electronics

Article

A Dynamic Addressing Hybrid Routing Mechanism Based on Static Configuration in Urban Rail Transit Ad Hoc Network

Zijie Han [1], Liu Liu [1,*], Zhibin Guo [2], Zhaoyang Su [1], Lei Suo [1], Shiyuan Cai [1] and Haitao Han [3]

1 School of Electronic and Information Engineering, Beijing Jiaotong University, Beijing 100044, China
2 Intelligent Network Innovation Center, China United Network Communications Co., Ltd., Beijing 100048, China
3 Traffic Control Technology Co., Ltd., Beijing 100071, China
* Correspondence: liuliu@bjtu.edu.cn; Tel.: +86-138-1189-3516

Abstract: With the rapid development of urban rail transit, the traditional urban rail wireless network based on fixed infrastructure is not in a position to meet the increasingly complex communication demand. At the same time, Ad Hoc network, as a special wireless mobile network, is developing rapidly. Applying this self-organized networking architecture to the urban rail vehicle–ground communication network can overcome the problems existing in the traditional urban rail communication system. The routing protocols that can achieve low delay and highly reliable data transmission are important in the urban rail transit scenario. Therefore, combined with the wireless Ad Hoc network and the characteristics of the urban rail transit scenario, this paper proposes a dynamic addressing hybrid routing mechanism based on static configuration. Using an improved AODV routing discovery algorithm and then writing the routing table into the router in advance for static configuration not only reduces network overhead but also prolongs the network's lifetime. It also saves the delay of routing discovery. Then, the cluster head node dynamically monitors the link status, dynamically finds the path when the link needs to be replaced, and selects different update paths according to different types of communication services. Finally, each algorithm's network performance parameters, like the routing discovery overhead, residual link lifetime, packet delivery rate, throughput, and end-to-end delay, are analyzed and compared.

Keywords: urban rail train–ground communication; self-organizing network; routing protocol; improved AODV; static configuration; dynamic addressing

Citation: Han, Z.; Liu, L.; Guo, Z.; Su, Z.; Suo, L.; Cai, S.; Han, H. A Dynamic Addressing Hybrid Routing Mechanism Based on Static Configuration in Urban Rail Transit Ad Hoc Network. *Electronics* **2023**, *12*, 3571. https://doi.org/10.3390/electronics12173571

Academic Editor: Juan-Carlos Cano

Received: 13 July 2023
Revised: 20 August 2023
Accepted: 21 August 2023
Published: 24 August 2023

1. Introduction

As the urbanization process has accelerated, the urban transportation industry has achieved rapid development. At the same time, the development of urban rail transit plays an important role because its advantages of environmental friendliness, safety and reliability, high speed, large traffic volume, and other advantages can help solve the relatively serious urban traffic congestion problem in China [1]. Along with the application of various new technologies and equipment, as well as the increased demand of passengers for travel convenience and personalization, new information technologies such as cloud computing, big data, the Internet of Things, artificial intelligence, 5G, satellite communication, and blockchain will be deeply integrated with urban rail transit and provide more services for the future urban rail transit systems. Their application will also cover the shortages of exiting communication technologies in terms of capacity and reliability [2] and achieve large-scale, comprehensive, and efficient operation control and management. To promote the interconnection of urban rail transit systems to the Internet, collaborative and intelligent development has become a trend.

Urban rail transmissions transfer business information like train control systems, passenger information systems (including train access video monitoring and train access video playback) through built train–ground wireless communication networks [3]. The traditional urban rail transit vehicle–ground communication network is based on a fixed infrastructure, which transmits information through central nodes. Central nodes are interconnected through cables or optical fibers, and each terminal directly communicates with the central node. Typical applications are wireless local area networks, wireless cellular networks, etc. This traditional network structure relies on base stations or wireless access points for communication. When the fixed infrastructure is interfered with or damaged, it will affect the communication of the network and will be unable to meet the needs of future development.

In recent years, wireless Ad Hoc network technology has developed rapidly as a new type of network communication technology. Ref. [4] discusses the most important results from 2000 to 2022 from various authors. It is widely used in satellite communications, vehicle networking, and other fields. Using a self-organized network architecture with decentralized and distributed control advantages in urban rail transit can overcome the problems existing in traditional urban rail communication systems. Therefore, the rail self-organization scheme for urban rail transit with high real-time and high bandwidth wireless communication has been proposed in recent years. Rail Ad Hoc networks are a new generation of digital infrastructure in the field of rail transit. They provide safe, efficient, and convenient standardized services through environmental awareness, data fusion computing, and decision control, including communication, positioning, timing, clearance detection, trackside equipment control, and other functions. Trackside equipment with wireless communication capabilities is installed along the rail line, and communication equipment is installed on the train.

In the communication technology of urban rail Ad Hoc networks, the network layer is an important layer that can achieve the conversion of network addresses to physical addresses and find suitable paths for communication. In urban rail scenarios, communication between vehicles generally exceeds the single-hop range, and suitable routing protocols need to be used to perform multi-hop forwarding through trackside equipment to complete data transmission functions. To fully utilize the performance of urban rail Ad Hoc networks, efficient routing protocols are essential. However, there is little research work directly aimed at urban rail Ad Hoc network routing technology at home and abroad. Therefore, actively researching key routing technologies for urban rail transit Ad Hoc networks based on low-latency and high-reliability communication have important scientific significance and application value.

In summary, urban rail Ad Hoc network routing technology has important significance in reducing communication delays, improving transmission reliability, and reducing construction costs. Researchers at home and abroad have conducted many in-depth studies on wireless Ad Hoc network routing protocols, obtaining many meaningful research results, which have reference significance for studying urban rail Ad Hoc network routing technology. However, it still needs to be pointed out that the current research is mostly based on wireless Ad Hoc networks and less so combined with the actual application scenarios of urban rail transit. To fully utilize resources and ensure stable data transmission, further research on and optimization of urban rail Ad Hoc network routing protocols are needed to improve the performance of urban rail Ad Hoc network routing protocols and better adapt to the communication environment of urban rail.

