for the most demanding applications.

Table 1: Evolution of vehicular communication technologies

Feature	DSRC (802.11p)	LTE-V2X	NR-V2X	6G V2X (target)
Spectrum	5.9 GHz	5.9 GHz	FR1 + FR2	sub-THz/THz, mmWave, FR1
Peak rate	27 Mbps	~100 Mbps	~1 Gbps	≥ 100 Gbps
Latency	~100 ms	20–100 ms	3–10 ms	<1 ms
Reliability	~90 %	~95 %	99.999 %	$1 - 10^{-7}$
Positioning	GNSS	GNSS	sub-metre	cm-level (ISAC)
Intelligence	none	none	limited	native AI
Coverage	roadside	cellular	cellular	3D (space– air–ground)

2.2 Key Requirements

From the use cases identified in [11, 22, 34], five requirement classes stand out:

- *Ultra-low latency and extreme reliability* for collision avoidance, cooperative manoeuvring, and remote driving.
- *Very high throughput* for raw sensor sharing, HD-map distribution, and in-vehicle extended-reality (XR) entertainment.
- *High-precision positioning and sensing* to complement on-board sensors and enable cooperative perception.
- *Ubiquitous coverage* on highways, rural roads, tunnels, and border regions where terrestrial deployments are sparse.
- *Security, privacy, and trust* in an open, highly dynamic network of heterogeneous and partially untrusted nodes [27].

Meeting these requirements jointly, rather than individually, is the central challenge that 6G seeks to address.

3 6G Enabling Technologies for VANETs

3.1 Terahertz and Sub-THz Communication

The 0.1–10 THz band offers contiguous bandwidths of tens of gigahertz, enabling data rates of hundreds of Gbps over short links [10, 30]. For VANETs, THz links are attractive for high-volume V2V and V2I exchanges such as bulk sensor-data offloading at roadside units (RSUs), platoon-internal backhaul, and in-cabin wireless networks.

The obstacles are severe. Free-space path loss and molecular absorption (notably water vapour) limit range to tens of metres, and THz links rely on pencil-beam antennas formed by large arrays. At vehicular speeds, beam coherence time shrinks to milliseconds, so beam training overhead can consume most of the link time. Blockage by trucks and buses causes abrupt link outages. Research directions therefore include sensing- or position-aided beam tracking, multi-connectivity with lower bands for fallback, and channel models that capture vehicular scattering at THz frequencies [22,30].

3.2 Reconfigurable Intelligent Surfaces

A reconfigurable intelligent surface (RIS) is a planar array of low-cost, nearly passive elements whose reflection phase can be controlled electronically, allowing the propagation environment itself to be shaped [4, 9, 38]. In urban VANETs, RISs mounted on building facades, overpasses, or road signs can create virtual line-of-sight paths around blockages, extend mmWave/THz coverage at intersections, and suppress interference.

Vehicular deployment raises specific issues. Accurate cascaded channel state information (CSI) for a large passive array is hard to acquire when the channel changes rapidly; this motivates beam-codebook and location-based configuration schemes that avoid full CSI estimation. Control latency for reconfiguring the surface must fall below the channel coherence time. Vehicle-mounted RIS and transmissive or simultaneously transmitting-and-reflecting (STAR) surfaces on windows have also been proposed to improve penetration into the cabin. Finally, RIS-aided links introduce new attack surfaces, because a malicious surface could steer energy to eavesdroppers.

3.3 Integrated Sensing and Communication

Integrated sensing and communication (ISAC) uses a shared waveform, spectrum, and hardware for both radar sensing and data transmission [8, 18, 37]. Vehicles and RSUs already carry radar at 77 GHz, and 6G mmWave/THz radios have bandwidths that yield fine range resolution, making vehicular networks a natural ISAC use case.

ISAC benefits VANETs in two directions. First, *sensing-assisted communication*: echoes of the downlink signal can estimate a vehicle's position and velocity, enabling predictive beamforming that sharply reduces beam-training overhead. Liu et al. showed that radar-assisted predictive beamforming at an RSU can track vehicles with markedly lower overhead than feedback-based schemes [19]. Second, *communication-assisted sensing*: vehicles can share radar or perception results to extend each other's field of view, supporting cooperative perception at intersections. Open problems include waveform design that balances sensing accuracy and communication rate, mutual interference among many vehicular ISAC transmitters, and the privacy implications of ubiquitous network-based sensing.

