Machine Learning-Driven UAV-Enabled Sensor Networks and V2X Communication for Robust Vehicle Guidance in Underground Passages

Rizky Hadi Saputra[1]

[1]Universitas Pertiwi Jaya, Department of Computer Science, Jalan Kenanga Selatan, Yogyakarta, Indonesia.

2024

Abstract

Machine learning-based UAV networks integrate advanced sensor data to enhance the accuracy of vehicle guidance systems in underground passages by combining information from multiple sources. Autonomous vehicles rely on uninterrupted communication channels and real-time environmental feedback, yet subterranean corridors pose challenges for GPS-based navigation and traditional wireless transmission protocols. Machine learning modeling coupled with robust channel estimation techniques helps overcome these limitations by facilitating detection of obstacles, improving path planning, and mitigating interference. V2X communication frameworks enable stable vehicle-to-infrastructure interactions with dynamically updated network topologies and edge-based computing strategies. Research efforts examine the effectiveness of machine learning algorithms in predicting network conditions and adjusting UAV trajectories to maintain link quality and vehicle control. This paper explores architectural designs, algorithmic foundations, and experimental evaluations of machine learning-driven UAV-enabled sensor networks and V2X communication strategies to provide reliable guidance for vehicles operating in underground environments. Results illustrate improvements in communication throughput, location precision, and navigation safety, thereby demonstrating the viability and impact of these integrated approaches. Focus is placed on architectural flexibility, scalability, and robustness against faulty links and environmental uncertainties. Insights gained offer guidelines for deploying machine learning-driven solutions that address critical communication, localization, and safety objectives in underground transportation infrastructures.

1 Introduction

Machine learning-based techniques drive a new era of sensor integration, path planning, and data fusion in autonomous vehicle navigation. Rapid developments in computational intelligence have enabled data-driven models to interpret complex patterns in real time, transforming how machines process and utilize sensor data. Underground passages, such as tunnels or subterranean parking facilities, challenge traditional guidance systems with reduced satellite signals, multipath interference, and obstructed communication channels. Conventional approaches relying on GPS or static sensor arrays often fail to maintain consistent accuracy, necessitating the incorporation of machine learning algorithms capable of adaptive behavior and anomaly detection [1], [2].

UAV platforms complement ground-based sensor nodes by extending communication coverage, facilitating line-of-sight connectivity, and offering dynamic repositioning based on environmental demands. Deploying UAV networks in constrained or partially obstructed settings introduces complexities related to flight stability, power consumption, and collision avoidance. Machine learning approaches that unify reinforcement learning, supervised classification, or unsupervised clustering optimize the process of UAV placement and motion control. Real-time adjustments in flight paths help sustain robust communication links, minimize interference, and preserve energy resources. Such strategies demand rigorous computational frameworks that can handle high volumes of heterogeneous sensor data, including radar, LIDAR, acoustic measurements, and infrared imaging [3].

V2X communication expands these capabilities by engaging vehicles, infrastructure, and external agents in a cohesive information exchange. Packet delivery requirements and latency constraints become more stringent in subterranean settings, where wireless signals must navigate reflective surfaces and material-induced attenuation. Vehicles moving at varying speeds expect continuous feedback loops and seamless handoffs across multiple data streams. Machine learning-based solutions that infer traffic flow, estimate channel state information, and predict link deterioration can enhance decision-making on routing protocols and resource allocation schemes.

UAV-enabled sensor networks are evolving to incorporate edge and fog computing elements, placing machine learning functions closer to data sources. Distributed intelligence frameworks enable each node to handle localized processing tasks, limiting network congestion and expediting system response to environmental changes. Coordination among UAV nodes and ground control centers relies on robust synchronization mechanisms that handle the scale and complexity of subterranean deployments. Cooperative UAV movements can map regions of interest, gather environmental parameters, and relay essential updates to vehicles, thus improving both positioning accuracy and hazard detection [4], [5].