This paper proposes a dynamic addressing hybrid routing mechanism based on static configuration (DASC) in urban rail Ad Hoc networks. The contributions are as follows:

(1) In the static configuration stage, first, the improved AODV routing discovery algorithm combines the characteristics of fixed node location in urban rail scenarios and considers the remaining link lifetime between the trains and the fixed wayside nodes after clustering. It not only reduces network overhead but also prolongs the network's lifetime.
(2) Then, fixed nodes are selected and the path to each router is written in advance for static configuration to eliminate the delay in the routing discovery process.

(3) After the static configuration is completed, the cluster head dynamically monitors the packet loss rate of each link to determine whether there are links that need to be replaced. When a link that needs to be replaced is found, the dynamic addressing phase is enabled. The source node serving initiates a route replacement request to enable the route discovery algorithm, which updates the path for different types of communication services, effectively improving the packet delivery rate.

The rest of this paper is structured as follows: Section 3 introduces the network model. Section 4 presents the routing algorithm and proposes the specific network operation steps. In Section 5, the simulation results of routing discovery overhead, remainder link lifetime, packet delivery rate, throughput, and end-to-end delay are shown and compared with that of traditional AODV. Finally, Section 6 concludes the paper.

2. Related Works

In recent years, researchers at home and abroad have fully studied and optimized routing protocols that meet the communication environment of wireless Ad Hoc networks based on their characteristics. The earliest innovative research on routing technology was mainly concentrated in the mid-1990s. The MANET research team composed of IETF mainly studied the design and standardization of routing protocols for wireless Ad Hoc networks [5]. These protocols can be categorized into reactive, proactive, and hybrid routing protocols. Representative routing protocols include Dynamic Source Routing (DSR) [6], Optimized Link State Routing (OLSR) [7], Destination Sequence Distance Vector (DSDV) [8], and Ad Hoc On-Demand Distance Vector (AODV) [9].

In the DSDV routing protocol, mobile nodes periodically broadcast their routing information to their neighbors. Each node is required to maintain their routing table. The AODV protocol finds routes using the route request packet, and the route is discovered when needed. Research has shown that AODV performs better than DSDV in packet delivery ratio, throughput, and routing overhead. The delay of AODV is greater than DSDV [10]. For real-time applications, AODV performs better than the DSDV routing protocol [11]. In addition, in urban rail transit scenarios, the trackside nodes are fixed, and trains run along the track. Compared to traditional wireless Ad Hoc network nodes, the communication between them is relatively fixed, and it is not necessary to use active routing protocols to obtain the routing tables of all nodes. Therefore, active routing protocols will incur a significant amount of unnecessary overhead in this scenario. Although the delay of the AODV routing protocol is higher than that of DSDV, the algorithm proposed in this article uses static configuration to pre-configure the routing table, eliminating the delay of route discovery. In summary, the AODV routing protocol has more advantages in urban rail application scenarios compared to active routing protocols such as DSDV. Therefore, this article proposes new improvements based on the AODV routing protocol.

To continuously improve the performance of routing protocols and better adapt to the communication environment, a large number of studies have optimized routing protocols from different perspectives. Compared with the traditional AODV, the proposed improved protocol has advantages in terms of the packet delivery fraction, overhead, and route setup time.

Many researchers have made improvements to classic protocols. Sheng Liu et al. present an optimized protocol, called B-AODV, based on the shortage of routing finding and routing repair of AODV. In B-AODV, first, through a reverse request by sending BRREQ to replace RREP, it reduces the time of routing finding. Second, two hops IP recorded in control messages and the routing table can improve the rate of routing repair and reduce the time of routing finding [12]. Abdalla M. Hanashi et al. propose a new probabilistic approach that dynamically fine-tunes the rebroadcasting probability of a node for routing request packets (RREQs) according to the number of neighbor nodes. Their proposed approach demonstrates better performance than blind flooding, fixed probabilistic, and adjusted flooding approaches [13]. Ref. [14] presents a new fitness function (FFn) used in the Genetic Algorithm (GA) to obtain the optimized route from those routes offered by the Ad Hoc On-demand Multipath Distance Vector (AOMDV) routing protocol. These protocols provide an optimization process to select the efficient routes that have the highest fitness values implementing the shortest route and less data traffic. Ref. [15] proposes a new dynamic relationship zone routing protocol (DRZRP) for Ad Hoc networks. In this protocol, each node in the network establishes a neighboring zone with a radius of ρ hops and activates a relationship zone according to the service request frequency and service hotspot condition. DRZRP establishes proactive routing for the neighboring zone and relationship zone of the node, and the relationship zone of the node can be dynamically maintained, including initialization, relationship zone activation, and relationship zone inactivation. It matches the service relationship among nodes in the network and has comprehensive performance advantages in communication overhead and routing request delay, which improves the quality of the network service. Ref. [16] proposes an improved routing protocol, called L-AODV, which collects the link quality information during the broadcasting progress in network. According to the link quality information included in the arrived RREQ packets, the destination nodes choose the path after evaluating the performance by computing path cost. Experimental results show that the L-AODV routing protocol is improved in packet delivery rate. Ref. [17] presents an AODV with end-to-end reliability (AODV-EER). The main idea of the proposed modification in AODV is to find the route with the lowest drop rate from source to destination. It also proposes a backward route entry mechanism in order to initiate repair action after primary route breaks. The experiments clearly indicate that the proposed protocol performs better than the traditional AODV protocol. Ref. [18] proposes a new modified AODV routing protocol, called EGBB-AODV, where the RREQ mechanism uses a grid-based broadcast (EGBB), which considerably reduces the number of rebroadcasted RREQ packets, and hence improves the performance of the routing protocol. A simulation study shows that EGBB-AODV outperforms AODV in terms of end-to-end delay, delivery ratio, and consumption power.

