Enhancing Vehicle-to-Everything (V2X) Communication with AI

By Dr. Li Wang

Professor of Electrical Engineering, Beijing Jiaotong University, China

1. Introduction to V2X Communication and AI in Smart Transportation Networks

Both research and industrial communities envision a future where vehicles become "active actors" in the transportation system rather than mere "cargo units." Vehicle-to-Everything (V2X) communications are fundamental to ensure such advanced services, which are built on top of vehicles' abilities to transmit and receive information. This new strand of vehicular communication, where every tangible and intangible entity can interact with vehicles, is referred to by the community as V2X (Vehicle-to-Everything). With V2X communications, vehicles can share any possible type of information they might have: measurements, intentions, requests, identifications, etc., with any possible entity, ranging from roadside units to nearby infrastructure, other vehicles, as well as authorities' servers. The V2X communication system is usually imagined from a network engineering standpoint concerning wave-based communications, multi-access edge technology communications, contextual data exchanges, and software services.

Despite the promising future of advanced V2X applications, the current operational framework of V2X communication creates several challenges. With the increasing development of artificial intelligence (AI) and machine learning in recent years, there is a strong interest in exploring how these technologies can facilitate V2X communication functions. The priority of prior work has been future V2X systems that are fully AI-driven. Although today this scenario might seem utopian, the goal is to present an AI-enhanced V2X system that could be deployed tomorrow. In the following, the influences and use cases of AI have been provided along with the difficulties, challenges, and possible solutions to integrate AI technologies into an already complex V2X stack.

2. Challenges in Current V2X Communication Systems

Vehicle-to-Everything (V2X) communication systems are facing several major challenges that need to be addressed with the development of technology. Latency and reliability are critical factors affecting the performance of V2X communication systems. Real-time information transfer is an important support for Intelligent Transportation Systems and driver safety. Quality of Service metrics of V2X communication systems vary according to different applications, but the maximum tolerable latency value is strict, which should be within 50 ms. The real-time test data shows that the existing V2X communication systems cannot meet the requirements of the application. Most of the research work demonstrates the wideband properties of the channels, which leads to technology-based solutions.

However, the autonomous driving system does not rely on the wideband channel. Scalability and interoperability are also challenges for V2X communication systems, which require communication modules to transfer signals between different entities of diverse vehicle manufacturers and technologies, considering the huge number of different types of vehicles. Different vehicle type applications based on collaboration and cooperation between various vehicle types are very complex. It is necessary to connect different vehicle types using V2X communication technologies, regardless of the type, model, brand, or manufacturer of the vehicle. The existing V2X communication systems must overcome the challenging problems mentioned above to improve development in the vehicle industry.

2.1. Latency and Reliability Issues

V2X communication is a fundamental technology for CAV systems aiming to improve the driving experience. Several research problems still exist, hindering a large-scale deployment of these technologies. This subsection addresses the latency and reliability issues. Delay in data transmission can dictate the failure of any real-time application, typically for a vehicle within 100 ms. The finer the latency, the smaller the distance traveled by the vehicle in the event of failure. Ideally, communication should be reliable at least for safety applications, as failure in the reception of data for safety applications, such as collision avoidance systems, would lead to severe effects on vehicles. The complex infrastructure of the vehicle is also responsible for the latency, mainly in the event of data transfer. The two main issues of the complex infrastructure are: (1) the huge volume of data transfer between electronic units and (2) the standard communication protocol, where the decision for communication will be made.

Network congestion: Several studies indicate that network congestion further adds to the latency. This has been categorized into higher and best-case latency. Further increasing the server-client communication would also be a matter of concern, as the finite time response of the server would further add to the latency within the vehicle. While the V2X communication protocol defines the period of occupancy, the exact reporting time of the controller (with respect to the main node of the network) cannot be defined and hence is non-deterministic. Remote attacking networks have been categorized into three different types depending upon the location of the attacker (low risk, medium risk, and high risk), based on which the recommended static firewall rules are applied. Unreliable communication not only degrades user experience but also system performance. Attacks and propagation may occur due to structural vulnerability. It is essential to diagnose the robustness of the system. It is required to design a reliability framework.

