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Design and Implementation of Intelligent Traffic Signal Light Control System Based on LoRa Technology

Frank Ce Wang[1,a,*]

[1]Jiangnan High School, Hangzhou, 310000, China
a. wangce0601@163.com
**corresponding author*

Abstract: The acceleration of urbanization has left cities around the world facing significant challenges, including traffic congestion and inefficient management. Intelligent transportation systems provide new technological means to address these issues, especially in traffic signal control, where advanced communication technologies play an important role in facilitating the process. The potential of long range radio (LoRa) technology in intelligent traffic signal control systems is attracting growing interest, largely due to its capacity for long-range transmission and low power consumption. This paper explores the potential benefits of LoRa technology in traffic flow monitoring and signal control by reviewing existing studies, especially in the field of long-distance transmission and low-power communication. The study indicates that LoRa technology can effectively boost the efficacy of traffic management, reduce traffic congestion, and provide technical support for the development of future intelligent transportation systems. Nevertheless, the stability of LoRa technology in high-density urban environments and its integration with other technologies still present challenges. Further research can investigate the anti-jamming ability, communication rate optimization, and its potential for wider application of LoRa technology in Intelligent Transport Systems (ITS) to promote more efficient urban traffic management.

Keywords: LoRa Technology, Intelligent Transportation, Traffic Signal Control, Low Power Communications.

1. Introduction

Traffic signal control systems play a vital role in regulating the flow of traffic and ensuring safety on roads. Traditional traffic signal control systems often rely on fixed-time schedules or simple actuated controls that cannot adequately adapt to the changing dynamics of traffic conditions. Technological advances have led to the creation of intelligent traffic signal control systems to optimize traffic flow, reduce congestion and improve safety. Long Range Radio (LoRa), a long-range, low-power wireless communication technology developed by Semtech, is based on spread-spectrum technology and aims to resolve the inherent contradiction between low power consumption and long-range transmission [1]. The implementation of LoRa-based WSN environmental monitoring using public transportation makes it possible to increase the transmission distance with lower consumption, thus making it easier to implement remote traffic control from a fixed location on the system [2]. This paper introduces the application of LoRa technology in

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intelligent transformation and offers suggestions for enhancing LoRa technology in traffic signal control. To this end, it draws upon data from other sources and conducts an analysis of the design of the hardware and software. The data presented herein facilitate an examination of the current status of the application and an identification of its prospective trajectory. This analysis, in turn, allows for an evaluation of the potential future development prospects of the technology in the context of intelligent transportation.

2. LoRa Technology and Intelligent Transportation

LoRa technology represents a low-power wide area network (LPWAN) technology that exhibits the characteristics of long-distance communication, low power consumption, and high reliability. As such, it is particularly well-suited to the application of intelligent transportation systems. The long-distance transmission and low-power consumption characteristics of LoRa technology enable the realization of highly efficient data transmission and real-time monitoring in the transportation system, providing crucial support for the intelligent control of traffic signals. Here, the prospects for the application of LoRa technology in intelligent traffic signal control systems are explored. And this technology has been widely employed in various fields such as pasture livestock monitoring, soil monitoring and smart street management. Its advantage is fast and convenient remote monitoring. For example, some large gas companies use LoRa technology to replace traditional manual recording, which not only improves data accuracy (up to 99% or more), but also dramatically reduces labor costs (over 60%). In rural environments, LoRa technology has a transmission range of up to 15-20 kilometers, compared to 2-5 kilometers in cities. The power consumption of LoRa can be as low as 1μA in standby mode and between 10mA and 30mA for data transmission. It has been demonstrated that LoRa technology, with its exemplary communication performance and minimal power consumption, offers considerable potential for providing efficacious solutions to intelligent traffic signal control systems, thereby further optimizing traffic management efficiency.