Ref. [19] proposes a new link lifetime prediction method for greedy and contention-based routing. The evaluation of the proposed method is conducted via the use of a stability-based greedy routing algorithm, which selects the next hop node having the highest link lifetime. Ref. [20] proposes a link-quality- and topology-quality-based routing protocol that uses the residual link lifetime of neighbors as the metric of link quality and uses the relationship of the distance between the intermediate node and the tie line of the source-destination as the metric of topology quality. By combining the two metrics to set the forwarding probability, the proposed protocol can not only avoid frequent route disconnect, but also restricts the propagation range of RREQ. The proposed protocol can significantly reduce routing overhead, as well as increase the packet delivery ratio and decrease end-to-end delay, thus improving routing performance. Many of the reactive protocols use a route searching mechanism where a route request is flooded in the network. Ref. [21] investigates this search procedure and tries to reduce it to a limited region with the aid of location information. Different search regions, applied both in a static and an adaptive way, are investigated, greatly reducing routing overhead. Ref. [22] proposes a new probabilistic protocol called Dichotomic AODV. It aims to reduce the number of messages in RREQ using a new probabilistic and dichotomic protocol for the discovery of the destination. This protocol significantly reduces the number of RREQ packets transmitted during route-discovery operations. Ref. [23] presents a scheme called dynamic hybrid routing (DHR). The basic idea is to configure several routing policies in advance and then dynamically rebalance traffic by applying different preconfigured routing policies to react to traffic fluctuations.

Most of the above studies are based on mobile Ad Hoc networks, but there are few studies on practical application scenarios. Ref. [24] utilizes network simulator 3 to apply AODV, DSDV, and OLSR routing on V2V nodes. The evaluation criteria for the comparison of these routing protocols include the use of QoS (Quality of Service) parameters such as PLR, packet overhead, and throughput. The results of the simulation demonstrate that AODV is the most optimal method among AODV, OLSR, and DSDV for our model.

AOMDV performs well, but it does not have intelligent decision capabilities to select immediate routes by their source without discovering new routes or selecting alternate routes via intermediate nodes during failure, which diminishes performance and enhances end-to-end delay. To conquer this dilemma, Ref. [25] proposes an AOMDV intelligent decision protocol (AOMDV-ID). AOMDV-ID acts as hybrid protocol (proactive and reactive). Ref. [26] proposes an improved AODV routing protocol based on restricted broadcasting by communication zones for transmitting data in a largescale VANET. Following the maximum grey correlation degree principle, a series of key communication zones is selected to construct a restricted broadcasting area for route discovery in AODV. Simulation results show that, compared with the traditional AODV, the proposed improved protocol has advantages in packet delivery fraction, overhead, and route setup time.

3. The Network Model

The Ad Hoc network can be divided into either a flat structure or a hierarchical structure [27]. In the network of the flat structure, all nodes are equal. Such a network structure has good robustness, and the node load in the network is also relatively balanced. But a flat structure encounters efficiency and scalability problems with increased network size. In the hierarchical network, the Ad Hoc network adopts a certain cluster algorithm to form several clusters. Each cluster network consists of a cluster head and several cluster members nodes.

Clustering is an effective method for solving the scalability of Ad Hoc networks. The hierarchical structure is introduced in the network, and the nodes divided into different layers should take different functions. Also, the utilization of clustering in an Ad Hoc network possesses the advantages of reducing routing overhead, increasing network capacity, and providing scalability. Therefore, the clustering structure plays an important role in network management. In this paper, the clustering structure is used to cluster the nodes so that in the static configuration stage, the cluster head nodes and the nodes within the cluster have their own global routing tables, respectively. When the train runs into a certain cluster, fixed nodes within the cluster are selected for communication. In the dynamic monitoring stage, each cluster head node plays a role in dynamically monitoring the link status. The network topology of the train and trackside nodes is shown in Figure 1.

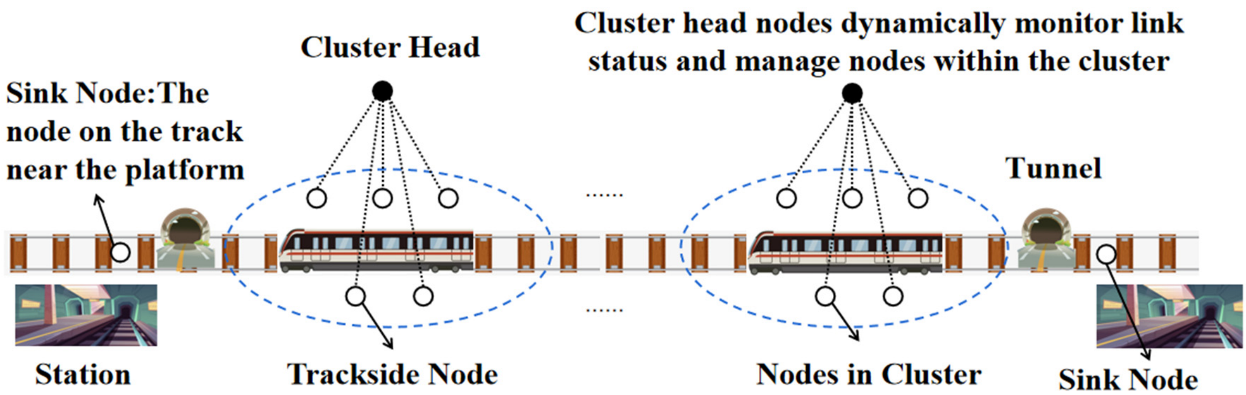

Figure 1. Network topology.

As is shown in Figure 1, in urban rail transit wireless Ad Hoc networks, the trackside nodes are arranged linearly along the track and are relatively stationary, the train nodes dynamically travel on the track, and the sink nodes are distributed at stations at both ends of the tunnel. The functions and working methods of each node are as follows:

(1) Train: Performs data transmission with the sink node of the platform. When the train runs within the range of a certain cluster, the nodes within the cluster are responsible for forwarding the messages sent by the train and selecting the most suitable node within the cluster by considering the residual link's lifetime.