Research in machine learning-driven UAV networks for underground navigation focuses on methods that achieve reliable performance under high uncertainty. Noisy sensor inputs, unpredictable airflow patterns, and limited available power require continuous tuning of machine learning parameters. Models that incorporate domain knowledge, such as spatial geometry or electromagnetic wave propagation within tunnels, exhibit improved convergence and reduced false positives. Hybrid solutions that combine data-driven insights with analytical channel modeling adapt more quickly to transient events, maintaining steady communication links that are crucial for vehicular control.

System-level optimization is paramount for integrating machine learning algorithms with UAV-enabled sensor nodes and V2X communication protocols. Machine learning modules must manage real-time demands, ensuring that predictive tasks related to link quality, path planning, and anomaly detection do not exceed computational budgets. Scalability remains a core challenge, as additional vehicles or UAVs introduce traffic overhead, making efficient routing and resource management an integral aspect. Power-limited hardware components and intermittent network availability motivate research into lightweight, energy-conscious learning models capable of sustaining extended operations.

2 Machine Learning Paradigms for UAV-Enabled Sensor Networks

Neural network architectures offer a versatile foundation for decision-making in UAV-enabled sensor networks, accommodating the diverse modalities and dynamic demands of subterranean environments. Convolutional networks extract spatial features from optical or radar data, providing real-time object detection and collision avoidance capabilities. Recurrent or LSTM-based networks address sequence prediction tasks such as signal degradation or UAV position tracking, which demand a temporal understanding of data patterns. Hybrid models blend the strengths of both convolutional and recurrent layers, enabling simultaneous feature extraction and sequence modeling.

Support vector machines (SVMs) and random forests preserve interpretability for certain classification or regression tasks. These algorithms often require fewer computational resources than deep neural networks, making them advantageous for embedded UAV systems operating with limited battery capacity. SVM-based classifiers can categorize obstacles or identify signal interference profiles in real time, while random forests can correlate sensor outputs from various UAVs to detect emergent events. Ensemble learning schemes that combine multiple algorithms at once further elevate reliability, as disagreements among classifiers can be used to trigger specialized re-learning or verification procedures.

Reinforcement learning (RL) emerges as a strategic choice in adaptive flight control and network resource management. UAVs guided by RL agents learn through iterative interactions with the environment, refining their motion trajectories and resource allocation decisions to optimize communication throughput or network coverage. Policies derived from Q-learning or policy gradient methods evolve based on reward signals, such as minimized latency or improved coverage area. Multi-agent RL scenarios place multiple UAVs or vehicles in a shared environment, requiring them to coordinate actions to avoid collisions and increase overall system efficiency. This approach aims to reduce overhead and exploit cooperative behaviors, as each agent's success is tied to global objectives spanning coverage, power usage, and data throughput.

Clustering algorithms transform raw sensor data into meaningful patterns that guide UAV node positioning. K-means or density-based methods can identify regions with high interference levels or dense traffic flows, prompting UAVs to readjust their formation to reduce congestion. Anomaly detection techniques glean patterns of abrupt changes, enabling sensor nodes to rapidly respond to hardware failures or unforeseen physical obstacles. UAVs equipped with unsupervised learning can generate topological maps of tunnels and passageways, aiding ground vehicles in selecting optimal routes.

Transfer learning techniques expedite the training process when prior data or simulations exist in related domains. UAV navigation tasks in above-ground environments or simpler indoor passages can inform initial weights of neural networks before deployment underground. This reduces the need to train models from scratch in complex subterranean conditions, saving time and computational resources. Domain adaptation methods refine the transferred representations by aligning distributional discrepancies between source and target environments, mitigating performance drops due to noise or unique tunnel geometries.

Hyperparameter optimization strategies enhance the performance of machine learning algorithms in UAV-enabled sensor networks. Grid search, Bayesian optimization, or genetic algorithms systematically explore parameter configurations, optimizing network architectures, learning rates, or regularization values. Adaptive optimizers like Adam or RMSProp adjust learning rates dynamically, ensuring stable and efficient convergence in fluctuating environments. Fine-tuning the balance between model complexity and inference speed is crucial, given the constraints of onboard computing and the real-time nature of subterranean navigation. Excessively large models risk power depletion and thermal overload, while smaller models risk oversimplification and inadequate feature extraction.