2.2. Scalability and Interoperability Challenges

As cities are becoming more populated, urban mobility demands innovative solutions to deal with the negative impacts of this growth. High-capacity V2X networks consist of several thousand vehicles and devices, such as traffic signs, sensors, and electronic license plates. With the growing demand for traffic data exchange, applications must allow for an increasing number of devices in the network. Moreover, new vehicles will be introduced to the network daily and will require updating. Devices are deployed in the smart environment on a daily basis. Heterogeneity is another aspect to evaluate; as in legacy V2I/V2V systems, where different manufacturers adhere to various communication protocols and standards, heterogeneous systems are frequently encountered. As a consequence, vehicles from various manufacturers cannot interoperate, complete, or interact with one another at the same level. A similar condition is expected in new V2X systems.

In addition, the increasing demand for rapid replies from small and big data across large areas could result in congestion and overload. Data congestion could be taxing on urban infrastructure. As vehicles generate continuous traffic data streams, congestion will combine with several factors that will affect the transfer of safety and traffic signaling data, making specialized emergency communications more difficult to handle. The existing variety in V2X solutions makes scalability a difficult issue; combining online, offline learning, and AI could form the foundation for large vehicular network research. It is essential for interoperability to provide standardized solutions that will allow cooperation between different interchange solutions used in everyday driving. V2X must be able to bridge the divide between the current and future condition of technology. Moving forward, compatibility is crucial. Interoperability will allow V2X to develop compatible networks that adapt to multiple communication technologies.

3. Applications of AI in V2X Communication

In this section, we explore the various applications of artificial intelligence in V2X communication. One of the prime applications is AI-based decision-making to handle the demand for real-time information processing for connected vehicles and intelligent transportation systems. Such AI-driven decision-making is expected to improve situational awareness and optimize traffic speed. Traffic Management and Optimization: One of the most common vehicles of V2X communications is the optimization of traffic regimes. Data on vehicles flowing between controllers and on signal light regimes at a traffic light show that by using AI for analysis and forecasting, an increase in control efficiency can be achieved. Collision Avoidance: Because of vehicle dynamics, time-to-collision (TTC)-based crash avoidance is useful in avoiding traffic conflicts compared with surrogate safety measures or other safety measures in some situations. Using data from multiple sources, we can more effectively predict risks to traffic safety. Traffic Flow and Safety Prediction: By using AI, a promising direction to improve decision-making for connected vehicles and infrastructure is by predicting future traffic flow using multiple sources of data and applying analytics to that data. Authorities could increase the reliability of evacuation plans by adopting a variety of data feeds and on-the-fly predictive analytics that may enable scenario simulations. The behavior of autonomous vehicles could be important for understanding vulnerabilities in traffic dynamics and road congestion. Autonomous vehicle functionality needs to be incorporated into the design of dispatching strategies. In urban areas, vehicle headway approaches an exponential distribution; the larger the intelligent-driven traffic share, the smaller the coefficient of variation. Finally, as a result of this research, it was identified that mean vehicle velocity and headway distribution during traffic jams are frequency-dependent. The results of the present research, which offer information on space headways and travel speeds, reached the advancing traffic and are very useful in designing a traffic flow simulation model and achieving realistic initial conditions for such models.

3.1. Traffic Management and Optimization

In recent years, V2X technology has quickly gained acceptability in the automotive industry as potentially vital for future transportation systems. This subsection focuses specifically on the utilization of AI in traffic management and optimization in support of more efficient V2X. AI algorithms can be utilized to analyze large amounts of data to understand patterns in traffic flow, and regular congestion points can be predicted. By using real-time data and AI algorithms, traffic signals can be dynamically changed according to the traffic demand, enabling a decrease in travel times and emissions. The grand promise of reduced CO2 emissions is an important political driver behind investments in V2X technologies in several EU member states.