(2) Trackside nodes: Forward data transmitted between trains and stations and storing routing tables for route discovery.
(3) Cluster head nodes: Master the routing information of the cluster nodes and are responsible for dynamically monitoring the link status to further determine whether the link needs to be replaced.
(4) Sink nodes: The node on the track near the platform serves as a sink node to collect data transmitted by the train and surrounding nodes.

The dynamic addressing section of this article will select paths based on three types of services with different requirements for delay and packet loss rates. The descriptions of the three services are as follows:

(1) Service 1: It has high requirements for delay and packet loss rate and features high reliability and low delay, such as train operation control service.
(2) Service 2: It has higher requirements for packet loss rate and features high reliability. For example, the passenger information service system mainly transmits video information from the ground to the train, with low requirements for delay.
(3) Service 3: It has higher requirements for delay, such as the intelligent monitoring of tunnels and other Internet of Things services, which require timely detection of problems within the tunnel.

4. Algorithm Description

This paper proposes a dynamic addressing hybrid routing mechanism based on static configuration (DASC). The algorithm consists of the improved AODV algorithm, static configuration, and dynamic addressing. In this section, the algorithm, the calculation of network parameters, and the network operation process will be introduced in detail.

4.1. Improved AODV Routing Discovery Algorithm

AODV is a classic on-demand routing protocol in Ad Hoc networks. It does not need to maintain the routing to all nodes and searches for the desired route only when needed [9]. When the source node wants to send a data packet to the destination node, the source node will start the route discovery process and establish a positive and reverse path. As shown in Figure 2, the letters A–E in Figure 2 represent nodes, source node A broadcasts a route request (RREQ) message to adjacent node B and C, then C and B will establish a reverse routing, and B will continue to forward the RREQ message to C. At this time, C returns to A with two reverse paths. So, the minimum jump path is selected to forward route reply (RREP) to find the shortest path from the source node to the target node [28].

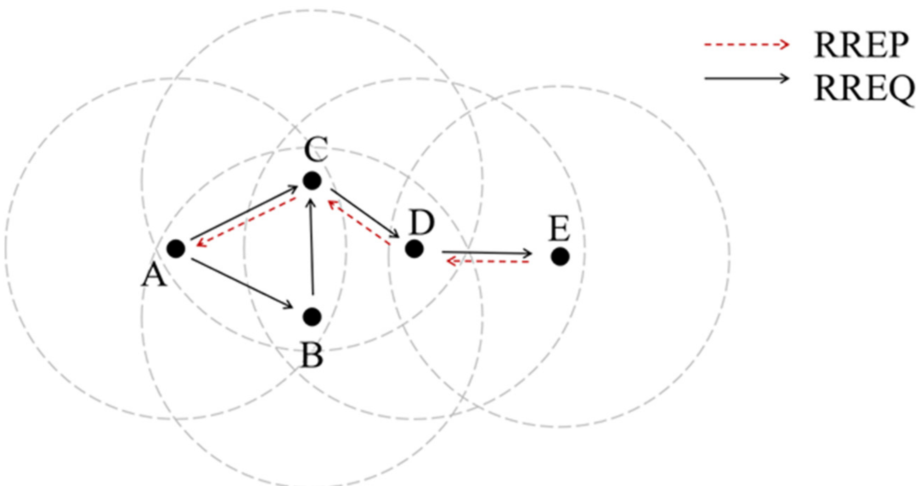

Figure 2. Route establishment process.

Because of its on-demand characteristics, the AODV routing protocol only establishes and maintains the required routes, reducing the burden of routing tables. Therefore, it has certain advantages in saving network overhead and channel resources, but it still has the following shortcomings:

(1) In the route discovery process, it broadcasts RREQ messages to the target node in the form of flooding [12]. Since each node rebroadcasts the RREQ packet when each node receives the RREQ packet, the possible number of rebroadcasts when the destination node is reached at the destination node is around N^2, where N is the total number of network nodes. This method of broadcasting may lead to excessive redundant retransmissions in the congestion network, bring a large delay, and result in a large network overhead [22].

(2) The AODV routing protocol is based on the fewest hops as the basis for the chosen path. This method of judgment is not very reasonable in actual applications because the minimum jump is not the same as the shortest communication distance. The farther the distance is, the greater the loss.

To address the shortcomings of the AODV routing discovery algorithm, a better algorithm is designed in this paper to decrease routing discovery overhead and avoid route breaking.

First, this paper adds a routing cost to RREQ messages to reflect the link quality of the path. Every intermediate node which receives the RREQ packet computes the routing cost and records it to evaluate the path performance instead of using the minimum number of hops as the only judgment basis for selecting the path. Secondly, a probabilistic approach to flooding is considered to select the flood area to reduce the number of RREQs. In the fixed probability route discovery, the possible broadcast number of RREQ packets is $p \times N^2$ [22]. In the improved algorithm, a special zone for routing discovery is defined according to the nodes' geographic positions, which are known due to the fixed characteristics of the trackside nodes in the urban rail scenario, so flooding in the whole network is no longer needed. The improved algorithm restricts the flooding to the area in the direction of the source and direction node, which greatly reduces the overhead of route discovery. At the same time, in the application scenario of urban rail in this paper, because of the continuous power supply of trackside nodes, the situation of energy exhaustion does not exist. Therefore, this paper considers the direct use of existing paths, reducing the number of broadcast RREQ messages and further reducing the overhead of routing discovery. The specific improved routing discovery algorithm in this paper is as follows.