Intelligent Transportation Systems (ITS) aim to address the limitations of traditional traffic signal control, which often relies on fixed timings or simple actuation controls that are difficult to adapt to real-time traffic conditions. The traditional ITS still encounters challenges, including unfavorable weather conditions that can affect sensor accuracy and the inability to effectively integrate various data types. These limitations impede the overall efficiency of traffic management. Advanced ITSs utilize technologies such as information technology, computer science, data communications, sensors, electronic and automated control systems, and artificial intelligence (AI) to improve traffic safety, efficiency, environmental impact, as well as energy consumption. LoRa technology, characterized by long-distance communication and low power consumption, can reduce the impact of environmental factors on sensor performance and enables more flexible and reliable system control, which brings significant advantages to ITSs. transportation systems. The integration of LoRa technology at major traffic intersections can enable the remote monitoring of the entire traffic network, thereby enhancing the responsiveness of traffic signals and the overall efficiency of the system. In such context, this technology plays a pivotal role in transcending the constraints of traditional approaches, providing a pragmatic solution for modernizing traffic management and improving the adaptability of ITS [3].

3. Design Analysis of Intelligent Signal Control System

3.1. System Requirement

In regard to the functional requirements of traffic signal control, LoRa technology can realize dynamic adjustment of signal light duration according to real-time traffic conditions. For example,

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when the traffic flow is heavy, the green light time can be extended to ease the traffic pressure. Through this technology, the system is able to quickly adjust the signal hours at all intersections based on real-time data and forecast results. In addition, the system allows the relevant departments to control traffic signals remotely and respond flexibly to emergencies or traffic anomalies. In terms of performance requirements, LoRa technology provides the intelligent traffic monitoring system with high-precision data collection capability, which can record the traffic flow and the number of vehicles in different areas of the city in real time. The remote control function of LoRa technology enables the system to be centrally managed, and the central control system can instantly adjust the signal settings at each intersection without the need to operate them one by one, which greatly shortens the adjustment time and ensures a reasonably smooth traffic flow [4]. In terms of security requirements, LoRa technology is able to provide stable signal transmission under various weather conditions, including extreme environments such as sunny days and heavy rain. Besides, it has excellent anti-interference capability, which can avoid affecting traffic signals due to microwave interference in cities, thus ensuring that the entire traffic management system can operate normally under any circumstances. This high stability and anti-interference greatly improves the reliability and safety of the ITS.

3.2. System Structure

The system consists of three parts: traffic sensors, LoRa nodes, and a central control unit. Firstly, the traffic sensors are responsible for monitoring the traffic conditions on the road, including the presence of vehicles passing through and the size of the traffic flow. There are various types of sensors, either cameras, loop sensors, or other types of sensing devices, which provide a wealth of data that can greatly improve the accuracy of the analysis. The data collected by the sensors is transmitted directly to the LoRa node to ensure efficient operation of the system. Secondly, the LoRa node communicates with the central control unit through LoRa technology, acting as a bridge between the sensors and the central control unit. The LoRa node transmits the real-time data collected by the sensors to the central control unit, and at the same time receives commands issued by the central control unit, ensuring that the system is able to make a quick response based on the real-time traffic conditions. Finally, the central control unit is the core of the system, which processes data from LoRa nodes and sensors, monitors the status of traffic signals, and adjusts the timing of signals in real time according to changes in traffic flow. As the “brain” of the system, the central control unit automates analysis tasks and allows users to centrally control the entire traffic system through an application. The unit is usually a computer with powerful processing power to ensure the efficient operation of the ITS [5].

3.3. Signal Lamp Control Algorithms

In terms of timing control algorithms, an in-depth analysis of the traffic flow enables the identification of periods of high traffic flow during most of the time. Based on these data, the timing control algorithm can effectively record the time periods during which vehicles pass through the intersection and adjust the duration of the green light accordingly, thereby optimizing the timing of the traffic signal. While simple, this approach can provide basic traffic management support under certain conditions. In contrast, sensor control algorithms detect vehicle speed and traffic flow in real time by installing high-precision sensors at traffic intersections in order to achieve dynamic adjustment of signals. With higher sensitivity and accuracy, this algorithm is able to respond to changes in actual traffic flow in a timely manner, ensuring that the green light time can be effectively extended during peak periods, thereby improving traffic efficiency. In addition, sensor control algorithms are able to adapt to unexpected traffic conditions and provide more flexible

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signal control schemes. Moreover, other types of algorithms such as adaptive control algorithms or artificial intelligence algorithms are capable of identifying complex temporal patterns and predicting future traffic flows by learning and analyzing large amounts of traffic data. Although these types of algorithms have a high potential for automation in theory, they are still in the developmental stage, and their practical applications are not yet fully mature, facing the challenges of implementation complexity and data processing capability. In short, all types of algorithms have their unique advantages and disadvantages. Taking safety and convenience into account, sensor control algorithms are considered to be the best choice at present, which can provide more effective and flexible traffic signal control solutions in practical applications [6]. According to Figure 1, the whole steps of the public transportation service map can be understood.