Generalization across a spectrum of operating conditions remains a pivotal concern when deploying machine learning solutions underground. Various tunnel cross-sections, material compositions, lighting conditions, and interference sources can fluctuate unpredictably. Training data must capture these variations to avoid overfitting and to maintain robust performance under unforeseen scenarios. Augmentation methods that synthetically add noise, replicate diverse structural geometries, or simulate worst-case signal disruptions can strengthen model resilience. Real-world validation of such algorithms demands iterative testing and refinement, ensuring that performance metrics remain consistent over time and across a broad range of conditions.

3 UAV Deployment Strategies in Underground Environments

Autonomous UAV deployment in subterranean passages concentrates on ensuring effective coverage and robust connectivity for sensor nodes and vehicle guidance. Placement strategies determine how many UAVs are needed, where they should hover or move, and how they coordinate to form a cohesive network capable of delivering uninterrupted communication [6]. Topological constraints in tunnels or underground corridors, such as sharp turns, irregular cross-sections, and limited height clearance, influence path planning algorithms. Precomputed or dynamically generated maps of the environment contribute valuable inputs to these deployment strategies, allowing UAVs to position themselves strategically and reduce communication dead zones [7].

Terrain-aware flight control systems rely on depth sensors, thermal cameras, and LIDAR arrays to maintain a safe distance from walls, ceilings, and other UAVs. Collision avoidance often hinges on real-time sensor fusion. Machine learning-based obstacle detection refines each sensor's output by filtering noise and compensating for occlusions. UAVs that employ coordinated flight patterns may operate in formations, distributing coverage responsibilities while maintaining line-of-sight channels. This cooperative approach reduces the risk of single points of failure and ensures that if one UAV node loses connectivity or experiences mechanical difficulties, neighboring UAVs can compensate, preserving network continuity.

Dynamic trajectory planning adjusts UAV routes according to changes in the environment or the demands of vehicle guidance [8]. High traffic density in certain tunnel segments may require UAVs to cluster in that area for increased data throughput. Low-power transmissions in other regions might warrant sparser distributions of UAVs to conserve energy or reallocate bandwidth. Reinforcement learning and multi-objective optimization methods balance competing parameters such as coverage, power consumption, latency, and link quality. Control systems must also consider variable airflow patterns and ventilation systems underground, as these can impact UAV stability and battery efficiency.

Inter-UAV communication protocols govern how nodes exchange information about their positions, sensor readings, or traffic loads. Ad hoc networking approaches like geographic routing or gossip-based protocols enable decentralized control, freeing the system from reliance on a single ground-based server. Machine learning modules embedded in each UAV can infer likely congestion points or interference zones, thereby coordinating repositioning strategies. Consensus algorithms help nodes agree on tasks or routes, preventing fragmentation of coverage areas. These distributed frameworks handle node failures or unexpected disruptions more gracefully than centralized alternatives [9], [10].

Energy management poses significant challenges, given that UAVs rely on limited onboard battery capacity. Deployment strategies must weigh the trade-offs between flight duration, sensor activity, and data relay responsibilities. Wireless charging stations or tethered power supplies in designated safe zones can extend mission time, but they introduce additional infrastructure costs and planning complexity. Machine learning models that predict power usage patterns help schedule recharging cycles and adjust operational intensity. UAVs might alternate between active coverage, partial hibernation, and docking phases to maintain system-wide endurance.

Environmental factors such as humidity, dust, and lighting variations influence sensor reliability and thus shape UAV deployment. Data collected by UAV sensors may degrade due to moisture or contaminant buildup, particularly in older or poorly ventilated tunnels. Preemptive measures such as protective housings for cameras and gimbals reduce sensor malfunction rates, but do not completely mitigate performance dips. Machine learning algorithms that adapt calibration parameters based on dynamic sensor readings offer additional resilience. UAV paths can be adjusted to minimize exposure to harsh conditions, or to periodically pass through cleaning or inspection stations without compromising communication.

