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Intelligent Technologies in Traffic Flow Control: A Review

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Abstract: With the acceleration of global urbanization, traffic congestion has become a major bottleneck in the development of modern cities, leading to serious economic losses and a decline in the quality of life. To address this challenge, traffic flow prediction techniques have received much attention. This paper reviews the application of three key technologies, including 5G, artificial intelligence (AI), and vehicular networking (V2X) in intelligent traffic management. 5G technology provides a communication foundation with high speed rates, low latency, and large-scale device connectivity, which effectively supports real-time data transmission and communication needs. AI technology, on the other hand, with its powerful data processing capability, is able to make high-precision traffic predictions in dynamic traffic environments. However, the effectiveness of AI models is highly dependent on the support of high-quality data.V2X technology greatly improves road safety and traffic mobility by realizing real-time information exchange between vehicles and infrastructure. However, relying on a single technology alone cannot comprehensively solve complex transportation problems. For this reason, this paper proposes a technology fusion scheme of 5G, AI, and V2X, aiming to optimize the intelligence level of the traffic management system through the complementary advantages of each technology. The study shows that the synergistic application of the technologies can not only effectively alleviate traffic congestion but also improve the overall safety of roads, providing a feasible solution for the future intelligent transportation system in cities.

Keywords: Intelligent technologies, Traffic flow control, Vehicular networking.

1. Introduction

Transportation, as a core infrastructure for modern urban development, is not only crucial for economic growth and social well-being but also plays a key role in environmental protection [1]. However, with the acceleration of global urbanization and the continuous rise in the number of motor vehicles, traffic congestion has become increasingly serious and acts as a major bottleneck restricting the economic development of cities. Traffic congestion not only causes huge economic losses but also wastes a lot of personal time and significantly reduces the quality of life of urban residents [2]. To cope with this challenge, traffic flow prediction techniques have garnered widespread attention. Through the application of advanced intelligent technologies such as 5G, artificial intelligence (AI), and vehicle-to-electronic network (V2X), accurate real-time traffic condition prediction can be achieved through dynamic regulation, effectively alleviating traffic congestion. However, due to the complexity and dynamics of transportation systems, relying solely

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on a single technology proves insufficient to fully cope with complex transportation environments [3]. Therefore, this paper systematically explores the application of 5G, AI, and V2X in traffic flow prediction while analyzing their respective advantages and shortcomings. Furthermore, an improvement scheme for multi-technology fusion is proposed with an aim to provide practical references for future intelligent traffic management.

2. Overview of smart technologies

In the domain of traffic flow prediction, 5G, AI, and V2X are recognized as the three key technologies that drive the development of intelligent transportation. These technologies introduce new approaches to traffic flow prediction and effectively solve the problems of inefficiency and delayed response encountered in traditional prediction methods. In the following chapters, this paper will provide an overview of these three technologies and discuss their advantages and disadvantages in traffic flow prediction.

2.1. 5G

Over the past three decades, communication technology has experienced rapid development from 1G to 4G, and despite significant progress, 4G technology is still insufficient when facing demanding scenarios such as low latency and high bandwidth [4-5]. To address these challenges, 5G technology has emerged, which achieves significant improvements in communication performance by adopting cutting-edge technologies such as Massive MIMO, millimeter-wave (mmWave) frequency bands, network slicing, etc. Massive MIMO uses many antenna arrays to dramatically increase signal transmission efficiency and coverage, while mmWave frequency bands provide a much greater range of bandwidth. Massive MIMO uses massive antenna arrays to dramatically improve signaling efficiency and coverage, while millimeter-wave frequency bands provide greater spectrum resources to support higher-speed data transmission. At the same time, network slicing technology allows operators to create virtual private networks for different application scenarios (e.g., autonomous driving, telemedicine, etc.) to provide customized network services and ensure that network performance requirements are met under different scenarios [6]. Compared with previous generations of technology, 5G not only provides faster data rates and lower latency, but also supports concurrent connections of large-scale devices, providing a solid network foundation for application scenarios such as the Internet of Things and smart transportation. However, despite its many advantages, 5G may still face challenges in some extreme situations. For example, in the event of a surge in traffic or during unexpected events such as large-scale events, natural disasters, or emergencies, the capacity of the network may be limited, especially when a large number of devices are trying to access the network at the same time, and the allocation of resources may be insufficient, leading to the phenomenon of network congestion. Addressing these issues requires more efficient network management and resource optimization techniques to cope with the performance of 5G under extreme conditions.