Research has shown that traffic light management and traffic routing through AI can lower overall travel time and pollution levels. Fuzzy logic and neural networks have been employed to analyze and control traffic signal systems in a small control area, reporting up to a 25% reduction in travel time. Another case study shows a machine learning division that dynamically calculates the green light duration on each approach of an intersection. The system was deployed in a city, and the contribution showcases that the system has reduced waiting time and CO2 emissions for several signal-controlled intersections. Researchers have shown work in using machine learning to model traffic flow and time-to-destination, which is used to update Variable Message Signs. The estimated emission savings for this are significant. Signalized intersections modeled with reinforcement learning have shown a 20% reduction in delay compared to conventional actuated signals, and in new Smart Urban Traffic Zones, the model is being used to control signals. AI traffic prediction and real-time decision-making are suited to integrate along with wireless communication to already implemented physical infrastructure for the attraction of big data applications and support of smarter cities' initiatives. AI traffic control applications must integrate tightly with other management systems under an overarching traffic management framework. Full benefits of AI approaches will require changes in vehicle design.

A number of challenges exist around the introduction of AI traffic management systems. These relate to the integration and synchronization of different control systems—e.g., traffic lights signaling with traffic flow control, speed signaling, public transport priority, road pricing technologies, shared space concepts, and other traffic engineering measures and traffic control mechanisms—into one overarching traffic management framework. It also includes data privacy and system integration elements relating to dashboards for control from traffic management centers with unified information spreading—to provide appropriate incentives for network-wide behaviors and operations. AI sensor and communication technologies also have to co-evolve within this. Formal modeling and validation to high levels of safety assurance can be very complex for complex software models such as machine learning models. There are additional research gaps referred to in relation to data quality. AI systems are only as good as the input data, and one needs to understand the effect of bad quality or missing data on system outputs. Also, data standards need to be developed; specifically, uniform communication between AI agent-based control systems needs to be developed in order to drive cloud-scale decisions. Data privacy considerations are also a research gap. Robust and resilient control design incorporating AI needs further advanced study as well as flexibility, in order to mitigate changes in road conditions and potential cyber-attacks. Further discussion is related to data quality and fusion, together with sensor deployment and coverage.

3.2. Collision Avoidance Systems

AI has great potential to enhance the existing safety systems for vehicles. The collision avoidance system would get inputs from various sensors of the host vehicle and participating vehicles through communication. The data from the sensors related to road conditions can be used for real-time feeds to ascertain possible scenarios for collision. The scenarios would be a combination of absolute versions, such as vehicle collision with fixed/static objects, and relative versions, such as vehicle-vehicle collisions. Algorithms for collision scenarios and their severity, based on the state of interacting vehicles, can be used judiciously to devise possible collision avoidance measures. Several machine learning and deep learning techniques offer promise in reducing the system's response time and could be used online, especially during unstructured environments.

Several applications of AI algorithms in the development of collision avoidance systems have shown promise. The AI-based collision avoidance system for intelligent vehicle interactions with difficult traffic on expressway ramps adds a hierarchical structure to clustering techniques to create a model that can recognize collision risks. This technique allows for improved identification of potential collisions for a vehicle's decision-making process when merging onto an expressway. The AI algorithms can take hold of the situation, bring an immediate reaction to potential collisions, and act faster than human drivers. Through real-world case studies, AI-driven collision avoidance systems for severe incidents have exhibited an effective, consistent, and reliable solution. An essential aspect of integrating AI for collision avoidance in communications between robots and vehicles on the road is the design of the fail-safe protocol and integration of the same over various levels of system control across the autonomous systems.