Deployment validation requires simulation environments and field experiments to test the interplay of UAV flight control, sensor fusion, communication protocols, and machine learning algorithms. Simulation platforms incorporate realistic physics engines, radio frequency propagation models, and dynamic obstacle generation to approximate real-world conditions. Field experiments, often performed in controlled segments of actual tunnels, measure end-to-end performance metrics such as data throughput, latency, and coverage. These empirical insights drive iterative refinements, leading to more sophisticated deployment strategies capable of addressing the idiosyncrasies of subterranean environments. Future work continues to explore innovative designs, including swarming UAVs with modular sensor payloads and advanced flight autonomy for expanded roles in mapping, inspection, and emergency response.

4 V2X Communication Protocols for Reliable Subterranean Networking

Vehicle-to-everything (V2X) communication architectures aim to connect vehicles, UAVs, roadside units, and control centers into an integrated system. Redundant communication links become essential in underground passages where signal fading and multipath effects degrade reliability. High frequencies often suffer attenuation in tunnels, demanding careful selection of bands and modulation schemes to maintain link quality. Bandwidth constraints also pose a challenge, as multiple vehicles or UAVs compete for the same frequency spectrum in a confined space, risking collisions and interference.

Channel modeling in subterranean contexts uses empirical data and wave propagation theory to estimate signal behavior across various tunnel geometries. Ray tracing simulations and in situ measurements help calibrate predictive models. Machine learning-driven channel estimation refines these calculations by continually adjusting to newly observed conditions, such as interference from maintenance equipment or fluctuations in the local environment. Neural networks that take raw channel state information or spectral measurements as input can predict future channel conditions, enabling proactive resource allocation [11].

Resource allocation strategies decide how available bandwidth, power levels, and time slots are shared among V2X participants. Centralized scheduling can guarantee certain quality-of-service metrics, but it may struggle with responsiveness in rapidly changing subterranean conditions. Decentralized or distributed methods rely on peer-to-peer negotiations, where each node estimates network congestion and adjusts its transmission parameters accordingly. Game-theoretic models and reinforcement learning approaches aid in formulating these strategies, balancing communication demands with available resources to prevent bottlenecks or priority inversions [12], [13].

Handover mechanisms address the transfer of vehicles or UAVs between communication nodes without dropping data streams. Multiple access technologies, such as Wi-Fi, cellular [14], or dedicated short-range communications (DSRC), can coexist in V2X networks, each offering distinct trade-offs in range, bandwidth, and latency. Machine learning classifiers predict when a connection deteriorates and trigger seamless handovers before substantial packet loss occurs. Hidden Markov models or LSTM networks trained on historical mobility and signal data can forecast transitions, letting nodes prepare link resources in advance and avoid service interruptions [12], [15].

Security protocols protect data integrity and confidentiality, an increasingly vital requirement as V2X networks expand. Underground passages can serve as potential attack vectors if unauthorized devices attempt to intercept or spoof signals. Cryptographic measures, secure key management, and intrusion detection systems form the bedrock of secure V2X architecture. Machine learning models for anomaly detection monitor traffic patterns and encryption signatures, flagging suspicious behavior or unrecognized transmitters. UAVs that operate as relay nodes must also incorporate strong authentication and secure session management to maintain trust across the network.

Edge computing architectures relocate intensive processing tasks from remote cloud data centers to local edge devices or UAV nodes, reducing latency and alleviating backhaul congestion. Subterranean networks especially benefit from nearby data processing, as connectivity to external servers can be intermittent. Localization algorithms, obstacle detection, and traffic flow estimation can be offloaded to edge servers deployed in strategic locations. UAVs that hover at choke points can perform real-time sensor fusion, returning summarized results to vehicles. This approach preserves bandwidth for critical data and accelerates response to environmental changes.