The algorithm improves the judgment basis for selecting the path. A path P with length L is assumed, consisting of device D1, D2,..., Dn, and the corresponding link is [D_i, D_{i+1}]. The calculation of the cost of path P is shown in (1), where $C([D_i, D_{i+1}])$ is the link cost, which is shown in (2) [16].

$$C(P) = \sum_{i=1}^{L-1} C([D_i, D_{i+1}]), \tag{1}$$

$$C([D_i, D_{i+1}]) = \min\left[7, round(\frac{1}{(1-P_L)^4})\right], \tag{2}$$

where $1 - P_L$ is the probability that a data packet can be successfully sent on a certain link, and $C([D_i, D_{i+1}])$ indicates the link cost, which uses the values of 1, 3, and 7 to indicate the quality of the link. A value of 7 indicates poor link quality and the highest link cost, while values 1 and 3 divide the cost of the link. The calculation result of $round(1/(1-P_L)^4)$ is a number greater than 1, which can represent the link cost. When the calculation result is greater than 7, it indicates that the link quality is poor at this time, and the value of 7 is used as the link cost. When the calculation result is less than 7, the calculation result is used as the link cost. This article uses Formula (2) to use integers to assign link generation values to each link, thereby representing the quality of its link.

When the source node initiates the routing discovery algorithm, it selects the flooding area according to the location of the destination node. When a node receives the RREQ message, it will forward RREP via reverse routing by comparing the C(P) routing value, which can be obtained by (1) in the received RREQ message. Thereby, a path with high link quality will be determined, which balances the network traffic load and improves the overall performance of the network [16].

The improved algorithm also reduces the routing discovery overhead by storing existing paths directly in the routing table and setting flag bits in the routing table to indicate whether the node has a path to the destination node. Unlike the conventional AODV principle of looking for the minimum hop path, when a node finds that there is a path to the destination node, it directly uses the existing path without focusing on finding the minimum hop number. As shown in Figure 2, the following steps occur when a node sends data to the destination node:

(1) When node D is used as the source node, it sends the RREQ message with a link cost. After receiving the RREQ packet, each current node first observes whether there is a path to the destination node through the flag bit of the routing table. Assuming that there is no path at this time in the initial stage of network operation, it extracts the link cost value and accumulates it with the current cost value to store it again in the RREQ packet for forwarding. Then, destination node A will extract the carrying information of several RREQ packets from the cache queue, calculate the minimum routing cost value according to Formula (1), and then reply to the RREP message along the corresponding link to establish a reverse path, assuming the D $\rightarrow$ C $\rightarrow$ A route is established.

(2) When node E is used as the source node, it first sends RREQ messages and finds whether the node in the communication range has a path that can reach destination node A by observing the flag bit. At this time, node E finds that the flag bit in the Routing table of its adjacent node D shows its existing path to the destination node A, and the route of node E to node A is directly recorded as E $\rightarrow$ D $\rightarrow$ C $\rightarrow$ A.

(3) If the adjacent nodes of node E do not have a direct path to reach node A, node E normally performs the RREQ broadcasts similar to step 1 until it finds a path to A or an adjacent node within the communication range of a certain hop that has a path to reach node A.

The above routing discovery process has greatly reduced the overhead of routing discovery due to the characteristics of a fixed flooding area and the full utilization of the existing paths. The route with better link quality is selected based on the routing cost carried by the RREQ message, which improves the overall performance of the network. Therefore, the urban rail application scenario in this article has certain advantages over the conventional AODV routing.

4.2. Static Configuration in Clustered Networking

In the application scenario of the urban rail network, due to the high speed of trains, the network topology is highly dynamic. In the AODV routing protocol, each node in a network only discovers routing on demand. On the one hand, due to the continuous changes in network topology, routing discovery needs to be initiated continuously, resulting in a large amount of routing overhead. On the other hand, the delay in the routing discovery process cannot be ignored. Therefore, this paper separates the whole network into clusters. Whenever the train runs into a cluster, the train is transmitted with a fixed node in the cluster to avoid routes interrupted by changes in network topology. Regarding the selection of fixed nodes in the cluster, this paper uses the concept of residual link lifetime (RLL) to calculate the lifetime between the train and the fixed nodes in the cluster, then chooses the nodes with a longer residual link lifetime to ensure the stability of the link. Because the trackside nodes in the urban rail scenario are fixed, and when a fixed node within the cluster is selected, the routing table of the fixed node can be statically configured in advance, eliminating the delay of route discovery.

The network in the hierarchical structure is divided into several clusters composed of cluster heads and clusters. Unlike all nodes in a flat structure that need to maintain routing information for all other nodes in the network, cluster members only need to save routing information within the cluster, reducing overhead and making it more flexible. In hierarchical structures, different clustering algorithms are used depending on the requirements of the optimization criteria for the scenario. Reducing cluster maintenance and computing overhead, rationalizing the cluster structure, extending network lifetime, and maximizing cluster head distribution are common cluster optimization criteria. In the urban rail application scenario in this article, nodes are clustered. The role of cluster heads is to uniformly manage the location and routing information of nodes within the cluster and dynamically monitor the link status between nodes in the cluster. The communication requirements between cluster heads are not high. In addition, the location of trackside nodes in urban rail scenarios is fixed, so the requirements for cluster structure are not high. Therefore, clustering based on the geographical location of nodes is considered.

Among numerous clustering algorithms, the geographical adaptive fidelity (GAF) [29] clustering algorithm is a typical adaptive clustering algorithm based on the geographical location of nodes, which divides the entire area of node distribution into small virtual grids. The definition of virtual grids is that any two nodes within two adjacent cells can communicate directly, and nodes are divided into corresponding virtual networks based on their geographical location information. The GAF algorithm makes the network evenly clustered and has a stable topology. This paper uses the GAF algorithm for clustering, combining the characteristics of fixed location of urban rail nodes.