The main challenge in designing AI-driven collision avoidance systems is to ascertain the robustness of the solution across various protocols, especially in situations of interoperability and low-level communicative systems. The AI systems integrated with vehicle-to-vehicle and vehicle-to-robot communication must have a phasing-out system in case of loss in data transmission in the neutral network architecture designed with a backup safety system at the application level. A word of caution should be mentioned here. Although the high-level AI applications and tools demonstrate possible applications and implementations for collision avoidance, much discussion is ongoing since ethical considerations are a major issue of concern. AI and robotic systems are based on certain parameters, which, if they go wrong, can cause major accidents on the roads. This is one area of concern that cannot be taken lightly, and collectively, as system integrators, governments, and private entities are safeguarding and improving these systems. In essence, based on safety, security, and reliability, AI for these important issues doesn't have many options.

4. Machine Learning Models for V2X Communication Enhancement

Three main categories of machine learning models can be used to enhance V2X communication. (i) Traffic prediction models can be used to predict various expected traffic conditions on the road network. (ii) Object detection models can detect objects, pedestrians, and vehicles. These detection models should be able to detect objects in real-time in a variety of driving conditions and road situations. (iii) Situational decision-making models can be used to determine if there is an obstacle, whether to pass a pedestrian via an autonomous vehicle, etc. These models are developed as advanced deep neural networks to address difficulties such as high-dimensional state space, varying traffic conditions, and undefined urban environments. For traffic prediction, a temporal model such as recurrent neural networks can be employed in order to extract information about the future or the past. Another possible approach could involve convolutional neural networks since the dataset is represented in a 2D image with a temporally connected position using time as the third dimension. The choice of the model depends on the driving situation and the features of the dataset. Thus, having a diversity of frameworks for the V2X communication system can be beneficial when it is uncertain which situation will arise in the traffic system. The model architectures should be adjustable based on system requirements and dataset dimensions. Therefore, they can be efficiently trained on different urban environments and driving cases to obtain high performance.

Researchers have trained these machine learning models with independent datasets separately to investigate the impact of the urban environment, traffic type, and population density on the performance of the models. The models achieved state-of-the-art performance qualitatively and quantitatively based on different metrics on their datasets. Yet, real-time performance is limited, and data collected from smaller urban environments are not sufficient to test the models' generality and performance in an orthogonal city. The models were mainly developed based on a number of conditions that are difficult to control in urban traffic areas, such as varying weather, position of pedestrians, and vehicles. Many challenges exist before such models can be deployed for use. For example, the consideration of autonomous systems deployment should include the integration of the model with existing sensors and cameras that assist the autonomous driving systems. Autonomous driving systems cannot rely only on wireless communication to enable communication with other vehicles, especially older vehicles that were not adapted to the V2X communication system.

4.1. Recurrent Neural Networks (RNNs) for Traffic Prediction

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RNNs have strong potential for use in sequential data processing, and in traffic prediction in particular, they can achieve better results. The biggest advantage of RNNs is that they can remember past input patterns by keeping a memory of the past. Consequently, they are appropriate for solving problems in which temporal information can greatly affect the outputs, such as the prediction of traffic conditions. RNNs have been widely used successfully in traffic prediction in recent years. Anticipating traffic conditions can be valuable in a communication system. Therefore, a prediction model using deep learning has been proposed in order to navigate better for vehicles. Traffic forecasting can increase the accuracy of route estimation and further improve the performance of traffic congestion management. Moreover, another experiment has revealed the potential of RNNs in traffic condition prediction. The experimental results showed that RNNs can achieve better prediction accuracy when compared with a model that forecasts congested regions based on time intervals and road conditions. Nevertheless, the restricted input dimensions are one of the challenges that should be considered when applying RNNs in traffic prediction. Based on three years of traffic data, the study also used RNNs to predict travel speeds in multi-lane highways and succeeded in surpassing a benchmark. However, some of the largest traffic-related experimental challenges should be addressed. These problems include RNN training and the prediction model in the traffic data with minimum fluctuations, which could lead to static historical data. When training RNNs with this type of dataset, the model can only provide satisfactory predictions for a temporary period, as severer fluctuations may not properly execute learned patterns. Thus, the model requires continuous retraining and enhancement according to the latest patterns in traffic data in order to accurately predict real-time traffic conditions.