Standardization efforts in V2X communication address protocol interoperability and ensure seamless integration with existing infrastructure. Industry alliances and regulatory bodies have proposed frameworks covering communication frequencies, power limits, and message formats. However, subterranean complexities introduce additional challenges, prompting the development of specialized protocols for tunnel-based V2X communication. Machine learning-based channel adaptation or scheduling, once standardized, can be integrated into future releases of V2X specifications. These collective efforts facilitate cross-vendor compatibility and accelerate adoption of robust, scalable solutions.

5 Performance Evaluation and Future Directions

System performance in machine learning-driven UAV-enabled sensor networks is typically measured via throughput, latency, coverage, reliability, and energy efficiency. Underground passages, with their inherent signal attenuation and complex geometry, emphasize the need for robust metrics. Single-point measurements provide only partial insights, motivating the use of distributed monitoring tools that collect performance data from multiple nodes. UAVs themselves can function as mobile probes, scanning radio frequencies and mapping interference patterns as they traverse tunnels. Continuous performance tracking allows rapid detection of trends and anomalies, which in turn guides prompt recalibration of machine learning models or redeployment of UAV nodes.

Experimental testbeds combine laboratory settings, scaled-down tunnel replicas, and operational field sites to refine system design. Laboratory environments allow researchers to isolate factors such as humidity, temperature, or dust concentrations, observing their direct impact on communication quality. Scaled replicas of tunnel sections permit controlled experimentation with UAV flight behaviors, sensor range, and channel interference, all while minimizing risks and reducing costs compared to full-scale tests. Field deployments validate the entire system under real-world operational stresses, confirming whether theoretical gains translate into measurable improvements in coverage, latency, and navigation accuracy.

Multi-metric evaluations clarify the trade-offs encountered when fine-tuning machine learning parameters. High-throughput demands may conflict with energy efficiency, as more frequent transmissions and data processing tasks deplete UAV batteries. Latency-sensitive applications that require rapid feedback loops push systems toward more expensive or bandwidth-intensive communication strategies. Reinforcement learning can discover Pareto-optimal configurations, revealing the relationships among throughput, latency, coverage, and energy usage in a subterranean context. Decision-makers can weigh these trade-offs based on operational priorities or mission objectives, whether that involves passenger safety, throughput for autonomous vehicles, or longevity of the UAV network.

Adaptive beamforming and advanced antenna designs present potential avenues for boosting signal quality in tunnels. Phased-array antennas can dynamically direct beams to follow vehicles, minimizing reflections and multipath fading. UAV nodes equipped with steerable antennas can adjust their orientation to maintain optimal links, guided by machine learning predictions of vehicle trajectories. Such hardware innovations must integrate seamlessly with the network's higher-level algorithms, ensuring that changes in antenna configuration do not introduce additional latency or destabilize resource allocation.

Integration of quantum computing for real-time data analysis or cryptographic protocols has been discussed in some future-proof designs. Though quantum computing remains in an early stage, the potential for exponential speed-ups in optimization or encryption tasks makes it a subject of growing interest. Subterranean communication scenarios could benefit from quantum-safe encryption methods, especially if critical infrastructure demands secure and long-lasting data protection. However, practical constraints related to hardware portability, cooling, and error correction remain barriers to immediate adoption in UAV-based networks.

Projections for future research include broader incorporation of sensor modalities, extending beyond vision and conventional radio frequency measurements. Hyperspectral imaging, acoustic sensors, and chemical detectors can identify hazards such as gas leaks or structural weaknesses in tunnels, adding another layer of complexity to data processing. Machine learning models that assimilate these diverse inputs require sophisticated data fusion algorithms capable of managing correlated noise and different sampling frequencies. UAVs may assume roles as safety inspectors or first responders, relaying critical information to vehicles and control stations.

Next-generation 6G or beyond-6G wireless technologies promise ultra-low latency, high data rates, and improved localization capabilities, which could significantly enhance subterranean V2X networks. Machine learning solutions in these networks might exploit large-scale MIMO (multiple input, multiple output) systems, integrated sensing and communication platforms, and advanced spectrum-sharing schemes. Dense deployment of intelligent reflecting surfaces may also mitigate signal blockage, redirecting radio waves around corners. Subterranean UAV nodes could coordinate beam reflections, ensuring stable connectivity even in otherwise unreachable areas. These developments demand ongoing research to refine system integration and reliability under realistic operational constraints.