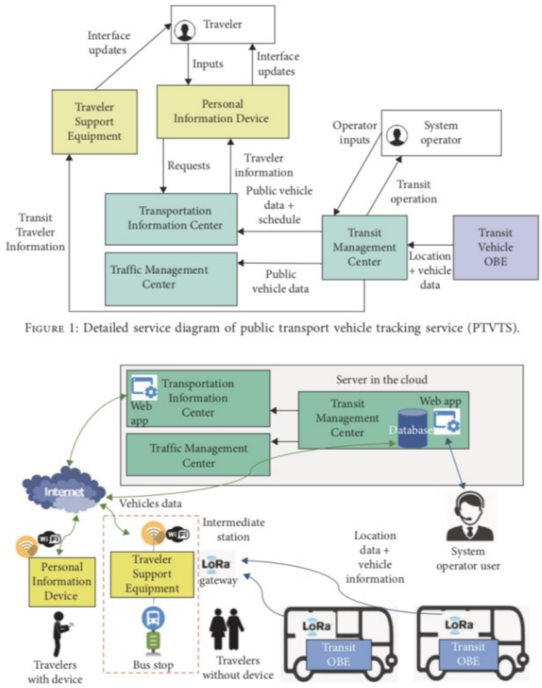

Figure 1: Detailed service of public vehicle tracking service

4. Applications of LoRa Technology in Intelligent Transportation Systems

4.1. Hardware Design

The hardware design mainly involves the construction of traffic sensors, LoRa nodes and central control unit. There are various types of traffic sensors, including induction loops and cameras. Among them, induction loops are usually installed on the road to detect the presence of vehicles, while cameras can be installed on utility poles or buildings near traffic intersections, with the capability of detecting vehicle speed and flow. These sensors can provide a wealth of real-time data to support traffic management at different locations in the city, ensuring accurate monitoring of traffic conditions. In addition, all sensors can be centrally managed and monitored through the system, greatly improving management efficiency [7]. The design of the LoRa node consists of three parts: the microcontroller, the LoRa module and the power supply. The main task of the microcontroller is to process the data from the traffic sensors and communicate effectively with the LoRa module. The LoRa module utilizes LoRa technology to realize the remote sending and receiving of data, which has the advantages of long distance and low power consumption, and provides a reliable data transmission solution for urban transportation systems. The power supply part can use batteries or solar panels to ensure the stable operation of the system under different environmental conditions. The LoRa nodes are able to transform the information from the sensors into real-time responses and promote the dynamic adjustment of traffic signals to cope with different situations of pedestrian and vehicular traffic, thus enhancing the intelligence and efficiency of traffic management .The central control unit consists of a computer or specialized controller, a communication module, and a power supply. The communication module is mainly responsible for receiving data from LoRa nodes and giving commands to traffic signals. The central control unit, as the key core of the hardware design, has the ability to control the entire traffic system, receive all kinds of information from the traffic sensors and LoRa nodes, and accurately find out the solutions to the problems and correct them.

4.2. Software Design

The software design part revolves around the intelligent traffic signal control system based on LoRa technology, including sensor data processing algorithms, signal timing generation algorithms and the design of communication protocols. With regard to the sensor algorithm, it is mainly responsible for processing sensor data from LoRa nodes and collecting key information such as vehicle speed and traffic flow. This algorithm can more accurately capture the changes in vehicle and traffic flow and thus realize real-time monitoring. In addition, the sensor algorithm can incorporate learning mechanisms from robotics to further improve the accuracy and reliability of data detection. The signal timing algorithm searches for the best signal timing solution by combining traffic flow data and models, using advanced optimization techniques such as genetic algorithms or particle swarm optimization. This algorithm aims to minimize traffic congestion and delays and improve the overall efficiency of urban transportation. The communication protocol, on the other hand, is key to ensuring reliable communication between the LoRa nodes and the central control unit. The protocol employs error detection and correction mechanisms to ensure the integrity and accuracy of data transmission, which in turn guarantees the stable operation of the system [8].