4.2. Convolutional Neural Networks (CNNs) for Object Detection

Communication between vehicles and other road agents, such as other vehicles, pedestrians, infrastructure, etc., is essential for safe and efficient driving. Vehicles use different sensors, such as GPS, radar, LiDAR, cameras, IMU, and so forth, to acquire the necessary information. Cameras and LiDAR are largely used in advanced driver assistance systems to capture visual data. Convolutional neural networks are designed to process visual data with high accuracy and, hence, they are particularly appropriate for object detection. Based on visual data analysis, vehicles can decide on the right action to take to avoid a collision. The primary objective of object detection is to recognize and classify objects within a vehicle’s environment in a high-speed and safe way. It is crucial for assisting the driving control system to avoid accidents and for enhancing situational awareness.

The accurate detection and timely response to a large range of objects from differently placed sensors, such as a camera, is essential for an advanced driver assistance system in order to ensure broad applicability. These cameras are installed in different parts of a car, such as the front, rear, left, right, or top, which results in enormous amounts of data that can contribute to intelligent vehicle communications. It enables vehicles to share vital information, such as road congestion, with each other. A convolutional neural network can read and understand sensor data in the form of images obtained by different sensors from different parts of a car. Accordingly, a convolutional neural network can detect people, cars, and traffic signs from different kinds of vehicle sensors, which can be used to enhance vehicle-to-everything communication. Therefore, convolutional neural networks can provide vehicle-to-everything with cooperative sensing from different vehicle sensors. Given the strength of convolutional neural networks, especially the ability to extract optimal and invariant features, diverse applications of convolutional neural networks for object detection have been developed. For instance, CCTV in urban environments has been programmed to identify pedestrians, cars, and motorcycles. Further, various experimental case studies have been conducted to demonstrate the high performance of utilizing convolutional neural network-based object detection in practical vehicle-to-everything applications. This includes the success of convolutional neural network-based object detection in managing traffic lights, reducing vehicle collisions, predicting pedestrians' crossing behaviors, and more. Some challenges remain for implementing a real-time system for other vehicle-to-everything applications due to the enormous computational requirements. However, research is indeed progressing in this field to decrease the processing time.

5. Case Studies and Real-World Implementations

Throughout the world, there are several case studies and real-world implementations of AI for enhancing V2X communications. These case studies and implementations bring new insights into how these systems are being built in practice, and what approaches and best practices different cities are adopting. Across this work, several lessons are clear. First, stakeholder cooperation is essential for successfully deploying these systems. Second, the role of policy and funding in supporting and shaping these deployments is crucial. Third, measures of the impact and effectiveness of AI in V2X communication are necessary. Each of these is explored in more detail below. Collaboration has led to successful AI real-world integrations in multiple ways, demonstrating that knowledge sharing is instrumental to mutually beneficial research opportunities. Some examples of this close collaboration include various projects using a number of cutting-edge solutions developed by partners on the project. These close partnerships lead to very successful deployments and improvements in safety and traffic efficiency through these key projects. With significant practical demonstrations of the unique value of AI in V2X communications already undertaken through these projects, there is undoubtedly much more to come during the rest of the program. Some of these cooperative efforts can be explained further in the following sections.

5.1. Successful AI Integration in V2X Systems

B. Successful Applications of AI in V2X

AI has been successfully integrated within V2X systems in several projects worldwide, with the purpose of enhancing vehicle communication and contributing to increased safety. In the United States, a transportation department deployed a Smart Lane system, aiming to mitigate the traffic congestion problems frequently encountered during certain hours of the day. The timeframe of the project deployment was the rush hour, between 6:00 and 9:00 AM, with the geographical location in downtown Austin.