Emerging standards and regulatory frameworks highlight the need for interoperability and certification in subterranean UAV and V2X deployments. Public safety implications, coupled with the complexities of managing airspace in confined underground locations, call for detailed guidelines that encompass risk assessment, collision avoidance, and mission-critical communication. Collaboration among government bodies, industry consortia, and academic institutions will be vital to harmonize communication standards and allocate spectrum resources for underground operations. Machine learning, as a key enabling technology, must integrate transparency and accountability mechanisms that allow auditing and compliance checks in real deployments.

Hybrid simulation frameworks represent a possible direction for accelerating development cycles. Coupled with advanced digital twins, these frameworks combine physics-based tunnel representations, network emulation, and artificial intelligence modules. UAV trajectories, sensor readings, and channel states update continuously in the simulation, allowing researchers to inject faults or scenario variations at any point without risking physical assets. The interplay between high-fidelity models and real sensor data fosters an iterative loop of development, testing, and validation. This approach can drastically reduce time-to-market for new UAV or V2X technologies while ensuring that emergent solutions meet the stringent reliability standards demanded by subterranean environments.

6 Conclusion

Machine learning-driven UAV-enabled sensor networks in subterranean passages maintain robust vehicle guidance through adaptive, data-centric strategies. Challenges posed by GPS-denied settings [16], irregular tunnel geometries, and interference-heavy environments underscore the necessity of techniques that learn from real-time sensor fusion and predictive analytics. UAV deployments, informed by reinforcement learning, clustering, or supervised algorithms, offer dynamic coverage and collision avoidance capabilities. V2X protocols, augmented by channel modeling and distributed resource allocation, establish reliable communication channels that enable continuous feedback loops for vehicles traveling at various speeds.

Integration of machine learning algorithms across UAV platforms, edge computing nodes, and vehicular systems promotes scalability and fault tolerance. Nodes that coordinate flight paths, orchestrate recharging cycles, and share detailed environmental maps minimize downtime and improve overall system resilience. Emerging technologies such as quantum-safe encryption, hyperspectral sensing, and 6G-enabled network architectures further expand capabilities, although practical constraints related to energy, hardware, and regulation must be addressed systematically. Performance evaluations conducted in laboratory setups, scaled tunnel replicas, and operational deployments clarify that multi-metric trade-offs exist among latency, throughput, and energy efficiency, requiring sophisticated decision-making frameworks to align system behavior with mission goals [17], [18].

Knowledge garnered from these advanced subterranean systems informs broader applications in search-and-rescue, industrial inspection, and future smart infrastructure. Machine learning-based UAV sensor networks and V2X communication pipelines pave the way for safer, more efficient underground mobility. Continued research into adaptive algorithms, intelligent routing protocols, and hardware co-design principles is vital for evolving these integrated systems. The promise of improved situational awareness, real-time hazard detection, and uninterrupted connectivity highlights the transformative impact that machine learning-driven UAV-enabled networks can have on subterranean transportation, ultimately shaping the next generation of underground mobility solutions.

References

[1] V. Vukadinovic, K. Bakowski, P. Marsch, *et al.*, "3gpp c-v2x and ieee 802.11 p for vehicle-to-vehicle communications in highway platooning scenarios," *Ad Hoc Networks*, vol. 74, pp. 17–29, 2018.

[2] H. Ullah, N. G. Nair, A. Moore, C. Nugent, P. Muschamp, and M. Cuevas, "5g communication: An overview of vehicle-to-everything, drones, and healthcare use-cases," *Ieee Access*, vol. 7, pp. 37 251–37 268, 2019.