3.4 Native Artificial Intelligence

6G is expected to embed AI across the protocol stack, from the physical layer to network orchestration [16,34]. In VANETs, machine learning addresses problems that are difficult to model analytically because of mobility, non-stationary channels, and large state spaces. Representative applications include:

- **Resource allocation:** deep reinforcement learning (DRL) lets each V2V link select sub-bands and power levels in a decentralised manner while protecting V2I links [39]; similar RL formulations have been applied to dynamic bandwidth allocation [2], and AI-driven adaptive load balancing improves energy efficiency in heterogeneous networks [26].
- **Beam and handover prediction:** learning-based predictors using position, trajectory, and camera inputs reduce beam-search time and handover failures.
- **Federated learning (FL):** vehicles train shared models (e.g., for perception or traffic prediction) without uploading raw data, reducing bandwidth and privacy exposure [17,20].

Challenges include model generalisation across cities and weather conditions, the communication cost of FL rounds with intermittently connected vehicles, inference latency on vehicle hardware, and the need for explainable and verifiable decisions in safety-critical loops.

3.5 Edge Computing, Fog Computing, and Digital Twins

Mobile/multi-access edge computing (MEC) places compute and storage at base stations and RSUs, cutting the latency of offloaded tasks [21]. In 6G-enabled VANETs, edge servers support cooperative perception fusion, HD-map updates, and AI inference, while parked or slow-moving vehicles can form vehicular fog clouds that contribute idle resources. A core research problem is joint optimisation of task offloading, service migration, and caching under mobility, as vehicles move between edge servers faster than services can be relocated.

Digital twins (DTs), continuously synchronised virtual replicas of vehicles, roads, and network state, are emerging as a 6G-native tool for network planning and proactive control [35]. A vehicular DT at the edge can predict congestion, simulate the effect of resource allocation decisions before applying them, and support safety validation of automated driving functions. Combining DTs with blockchain further enables secure, real-time asset management [33]. Maintaining DT fidelity, however, requires high-rate, low-latency state updates, which themselves consume scarce radio resources.

3.6 Integrated Space–Air–Ground Networks

6G envisions a three-dimensional network that integrates terrestrial cells with non-terrestrial networks (NTNs): low-Earth-orbit (LEO) satellite constellations,

high-altitude platforms, and unmanned aerial vehicles (UAVs) [13, 40]. For VANETs this provides coverage continuity on highways, in rural and remote areas, and during disasters when terrestrial infrastructure fails. UAVs can act as flying RSUs that hover over congested intersections or accident sites to provide temporary capacity and line-of-sight links.

Key difficulties include large and time-varying propagation delays and Doppler shifts for LEO links, frequent satellite handovers combined with vehicle mobility, UAV energy limits and trajectory optimisation, and the orchestration of traffic across heterogeneous segments, where multi-criteria vertical handover [29] and optimised channel allocation [28] developed for terrestrial heterogeneous networks offer useful building blocks. NTN links are therefore better suited to delay-tolerant services (software updates, map downloads, telemetry) than to tight safety loops, unless combined with local edge processing.

3.7 Security, Privacy, and Trust

Openness and mobility expose VANETs to Sybil, spoofing, jamming, replay, and false-data-injection attacks, while location traces from V2X messages threaten driver privacy [27, 36]. Connected roadside and in-vehicle IoT devices add further vulnerabilities [5]. 6G introduces both new threats (e.g., attacks on AI models and on RIS control, and sensing-based tracking via ISAC) and new defences:

- **Physical-layer security** exploiting narrow THz/mmWave beams and RIS-assisted secrecy beamforming.
- **Blockchain and distributed ledgers** for decentralised trust management and secure data sharing, including combinations with FL [20].
- **AI-based intrusion and misbehaviour detection** at the edge, building on machine-learning cyber-threat detection frameworks [32].
- **Post-quantum cryptography** and quantum key distribution to protect long-lived vehicle credentials against future quantum adversaries [23, 24].

The central tension is the overhead of authentication, consensus, and cryptographic operations against stringent latency budgets; lightweight, latency-aware security remains an active area.

4 Reference Architecture and Comparison

4.1 Layered Architecture

Fig. 1 presents a reference architecture that combines the enablers above into four layers. The *infrastructure layer* comprises space, aerial, and terrestrial segments, including RISs and RSUs. The *access and sensing layer* provides multi-band connectivity (FR1, mmWave, THz) and ISAC functions. The *edge intelligence layer* hosts MEC, vehicular fog resources, digital twins, and distributed AI. The

application layer serves cooperative driving, remote driving, infotainment, and traffic management. Security, privacy, and trust functions span all layers, and an AI-native orchestration plane coordinates resources across them.