Both the transportation department and the chipmaker company have reported a 25% decrease in traffic compared to a period when AI technology was not installed. In Oslo, a national institute of technology, in cooperation with a consulting firm and the department of transportation, conducted a pilot test of road pavement wear, crowds, and holes utilizing AI algorithms. One thousand pictures were inputted to classify the common challenges for Norwegian roads by creating a few classification artificial neural networks. By detecting and indicating the issue, prioritizing road repairs is more methodical. Using feature engineering and a specific object detection network, classes were trained, checked, and validated. AI's direct object detection algorithm is much more precise in humans in the first short test per class, with an average sensitivity of 68.9%. The AI classifier is the main groundwork for precise road assessment in the future. The AI vulnerability, health, and wear classifier has approximately 230,000 parameters, requiring high-quality annotated images, labeling, and great time accuracy.

6. Future Direction

V2X communications are expected to go beyond maintaining the safety and navigation of vehicles. The combination with new capabilities afforded by artificial intelligence, IoT, and edge computing will further enhance the communication capabilities. The advent of 5G wireless communication technologies is likely to see ubiquitous coverage, extremely high connectivity, and very low latency, and is expected to play a significant role in V2X communications. Integrating data from other sources, including IoT and big data from the cloud, is expected to better schedule distributed resources and increase the application scope of V2X communications because the Internet of Everything is essentially a key enabler technology for the integration of data from anywhere and everywhere in the global village. Therefore, V2X advances will certainly change the location and scope of many elements of intelligent transportation systems. The success of V2X is largely based on strong public acceptance and a well-functioning legal and financial framework. Clearly, further research should develop the V2X ecosystem beyond the computation of and set standards for how companies can collaboratively signal their social responsibility to avoid coordinating at a lower, sub-normative level of V2X standards. Finally, there are two challenging dimensions that future research in V2X must investigate: (1) the process of range development based on response operations and (2) the ethical and social concerns regarding the engagement of artificial intelligence in decision-making. The intelligent systems will transform the transportation and V2X environment journey into one that favors no division of society, takes into account individual destinies while respecting personal freedom, and ensures the integrity of the transforming process. With this shared vision, the success and widespread acceptance of V2X are certain.

7. Conclusion

In this paper, a detailed review of vehicle-to-everything (V2X) communication has been carried out. Various V2X systems have been discussed along with the challenges in implementing a V2X system. Furthermore, the role of artificial intelligence (AI) for addressing these challenges has been outlined. Finally, case studies involving AI applications in traffic management, real-time decision-making, and collision avoidance in V2X systems have been discussed. It has been shown that this technology can pave the way for energy-efficient traffic management for large metropolitan cities and real-time traffic congestion avoidance. The unpredictability of vehicular movement, changing behavior of drivers, and diverse communication technologies create a very challenging vehicular communication environment. AI-driven V2X systems will help in achieving communication speed, decreased number of collisions, energy efficiency in the transportation network, and facilitate real-time decision-making. In this paper, we also discuss the need and emergence of machine learning models for predicting the vehicle trajectory accurately in order to increase the efficacy of inter-vehicular communications. On the basis of the observations in these case studies, we argue the need for further research and investigation for leveraging AI in V2X communication for safer and energy-efficient communication between heterogeneous vehicles. The future work includes collaboration between industry, governments, and V2X applications. It would be interesting to observe the new AI trends like AI on edge and 6G communication, which are going to play a pivotal role in the current research trends. In conclusion, with the rising technical trends, V2X communication systems are taking a new form for the quality of safer and better services on the road. V2X AI-based systems are redefining the communication scenarios on various levels like intra-vehicle, inter-vehicle, vehicle to infrastructure, and vehicle to infrastructure, with the aid of virtual infrastructures.

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