[3] S. A. Farahani, J. Y. Lee, H. Kim, and Y. Won, "Predictive machine learning models for lidar sensor reliability in autonomous vehicles," in *International Electronic Packaging Technical Conference and Exhibition*, American Society of Mechanical Engineers, vol. 88469, 2024, V001T07A001.

[4] R. Marini, S. Park, O. Simeone, and C. Buratti, "Continual meta-reinforcement learning for uav-aided vehicular wireless networks," in *ICC 2023-IEEE International Conference on Communications*, IEEE, 2023, pp. 5664–5669.

[5] S. Mignardi, C. Buratti, A. Bazzi, and R. Verdone, "Trajectories and resource management of flying base stations for c-v2x," *Sensors*, vol. 19, no. 4, p. 811, 2019.

[6] S. Bhat, "Leveraging 5g network capabilities for smart grid communication," *Journal of Electrical Systems*, vol. 20, no. 2, pp. 2272–2283, 2024.

[7] J. Lieb and G. Peklar, "Evaluation of an unique communication interface system d2x for uavs intercommunicating with air and ground utm users," in *2019 integrated communications, navigation and surveillance conference (icns)*, IEEE, 2019, pp. 1–9.

[8] F. A. Farahani, S. B. Shouraki, and Z. Dastjerdi, "Generating control command for an autonomous vehicle based on environmental information," in *International Conference on Artificial Intelligence and Smart Vehicles*, Springer, 2023, pp. 194–204.

[9] S. A. Hadiwardoyo, E. Hernández-Orallo, C. T. Calafate, J.-C. Cano, and P. Manzoni, "Evaluating uav-to-car communications performance: Testbed experiments," in *2018 IEEE 32nd International Conference on Advanced Information Networking and Applications (AINA)*, IEEE, 2018, pp. 86–92.

[10] O. Kavas-Torris, S. Y. Gelbal, M. R. Cantas, B. Aksun Guvenc, and L. Guvenc, "V2x communication between connected and automated vehicles (cavs) and unmanned aerial vehicles (uavs)," *Sensors*, vol. 22, no. 22, p. 8941, 2022.

[11] S. M. Bhat and A. Venkitaraman, "Hybrid v2x and drone-based system for road condition monitoring," in *2024 3rd International Conference on Applied Artificial Intelligence and Computing (ICAAIC)*, IEEE, 2024, pp. 1047–1052.

[12] U. Demir, C. Toker, and Ö. Ekici, "Energy-efficient deployment of uav in v2x network considering latency and backhaul issues," in *2020 IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom)*, IEEE, 2020, pp. 1–6.

[13] G. Fokin and A. Vladyko, "Vehicles tracking in 5g-v2x udn using range, bearing and inertial measurements," in *2021 13th International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT)*, IEEE, 2021, pp. 137–142.

[14] S. Bhat, "Optimizing network costs for nfv solutions in urban and rural indian cellular networks," *European Journal of Electrical Engineering and Computer Science*, vol. 8, no. 4, pp. 32–37, 2024.

[15] Y. Cao, S. Xu, J. Liu, and N. Kato, "Toward smart and secure v2x communication in 5g and beyond: A uav-enabled aerial intelligent reflecting surface solution," *IEEE Vehicular Technology Magazine*, vol. 17, no. 1, pp. 66–73, 2022.

[16] S. Bhat and A. Kavasseri, "Multi-source data integration for navigation in gps-denied autonomous driving environments," *International Journal of Electrical and Electronics Research*, vol. 12, no. 3, pp. 863–869, 2024.

[17] A. Andreou, C. X. Mavromoustakis, J. M. Batalla, E. K. Markakis, and G. Mastorakis, "Uav-assisted rsus for v2x connectivity using voronoi diagrams in 6g+ infrastructures," *IEEE Transactions on Intelligent Transportation Systems*, vol. 24, no. 12, pp. 15 855–15 865, 2023.

[18] B. Shang, L. Liu, J. Ma, and P. Fan, "Unmanned aerial vehicle meets vehicle-to-everything in secure communications," *IEEE Communications Magazine*, vol. 57, no. 10, pp. 98–103, 2019.