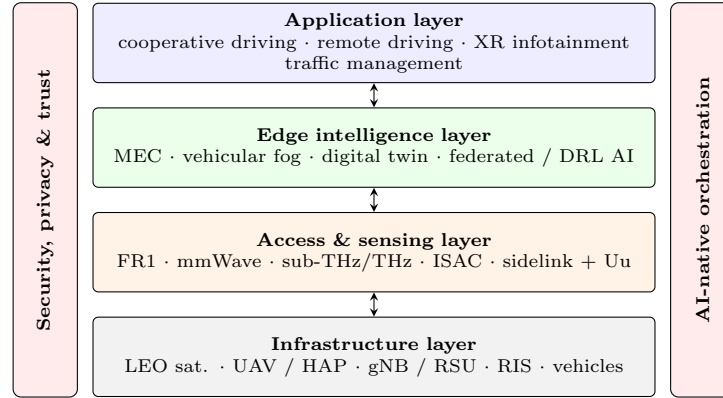


Fig. 1: Layered reference architecture for 6G-enabled VANETs

A typical end-to-end flow illustrates the interplay. An RSU with ISAC capability detects an approaching vehicle and predicts its trajectory; the orchestrator configures a nearby RIS and a THz beam toward the predicted position; the vehicle offloads raw sensor data to the edge, where a digital twin fuses it with data from other vehicles; the fused perception is returned via sidelink to neighbouring vehicles within a few milliseconds. When the vehicle leaves urban coverage, the session is handed to a LEO link for non-critical services, while safety messages continue over FR1 sidelink.

4.2 Comparative Analysis

Table 2 qualitatively compares the enablers against the requirement classes of Section 2 and lists their principal vehicular-specific limitations. No single technology satisfies all requirements; rather, the enablers are complementary. THz and RIS mainly address throughput and coverage in dense areas, ISAC addresses positioning and beam management, AI and edge computing address latency and adaptability, NTN addresses ubiquitous coverage, and security mechanisms address trust. ISAC and AI are notable for acting as *cross-cutting* enablers that mitigate the weaknesses of others, e.g., sensing-aided beam tracking for THz links and learned configuration for RIS.

5 Open Challenges and Research Directions

Mobility-aware THz and mmWave links. Robust beam management at vehicular speeds remains the gating issue for THz V2X. Promising directions combine ISAC-based tracking, map and trajectory priors, and multi-band cooperation in

Table 2: Qualitative comparison of 6G enablers for VANETs

Enabler	Lat.	Rate	Pos.	Cov.	Sec.	Main vehicular limitation
THz / sub-THz	●●	●●●	●●	●	●●	short range, blockage, beam tracking
RIS	●	●●	●●	●●●	●●	CSI acquisition, control latency
ISAC	●●	●●	●●●	●	●	waveform trade-off, interference
Native AI	●●●	●●	●●	●	●●	generalisation, explainability
MEC / DT	●●●	●	●	●	●	service migration, sync cost
SAGIN / NTN	●	●	●	●●●	●	delay, Doppler, handover
Security tech.	●	●	–	–	●●●	overhead vs. latency

Lat.: latency; Pos.: positioning; Cov.: coverage; Sec.: security. ● low, ●● medium, ●●● high contribution (author's assessment based on the surveyed literature).

which lower bands carry control signalling and act as fallback. Realistic vehicular THz channel measurements and models are still scarce.

Real-time, scalable RIS control. Configuring large RIS deployments for many fast-moving users requires low-overhead CSI acquisition, predictive configuration, and clarity on who owns and controls surfaces installed in public spaces. Energy-harvesting and self-configuring surfaces could reduce operational costs.

Trustworthy and efficient AI. Safety-critical vehicular functions require AI that is robust to distribution shift, resistant to adversarial and data-poisoning attacks, explainable, and certifiable. Communication-efficient FL that tolerates intermittent participation and heterogeneous vehicle hardware is another priority [17].

Joint communication–computing–sensing optimisation. 6G VANETs couple radio, compute, and sensing resources. Joint optimisation frameworks, preferably with low-complexity online solutions, are needed to allocate these resources under strict deadlines and mobility-induced uncertainty.

Seamless 3D mobility management. Handover across terrestrial cells, UAVs, and satellites [29], with service migration between edge servers, must be coordinated so that safety-critical sessions experience no interruption.