4.3. Combination and Implementation of the Systems

Based on LoRa technology for intelligent transportation systems, previous research conducted a series of tests at real traffic intersections, focusing primarily on the effectiveness of sensor data processing algorithms, signal timing generation algorithms, and communication protocols. These tests were designed to evaluate the system's ability to be applied in real-world situations, thereby providing more effective solutions for improving traditional transportation systems. In terms of implementation, traffic sensors were first installed at traffic intersections and connected to LoRa nodes. The LoRa nodes, in turn, were mounted on utility poles near the intersections and connected to a central control unit using a LoRa gateway. The central control unit is a computer running customized software that processes sensor data and generates signal timing. Once all the components are in place, the system can begin to function properly. The hardware design analyzes the data to provide better solutions for performing traffic management tasks. In the testing phase, the performance of the system was evaluated under different traffic conditions, including low, medium and high traffic scenarios. The testing focused on metrics such as traffic flow, delay and safety. The results show that the system can effectively adapt to dynamic traffic conditions, improving traffic flow and overall safety and validating the functional effectiveness of the system. LoRa technology has the ability to communicate over long distances, enabling transmissions of up to 15 kilometers, and performs well under low-power conditions. However, the technology also faces some challenges. For instance, due to the fact that LoRa employs public spectrum, it is susceptible to interference in environments with high population density. Therefore, it is crucial to implement intelligent systems to dynamically adjust the signal. In addition, LoRa's wireless communication data may be subject to attacks and tampering, making it especially important to employ encryption algorithms to ensure data security [9].

5. Future Prospects

In the future, traffic management will rely on the widespread deployment of LoRa sensors that collect data, including vehicle counts, speeds, and traffic flow in real time at key locations such as roads and intersections. This can provide traffic management with accurate feedback on traffic conditions so that signal timing can be adjusted in time to optimize traffic flow and reduce congestion. The long-range capability of LoRa technology enables traffic management centers to effectively monitor traffic flow over vast areas, circumventing the exorbitant deployment and maintenance costs associated with traditional wired networks. In parking lots, LoRa sensors can be installed to monitor the occupancy of parking spaces in real time and transmit the relevant information to the management system. Car owners can quickly obtain information about available parking spaces in the surrounding parking lots through mobile applications, improving parking efficiency. The results show that the solution can effectively adapt to dynamic traffic environments and significantly improve traffic flow and safety.

However, research should also focus on further improvements in LoRa technology. More advanced modulation and demodulation techniques and signal processing algorithms should be explored to maximize the data transmission rate without sacrificing other performances for more demanding scenarios such as HD video surveillance and real-time industrial control. In addition, research into new solutions for anti-jamming techniques, such as intelligent frequency hopping techniques and adaptive interference suppression algorithms, will help enhance the stability and reliability of LoRa devices in complex electromagnetic environments. LoRa technology is usually deployed as a standalone network, but it will be an important direction to integrate with other networks (e.g., 4G/5G, WiFi, and Bluetooth) to realize wider coverage and richer functionality in practical applications. The convergence of LoRa with other networks, including research on protocol conversion, seamless switching, and cooperative work, has the potential to better meet the diverse needs of modern traffic management [10].

6. Conclusion

This paper discusses the design and application of an intelligent traffic signal control system based on LoRa technology, emphasizing the importance of the system in modern urban traffic management. By integrating traffic sensors, LoRa nodes and a central control unit, the system is able to monitor the traffic flow in real time and dynamically adjust the signal timing in order to improve the efficiency and safety of traffic movement. Experimental results show that the system can effectively adapt under different traffic conditions and significantly reduce traffic delays and congestion. The long-range and low-power characteristics of LoRa technology make it an ideal choice for intelligent transportation systems that can provide stable communication connectivity in complex urban environments. Though the technology faces challenges in terms of public spectrum usage and data security, these issues are expected to be effectively resolved through sound system design and encryption measures. Further research can explore the performance of the system in larger-scale applications and the possibility of combining emerging technologies such as artificial intelligence to enhance its adaptive capability.

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