2.2. AI

AI aims to develop systems that can perform tasks that traditionally rely on human intelligence, which include problem solving, image recognition, natural language processing, learning, and decision making [7]. In recent years, AI has been widely used in traffic flow prediction due to its ability to process large-scale data. Compared with traditional statistical models, AI algorithms, especially deep learning models such as Long Short-Term Memory Networks (LSTMs) and Recurrent Neural Networks (RNNs), have shown greater adaptability in dynamic and variable traffic environments. [8-9] Recursive neural networks (RNNs) are suitable for processing sequential

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data and time-dependent tasks, such as time-series prediction of traffic flow, by combining data from previous time steps with current data. However, RNNs are prone to the “gradient vanishing” problem when dealing with long sequences, which makes it difficult to capture distance-dependent information. To overcome this limitation, Long Short-Term Memory (LSTM) introduces a gating mechanism that effectively retains and updates important information through a combination of forgetting gates, input gates, and output gates. As a result, LSTMs perform particularly well in capturing long-term dependency patterns in traffic flow and are able to cope with complex fluctuations in traffic flow. However, the training of AI models is highly dependent on a large amount of high-quality data, and their prediction accuracy may suffer when there is insufficient data.

2.3. V2X

Vehicular networking (V2X) is a technology for sharing real-time information through vehicles with other vehicles, pedestrians, and transportation infrastructure.V2X technology optimizes traffic mobility by interconnecting isolated traffic nodes and enabling the real-time exchange of traffic information, which significantly improves road safety and reduces congestion [9&14]. However, the effectiveness of V2X technology relies on the integration and processing of large amounts of real-time data and also requires strong communication support and network connectivity for sustained performance in high-density traffic environments.

3. Application of Intelligent Technologies

3.1. 5G

The application scenarios of 5G can be categorized into three: enhanced mobile broadband (eMBB), massive machine-type communication (mMTC), and ultra-reliable low-latency communication (uRLLC). Among them, mMTC and uRLLC are widely used in intelligent traffic flow prediction.

mMTC is an application scenario in 5G networks specifically designed for Internet of Things (IoT) devices, featuring low power consumption, large-scale device connectivity, and low data rate transmission. With mMTC technology, traffic lights, sensors, cameras, and vehicles are able to connect with each other to form a massive IoT network. The integration of IoT devices enables traffic signals to be intelligently adjusted according to real-time traffic density, which can effectively reduce traffic congestion and improve the efficiency of intersections, unlike traditional fixed-time signal system [7&10]. Li points out that uRLLC, with its ultra-low latency and high reliability, provides the system with high-speed data transmission capability, ensuring that real-time status information of multiple vehicles can be synchronized and uploaded to the cloud. Compared with traditional transportation systems, the system is able to process and react more quickly, adapting to complex urban transportation scenarios [8&11].

3.2. AI

Traditional statistical models, such as the autoregressive integral sliding average model (ARIMA), had been widely used in early traffic flow forecasting. The advantage of such models lies in their high interpretability, but they show greater limitations in coping with dynamically changing traffic environments. With the advancement of technology, machine learning models have gradually become mainstream due to their ability to handle big data and high accuracy prediction, especially deep learning techniques, such as Long Short-Term Memory Networks (LSTMs) and Recurrent Neural Networks (RNNs), which have been widely used in short-term traffic flow prediction [12].

Li combined Support Vector Regression (SVR) and Artificial Bee Colony Optimization (ABC) algorithms to take advantage of SVR's handling of small samples and high-dimensional data, and optimized the parameters of SVR through ABC, which made the prediction results more accurate in complex and dynamic traffic environments. The experimental results show that the combined model outperforms the traditional model in real traffic data, which helps to optimize traffic signal control, reduce congestion, and thus improve traffic management efficiency. This suggests that AI-driven intelligent prediction algorithms have a wide range of application prospects in future traffic control [10&13]. Ho and Loannou use artificial neural networks (ANNs) to model and control highway traffic flow with the aim of optimizing traffic flow and reducing traffic congestion by regulating vehicle speed. The study models the traffic flow as a dynamic nonlinear system, learns the variation patterns of traffic flow density and speed through ANNs based on the analogy of fluid dynamics, and designs a controller to optimize the speed and flow distribution. And the effectiveness of the controller is verified by simulation experiments, which significantly reduces the congestion caused by uneven traffic density distribution [11&14].

3.3. V2X

Xu used SUMO (Simulation of Urban Mobility) and OMNeT++ to build a simulation environment for ITS. SUMO was used to simulate the real road network and vehicular traffic flow, while OMNeT++ and Veins were used to simulate the process of V2X communication. The simulation results show that V2X technology has a significant effect in reducing the vehicle waiting time, increasing the average speed, and increasing the traffic flow. Especially, the introduction of V2X technology significantly improves the traffic efficiency when the number of vehicles increases. For example, when the number of vehicles reaches 2,500, the average speed increases by about 40% and the traffic flow increases by 36% with V2X enabled [14-15]. V2X technology can bring a wealth of real-time data, such as vehicle location and speed, to Intelligent Transportation Systems (ITS). However, to protect user privacy, the V2X standard specifies that vehicle identifiers will be changed periodically. Brahim proposes a matching algorithm that utilizes the static attributes of vehicles (e.g., vehicle length, width, etc.) and dynamic attributes, such as path history, to perform unique identifier matching, which safeguards privacy and enables continuous vehicle tracking and traffic flow computation [15-16].