Lightweight security and privacy. Authentication and misbehaviour detection must operate within millisecond budgets. Privacy-preserving ISAC, pseudonym management resistant to sensing-based tracking, and migration to post-quantum schemes are open problems [23, 36].

Energy and sustainability. THz front-ends, dense RIS and RSU deployments, and AI workloads raise energy consumption. Energy-aware design, especially for electric vehicles where communication and computing draw on the traction battery, is an under-explored aspect; adaptive load balancing [26] and cellular–IoT integration strategies [1] offer starting points.

Standardisation and testbeds. IMT-2030 V2X specifications are at an early stage. Interoperability between NR-V2X and 6G sidelinks, spectrum allocation for vehicular THz, and large-scale testbeds or digital-twin-based validation platforms are needed to move from simulation to deployment [22, 35].

6 Conclusion

This paper surveyed the 6G technologies most relevant to VANETs. Terahertz communication and RIS promise multi-Gbps capacity and controllable propagation; ISAC unifies positioning, perception, and connectivity; native AI and edge computing with digital twins deliver adaptive, low-latency decision-making; integrated space-air-ground networks extend coverage; and new security paradigms address the expanding threat surface. Their benefits are largely complementary, and ISAC and AI act as cross-cutting enablers that compensate for the weaknesses of other technologies. Realising 6G-enabled VANETs will depend on solving mobility-aware beam management, real-time RIS control, trustworthy AI, joint resource optimisation, seamless 3D mobility, and lightweight security, alongside timely standardisation. We hope the architecture and comparative analysis presented here provide a useful starting point for research in this area.

References

1. Adhikari, M.S., Gupta, R., Raj, D., Sagar, A.K., Ather, D., Agrawal, A.K.: Enhancing energy efficiency in IoT via cellular network integration. In: Panwar, A., et al. (eds.) *Energy Efficient Internet of Things-Based Wireless Sensor Network*, pp. 91–133. Wiley (2026). <https://doi.org/10.1002/9781394314751.ch4>
2. Agarwal, A.K., Kaur, H., Rakesh, N., Krishna, K.R., Dewangan, B.K., Raj, D.: Dynamic bandwidth allocation in elastic optical networks using reinforcement learning. In: *Proc. OPTIMA 2025, Tashkent, Uzbekistan*. pp. 601–607. IEEE (2025). <https://doi.org/10.1109/OPTIMA67660.2025.11380328>
3. Al-Sultan, S., Al-Doori, M.M., Al-Bayatti, A.H., Zedan, H.: A comprehensive survey on vehicular ad hoc network. *Journal of Network and Computer Applications* **37**, 380–392 (2014). <https://doi.org/10.1016/j.jnca.2013.02.036>
4. Basar, E., et al.: Wireless communications through reconfigurable intelligent surfaces. *IEEE Access* **7**, 116753–116773 (2019). <https://doi.org/10.1109/ACCESS.2019.2935192>
5. Cambosuela, L., Raj, D., Astya, R., Sagar, A.K., Nand, P.: Exploring the vulnerabilities and risks in assessing Internet of Things (IoT) devices: A comprehensive analysis and proposed solutions. In: *Proc. NETCRYPT 2025, New Delhi, India*. pp. 240–246. IEEE (2025). <https://doi.org/10.1109/NETCRYPT65877.2025.11102527>
6. Chen, S., et al.: Vehicle-to-everything (V2X) services supported by LTE-based systems and 5G. *IEEE Communications Standards Magazine* **1**(2), 70–76 (2017). <https://doi.org/10.1109/MCOMSTD.2017.1700015>
7. Chowdhury, M.Z., Shahjalal, M., Ahmed, S., Jang, Y.M.: 6G wireless communication systems: Applications, requirements, technologies, challenges, and research