When selecting the node in the cluster that communicates with the train, this article introduces the concept of the residual link lifetime [20]. The train node moves in a fixed direction and speed on the track. Assuming that the current position of the training node N_i is (x_i, y_i), the speed is (u_i, v_i), and the current position of the node in N_j is (x_j, y_j), and the speed is (uj, vj), define x_{ij}, y_{ij}, u_{ij}, and v_{ij} as

$$\begin{cases} x_{ij} = x_i - x_j \\ y_{ij} = y_i - y_j \\ u_{ij} = u_i - u_j \\ v_{ij} = v_i - v_j \end{cases}. \tag{3}$$

The distance between two nodes after t seconds is computed as

$$D(t) = \sqrt{(x_{ij} + u_{ij}t)^2 + (y_{ij} + v_{ij}t)^2}. \tag{4}$$

Two nodes move independently. When one node reaches the transmission boundary of the other node after t seconds, the link will be disconnected. At this point, $D(t) = R$, where R is the communication radius and t represents the connection time of the two nodes. Following the above equation, the calculation result t of the function is defined as the residual link lifetime (RLL); it can be obtained that RLL is

$$RLL = \frac{-B + \sqrt{B^2 - 4AC}}{2A}, \tag{5}$$

$$\begin{cases} A = {u_{ij}}^2 + {v_{ij}}^2 \\ B = 2(x_{ij}u_{ij} + y_{ij}v_{ij}) \\ C = {x_{ij}}^2 + {y_{ij}}^2 - R^2 \end{cases}. \tag{6}$$

Calculate the residual link lifetime of all nodes in the cluster when the train nodes run into the cluster, and select the node in the cluster with the longest residual link lifetime as the node communicating with the train. At this time, the segment of the link has good stability. Next, statically configure the fixed source node using an improved routing discovery algorithm. After static configuration, perform the following dynamic addressing algorithm.

4.3. Dynamic Addressing

In the application scenario of urban rail transit, when the channel quality gradually deteriorates, and the packet loss rate gradually increases, a certain segment of the link is no longer suitable as a communication link. For traditional AODV routing protocols, the routing discovery algorithm is only initiated when the communication link breaks. But due to the real-time nature of urban rail transit, on the one hand, replacing a link when it fails causes significant losses. On the other hand, restarting the routing discovery algorithm due to path interruption also has a certain impact on the overall performance of the network. Therefore, a dynamic addressing algorithm is proposed to monitor link status and dynamically update routes to minimize the losses and avoid the overhead of initiating route discovery, ensuring the communication reliability of the urban rail Ad Hoc network.

In the dynamic addressing section, the source node of each path periodically sends detection packets to calculate the packet loss rate of each link segment. We define a packet loss threshold that determines whether the link needs to be replaced at this time. Each cluster head dynamically monitors whether the packet loss rate of each link segment in the path is lower than the threshold. When the packet loss rate of a certain link segment is bigger than the threshold, the link segment needs to be replaced. Each cluster head maintains the links of its member nodes and executes the dynamic addressing algorithm. Finally, the algorithm selects different updated paths according to different types of communication services.

The algorithm proposes the following six schemes for replacing links and calculates the path state weights for each scheme based on the traffic types of communication services. Then, it selects a new path corresponding to different service types based on the weights. Later, through simulation verification, the algorithm in this paper is compared with traditional AODV routing protocols.

Let us assume that a statically configured path A $\rightarrow$ B $\rightarrow$ C $\rightarrow$ D $\rightarrow$... is found. When it is found that link A $\rightarrow$ B needs to be replaced, this link will not be selected again in the next dynamic addressing of this cycle. Routing discovery will be enabled to select a new path according to the scheme shown in Table 1.

Table 1. Dynamic addressing scheme.

Schemes	Source Node for Routing Discovery	Destination Node for Route Discovery
Scheme 1	A	B
Scheme 2	A	C
Scheme 3	A	D
Scheme 4	Consider both Scheme 1 and Scheme 2 and select a link with a low packet loss rate	
Scheme 5	Consider both Scheme 1 and Scheme 3 and select a link with a low packet loss rate	
Scheme 6	Consider Scheme 1, Scheme 2, and Scheme 3 and select a link with a low packet loss rate	

If only to find the paths between nodes A and B, there may be too many hops between the two nodes, resulting in excessive hops between the two nodes and increasing data forwarding delay. Therefore, based on Scheme 1, Scheme 2 and Scheme 3 are proposed, Scheme 4, Scheme 5, and Scheme 6, which combine the above three schemes, are further proposed. The reason why Schemes 4~6 are proposed is to fully consider the combination of various options and then select the best update path.

Then, detection packets are sent to calculate the packet loss rate of the newly found path and compare it with the original. The better path is selected, and all bad links in the statically configured path from the source node to the destination node are sequentially replaced. Different new paths are obtained using Schemes 1 to 6.

Due to the different types of communication services having different requirements for packet loss rate and delay, the update paths in Schemes 1 to 6 also have different performances in packet loss rate and delay. Therefore, this algorithm selects different update paths based on different service types.

Service 1 has equally important requirements for packet loss rate and delay, Service 2 has higher requirements for packet loss rate, and Service 3 has higher requirements for delay. When a certain segment of the link needs to be replaced, the path is updated using Schemes 1 to 6, and the path state weights of the three services corresponding to the six schemes are calculated. The scheme with the lowest weight value is selected as the new path for transmitting this type of service. Before calculating the weight, it is necessary to normalize the data. The specific weight calculation formula for the train running to a certain point is computed as

$$loserate'(i) = \frac{loserate(i) - \min(loserate)}{\max(loserate) - loserate(i)}, \tag{7}$$

$$T\_delay'(i) = \frac{T\_delay(i) - \min(T\_delay)}{\max(T\_delay) - T\_delay(i)}, \tag{8}$$

$$weight\_1(i) = 0.5 * loserate'(i) + 0.5 * T\_delay'(i), \tag{9}$$

$$weight\_2(i) = 0.7 * loserate'(i) + 0.3 * T\_delay'(i), \tag{10}$$

$$weight\_3(i) = 0.3 * loserate'(i) + 0.7 * T\_delay'(i), \tag{11}$$

where the range of i is 1 to 6, which represents the six schemes for updating the path. $Loserate(i)$ represents the packet loss rate value of the new path updated by the six schemes. $Loserate'(i)$ represents the normalization of the packet loss rate. $T\_delay(i)$ represents the delay value of the new path updated by the six schemes, and $T\_delay'(i)$ represents the normalization of delay. Moreover, $weight\_1$, $weight\_2$, and $weight\_3$ represent the path state weight values of six new paths corresponding to the three service types. Finally, we select a new path with the lowest weight as the update path for this service type.