4. Technological convergence

4.1. Necessity and advantages

Although 5G, AI, and V2X technologies have each demonstrated significant advantages, they still have limitations when applied individually. 5G has the advantage of low latency and high bandwidth, but it cannot realize complex intelligent decision-making by relying on communications alone; AI excels at processing large-scale data and making predictions, but its responsiveness and accuracy may be limited when it lacks the support of real-time data; and V2X, although it is able to realize efficient communication between vehicles and the environment, its performance relies on fast network connectivity and intelligent analysis capabilities. Therefore, the integration of the three is crucial. 5G provides real-time and stable data transmission for AI to ensure that intelligent algorithms can make decisions quickly, while AI improves inter-vehicle collaboration and traffic management efficiency through in-depth analysis of the massive amount of data provided by V2X, thereby effectively compensating for the shortcomings of each technology and achieving more efficient and intelligent traffic management results.

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4.2. Case Studies

Abdellah explored the use of Deep Learning (DL), specifically Long Short-Term Memory (LSTM) models, to leverage the efficient communication capabilities of 5G networks to predict traffic flow in V2X networks. By predicting traffic flow and network load changes, it helps to prevent communication congestion and communication bottlenecks that V2X networks often face when the number of vehicles increases, and unexpected traffic events occur. With these predictions, 5G networks can dynamically adjust resource allocation to improve the overall efficiency and quality of service (QoS) of the network. The article verifies the prediction performance of the LSTM model in a 5G V2X environment by testing with different packet transmission rates (e.g., 4 to 14 packets per second), and ultimately finds that 4 packets/second performs best [16-17].

J presents a traffic prediction method based on the Restricted Boltzmann Machine (RBM) and Cuckoo Search Optimization (CSO) algorithms for traffic analysis in V2X (Vehicle to Vehicle) communication systems in 5G networks. It copes with the complexity and uncertainty of V2X communication in 5G networks and improves the network performance and resource allocation efficiency. Experiments show that the CSORBM-TA technique performs well under different packet transmission rates, especially in reducing the mean absolute percentage error (MAPE) and root mean square error (RMSE), which are significantly better than the traditional prediction model.The model has the best performance with a MAPE value of 9.26 and a RMSE value of 0.5187 for a 4 packet/sec transmission rate. Compared with other common deep learning models (e.g., LSTM, GRU, and MLP), CSORBM-TA performs better in terms of prediction accuracy with a MAPE value of 17.21%, which is much lower than that of the LSTM model at 20.34% [17-18].

Both cases demonstrate the potential of the convergence of the three to improve network efficiency and reduce congestion in ITS. 5G provides an efficient communication infrastructure for V2X, the massive real-time data generated by V2X drives the application of AI, and AI helps the 5G network better manage and optimize its resources through accurate traffic flow prediction, ultimately enabling the efficient operation of an ITS.

5. Conclusion

The development of Intelligent Transportation Systems (ITS) relies on the synergistic application of several cutting-edge technologies. In this paper, the researcher systematically discusses the application of 5G, artificial intelligence (AI), and vehicle-to-electronic network (V2X) in traffic flow prediction, along with their advantages and disadvantages. 5G technology significantly enhances real-time data transmission capabilities by providing a network infrastructure with high speed, low latency, and large-scale connectivity; however, there is still a risk of network congestion in the face of sudden traffic surges. With its ability to process large-scale data and optimize decision-making processes, 5G technology has gradually emerged as a core tool for traffic flow prediction. Nevertheless, it heavily relies on a large amount of high-quality data and exhibits limited interpretation in certain complex scenarios. V2X technology plays a key role in improving both traffic safety and mobility by establishing connections between vehicles and their surroundings while enabling real-time information sharing, but its effectiveness is contingent upon an efficient network infrastructure and robust data integration capabilities.

Although each of these technologies has demonstrated significant advantages, they still have limitations when applied individually. Therefore, integrating 5G, AI, and V2X technologies with each other and taking full advantage of their complementary strengths in data transmission, intelligent analytics, and real-time communication will be a key direction for further optimization of future ITS. Through the integration of technologies, more efficient and intelligent traffic

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management can be achieved, ultimately easing urban traffic congestion, improving road safety, and promoting the overall development of intelligent transportation.

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