- directions. *IEEE Open Journal of the Communications Society* **1**, 957–975 (2020). <https://doi.org/10.1109/OJCOMS.2020.3010270>
8. Cui, Y., Liu, F., Jing, X., Mu, J.: Integrating sensing and communications for ubiquitous IoT: Applications, trends, and challenges. *IEEE Network* **35**(5), 158–167 (2021). <https://doi.org/10.1109/MNET.010.2100152>
9. Di Renzo, M., et al.: Smart radio environments empowered by reconfigurable intelligent surfaces: How it works, state of research, and the road ahead. *IEEE Journal on Selected Areas in Communications* **38**(11), 2450–2525 (2020). <https://doi.org/10.1109/JSAC.2020.3007211>
10. Elayan, H., Amin, O., Shihada, B., Shubair, R.M., Alouini, M.-S.: Terahertz band: The last piece of RF spectrum puzzle for communication systems. *IEEE Open Journal of the Communications Society* **1**, 1–32 (2020). <https://doi.org/10.1109/OJCOMS.2019.2953633>
11. Garcia, M.H.C., et al.: A tutorial on 5G NR V2X communications. *IEEE Communications Surveys & Tutorials* **23**(3), 1972–2026 (2021). <https://doi.org/10.1109/COMST.2021.3057017>
12. Giordani, M., Polese, M., Mezzavilla, M., Rangan, S., Zorzi, M.: Toward 6G networks: Use cases and technologies. *IEEE Communications Magazine* **58**(3), 55–61 (2020). <https://doi.org/10.1109/MCOM.001.1900411>
13. Giordani, M., Zorzi, M.: Non-terrestrial networks in the 6G era: Challenges and opportunities. *IEEE Network* **35**(2), 244–251 (2021). <https://doi.org/10.1109/MNET.011.2000493>
14. Hartenstein, H., Laberteaux, K.P.: A tutorial survey on vehicular ad hoc networks. *IEEE Communications Magazine* **46**(6), 164–171 (2008). <https://doi.org/10.1109/MCOM.2008.4539481>
15. Kenney, J.B.: Dedicated short-range communications (DSRC) standards in the United States. *Proceedings of the IEEE* **99**(7), 1162–1182 (2011). <https://doi.org/10.1109/JPROC.2011.2132790>
16. Letaief, K.B., Chen, W., Shi, Y., Zhang, J., Zhang, Y.-J.A.: The roadmap to 6G: AI empowered wireless networks. *IEEE Communications Magazine* **57**(8), 84–90 (2019). <https://doi.org/10.1109/MCOM.2019.1900271>
17. Lim, W.Y.B., et al.: Federated learning in mobile edge networks: A comprehensive survey. *IEEE Communications Surveys & Tutorials* **22**(3), 2031–2063 (2020). <https://doi.org/10.1109/COMST.2020.2986024>
18. Liu, F., et al.: Integrated sensing and communications: Toward dual-functional wireless networks for 6G and beyond. *IEEE Journal on Selected Areas in Communications* **40**(6), 1728–1767 (2022). <https://doi.org/10.1109/JSAC.2022.3156632>
19. Liu, F., Yuan, W., Masouros, C., Yuan, J.: Radar-assisted predictive beamforming for vehicular links: Communication served by sensing. *IEEE Transactions on Wireless Communications* **19**(11), 7704–7719 (2020). <https://doi.org/10.1109/TWC.2020.3015735>
20. Lu, Y., Huang, X., Zhang, K., Maharjan, S., Zhang, Y.: Blockchain empowered asynchronous federated learning for secure data sharing in Internet of Vehicles. *IEEE Transactions on Vehicular Technology* **69**(4), 4298–4311 (2020). <https://doi.org/10.1109/TVT.2020.2973651>
21. Mao, Y., You, C., Zhang, J., Huang, K., Letaief, K.B.: A survey on mobile edge computing: The communication perspective. *IEEE Communications Surveys & Tutorials* **19**(4), 2322–2358 (2017). <https://doi.org/10.1109/COMST.2017.2745201>
22. Noor-A-Rahim, M., et al.: 6G for vehicle-to-everything (V2X) communications:

- Enabling technologies, challenges, and opportunities. Proceedings of the IEEE **110**(6), 712–734 (2022). <https://doi.org/10.1109/JPROC.2022.3173031>
23. Quraishi, S.J., Raj, D., Ather, D., Gupta, A.K., Setia, S., Pathak, S.: A comparative analysis of post-quantum cryptographic schemes over discrete algebraic structures for enhanced information security in large-scale networks. Journal of Discrete Mathematical Sciences and Cryptography **29**(9-A), 3435–3451 (2026). <https://doi.org/10.47974/JDMSC-2860>
24. Rai, S., Upadhyay, A.K., Sharma, D., Raj, D., Gupta, A.K., Ather, D.: Quantum cryptography—A modern approach. Journal of Discrete Mathematical Sciences and Cryptography **26**(7), 1991–2006 (2023). <https://doi.org/10.47974/JDMSC-1839>
25. Raj, D., Ather, D., Sagar, A.K.: Advancing vehicular ad-hoc network solutions in emerging economies: A comparative analysis of V2V protocols through simulation studies. SN Computer Science **5**, 1077 (2024). <https://doi.org/10.1007/s42979-024-03411-1>
26. Raj, D., Ather, D., Sagar, A.K.: Integrative strategies for enhancing energy efficiency in AI-driven heterogeneous networks using adaptive load balancing. In: Data Mining and Information Security (ICDMIS 2024). LNNS, vol. 1385, pp. 149–162. Springer, Singapore (2026). https://doi.org/10.1007/978-981-96-6046-9_10
27. Raj, D., Sagar, A.K.: Vehicular ad-hoc networks: A review on applications and security. In: Communications in Computer and Information Science, vol. 1921, pp. 241–255. Springer, Cham (2023). https://doi.org/10.1007/978-3-031-45124-9_19
28. Raj, D., Sagar, A.K., Ather, D.: Optimized channel allocation algorithm for performance enhancement in heterogeneous networks. MATRIX Academic International Online Journal of Engineering and Technology **8**(1), 1–12 (2025). <https://www.maijet.com/index.php/matrix/article/view/74>
29. Raj, D., Sagar, A.K., Ather, D.: Optimizing vertical handover using multi-criteria decision making in heterogeneous networks. Journal of Information Technology Management **17**(Special Issue), 63–86 (2025). <https://doi.org/10.22059/jitm.2025.102922>
30. Rappaport, T.S., et al.: Wireless communications and applications above 100 GHz: Opportunities and challenges for 6G and beyond. IEEE Access **7**, 78729–78757 (2019). <https://doi.org/10.1109/ACCESS.2019.2921522>
31. Saad, W., Bennis, M., Chen, M.: A vision of 6G wireless systems: Applications, trends, technologies, and open research problems. IEEE Network **34**(3), 134–142 (2020). <https://doi.org/10.1109/MNET.001.1900287>
32. Shukla, R.S., Ather, D., Raj, D., Jain, A., Sarkar, T., Rakhra, M.: A secure and intelligent framework for cyber threat detection using machine learning. Journal of Discrete Mathematical Sciences and Cryptography **29**(6), 2441–2457 (2026). <https://doi.org/10.47974/JDMSC-2752>
33. Singh, M.K., Pal, K., Reddy, L.C., Verma, A.S., Raj, D.: Secure and efficient integration of blockchain, digital twins, and metaverse for real-time asset management. In: Proc. 3rd ICDT 2025, Greater Noida, India. pp. 25–29. IEEE (2025). <https://doi.org/10.1109/ICDT63985.2025.10986435>
34. Tang, F., Kawamoto, Y., Kato, N., Liu, J.: Future intelligent and secure vehicular network toward 6G: Machine-learning approaches. Proceedings of the IEEE **108**(2), 292–307 (2020). <https://doi.org/10.1109/JPROC.2019.2954595>
35. Wang, C.-X., et al.: On the road to 6G: Visions, requirements, key technologies, and testbeds. IEEE Communications Surveys & Tutorials **25**(2), 905–974 (2023).

- <https://doi.org/10.1109/COMST.2023.3249835>
36. Wang, M., Zhu, T., Zhang, T., Zhang, J., Yu, S., Zhou, W.: Security and privacy in 6G networks: New areas and new challenges. *Digital Communications and Networks* **6**(3), 281–291 (2020). <https://doi.org/10.1016/j.dcan.2020.07.003>
 37. Wei, Z., et al.: Integrated sensing and communication signals toward 5G-A and 6G: A survey. *IEEE Internet of Things Journal* **10**(13), 11068–11092 (2023). <https://doi.org/10.1109/JIOT.2023.3235618>
 38. Wu, Q., Zhang, R.: Towards smart and reconfigurable environment: Intelligent reflecting surface aided wireless network. *IEEE Communications Magazine* **58**(1), 106–112 (2020). <https://doi.org/10.1109/MCOM.001.1900107>
 39. Ye, H., Li, G.Y., Juang, B.-H.F.: Deep reinforcement learning based resource allocation for V2V communications. *IEEE Transactions on Vehicular Technology* **68**(4), 3163–3173 (2019). <https://doi.org/10.1109/TVT.2019.2897134>
 40. Zeng, Y., Zhang, R., Lim, T.J.: Wireless communications with unmanned aerial vehicles: Opportunities and challenges. *IEEE Communications Magazine* **54**(5), 36–42 (2016). <https://doi.org/10.1109/MCOM.2016.7470933>