The following will give an example of the specific dynamic addressing section, as shown in Figure 3, the cross symbols indicate that the link needs to be replaced, and the letters A–M represent the nodes. Suppose a statically configured path $A \to B \to C \to D \to E \to F \to G$. When the cluster head dynamically monitors the packet loss rate and finds that the packet loss rate of the three links $A \to B$, $B \to C$, and $D \to E$ is bigger than the threshold, the link needs to be replaced. Initiate the routing discovery algorithm and select a new path according to the six schemes in Table 2.

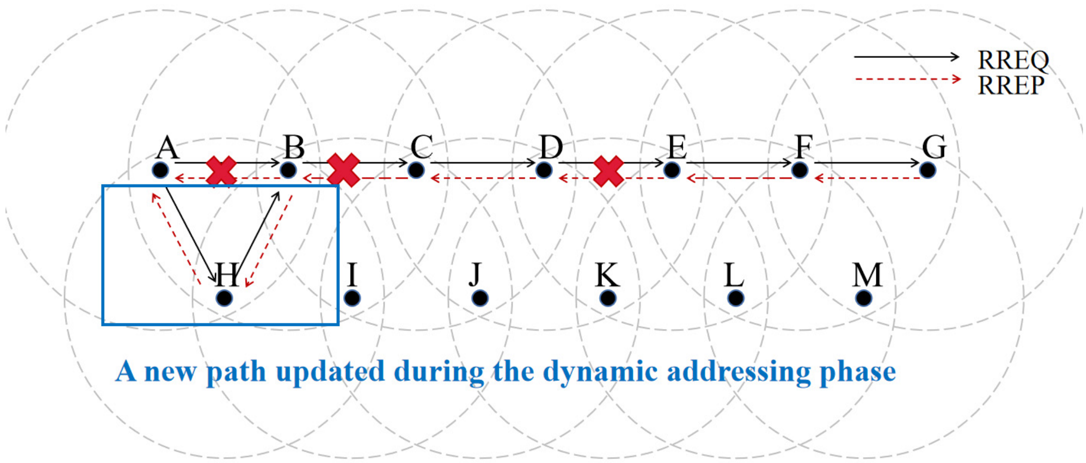

Figure 3. Dynamic addressing process.

Table 2. Example of dynamic addressing.

Schemes	Path between AB	Path between BC	Path between DE	New Path
Scheme 1	(A,H,B)	(B,I,C)	(D,K,E)	(A,H,B,I,C,D,K,E,F,G)
Scheme 2	(A,H,I,C)		(D,K,L,F)	(A,H,I,C,D,K,L,F,G)
Scheme 3	(A,H,I,J,D)		(D,K,L,M,G)	(A,H,I,J,D,K,L,M,G)
Scheme 4	(A,H,B)	(B,I,C)	(D,K,L,F)	(A,H,B,I,C,D,K,L,F,G)
Scheme 5	(A,H,B)	(B,I,C)	(D,K,L,M,G)	(A,H,B,I,C,D,K,L,M,G)
Scheme 6	(A,H,B)	(B,I,J,D)	(D,K,L,M,G)	(A,H,B,I,J,D,K,L,M,G)

If Service 1 is being transmitted, first calculate the packet loss rate and delay of the path updated by the above six schemes, then calculate the weight of each path through Formulas (7)–(9). Similarly, for Service 2 and Service 3, calculate the weight through Formulas (10) and (11) and ultimately select the path with the lowest weight value as the update path.

4.4. Calculation of Network Parameters

The Logarithmic distance path loss model is as

$$P_L = 20\lg(\frac{4\pi d}{\lambda}) + 10n\lg d + X_\sigma, \tag{12}$$

where d is the distance between two communication points, $\lambda = c/f_c$, n is the path loss exponent, and X_σ represents a Gaussian random variable with a mean value of 0 and a standard deviation of σ.

The packet delivery ratio is an important indicator to evaluate whether a routing protocol is reliable, and it is the ratio between the number of packets that reach the destination and the number of packets generated by the source.

When calculating the end-to-end delay, which is the average time to receive data from the source to the destination, this paper uses the M/M/1 model to analyze the queuing time. The probability distribution of the service time is exponential with a mean $1/\mu$ sec. $E[X] = 1/\mu$ is the average service time, and the second-order moment is $E[X^2] = 2/\mu^2$. $E[W]$ is the average latency of the packets in the queue, and $E[Q]$ is the average queue length when the packets arrive. $E[T]$ is the average latency of the data packets within the system. The calculation formula is as follows:

$$E[W] = \frac{\lambda E[X^2]}{2(1-\rho)} = \frac{\rho}{\mu(1-\rho)}, \tag{13}$$

$$E[Q] = \frac{\lambda^2 E[X^2]}{2(1-\rho)} = \frac{\rho^2}{1-\rho}, \tag{14}$$

$$E[T] = \frac{1}{\mu} + \frac{\rho}{\mu(1-\rho)} = \frac{1}{\mu - \lambda}, \tag{15}$$

where μ represents the service rate, which refers to the number of packets that a router can serve per unit of time. λ is the number of packets arriving at a router per unit of time, $\rho = \lambda/\mu$.

When calculating the end-to-end time delay, it is necessary to consider the queuing delay when packets are forwarded through each router. Therefore, λ is not a fixed value but is determined based on the arrival rate of the previous router and the average waiting time of the packets in the previous system. The arrival rate of the kth router λ_k is

$$\lambda_k = \frac{1}{\frac{1}{\lambda_{k-1}} + E(T)_{k-1}}. \tag{16}$$

The end-to-end delay of AODV consists of propagation delay, queuing delay, and route discovery delay. The delay of DASC consists of propagation delay and queuing delay, eliminating the delay of route discovery.

Routing discovery overhead is the ratio between the number of control packets (RREQ and RREP) and the number of messages that are sent in the network:

$$cost = \frac{num\_RREQ + num\_RREP}{num\_packet}, \quad (17)$$

where *cost* is the routing discovery overhead; *num_RREQ* is the valid RREQ packets for routing discovery broadcasts; *num_RREP* is the number of packets sent during route discovery to establish a reverse path, which equals to the number of hops in the path discovered by the route; and *num_packet* is the total number of data packets sent by the source node.

4.5. The Network Operation Process

The network operation flow chart is shown in Figure 4.

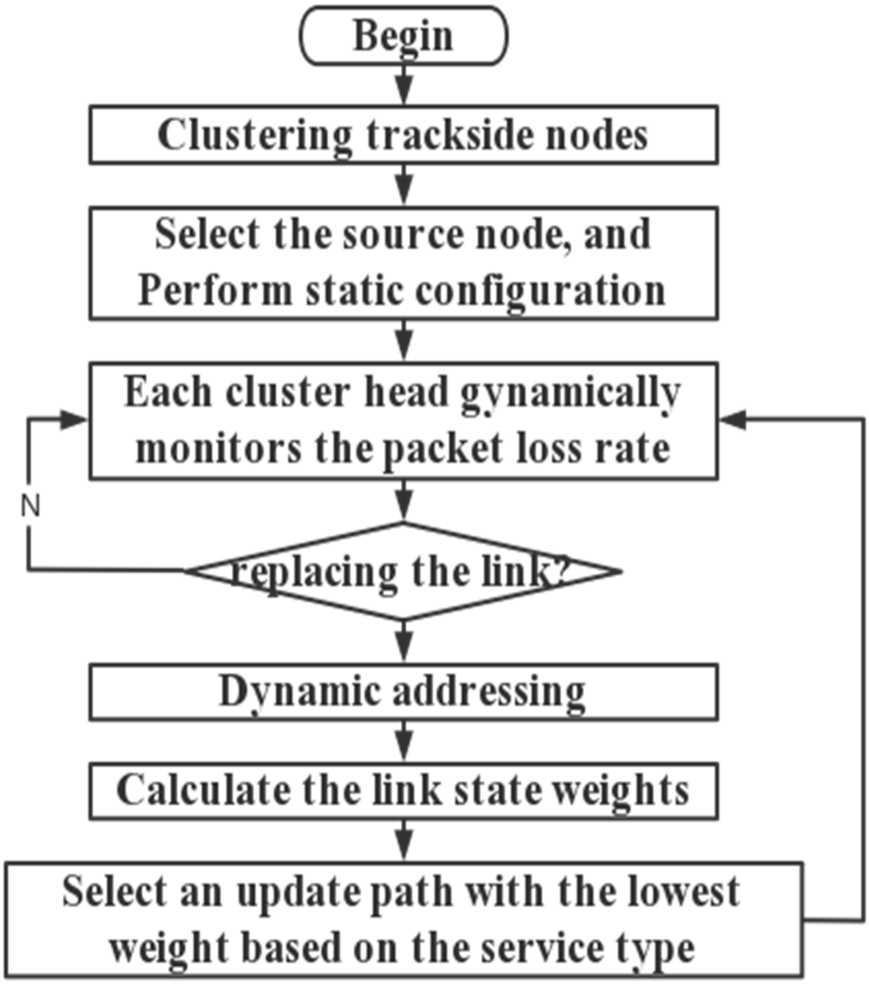

Figure 4. The flow chart of the network operation.

According to the above discussions, the proposed method is presented in Algorithm 1.

Algorithm 1: A dynamic addressing hybrid routing mechanism based on static configuration (DASC)

Result: dynamically update routing table;
Using GAF clustering algorithm to divide nodes into different clusters
Step 1: choose the nodes communicating with the train
calculate the residual link lifetime of all nodes in the cluster $RLL = \frac{-B+\sqrt{B^2-4AC}}{2A}$
select the node in the cluster with the longest remaining link lifetime
Step 2: static configuration
using improved AODV algorithm for route discovery
for static configuration **do**
    the selected nodes in step 1 as the source nodes
    source node sends the RREQ message with link cost
    current node receives the RREQ packet and observes the flag bit
    for there is no path to the destination node **do**
        extract the link cost value and accumulates it with the current cost value
        store it again in the RREQ packet
        if current node is the destination node **then**
            extract the carrying information of several RREQ packets
            calculate the minimum routing cost value $C(P) = \sum_{i=1}^{L-1} C([D_i, D_{i+1}])$
            reply to the RREP message along the corresponding link
            establish a reverse path
        end
    end
    if there is a path to the destination node **do**
        directly write existing paths to the routing table
    end
end
Complete the configuration of the routing table
Step 3: dynamic addressing
Each cluster head dynamically monitors the packet loss rate of each link in the path
for the packet loss rate of a certain link is higher than the threshold **do**
    obtain new paths by using Scheme 1~6
    calculate end-to-end delay and loss rate
    normalization $T\_delay'(i) = \frac{T\_delay(i)-\min(T\_delay)}{\max(T\_delay)-T\_delay(i)}$
    normalization $loserate'(i) = \frac{loserate(i)-\min(loserate)}{\max(loserate)-loserate(i)}$
    select a new path with the lowest weight as the update path
    if service 1 is being transmitted **then**
        calculate $weight\_1(i) = 0.5 * loserate'(i) + 0.5 * T\_delay'(i)$
        choose a new path with the lowest weight as the update path
    end
    if service 2 is being transmitted **then**
        calculate $weight\_2(i) = 0.7 * loserate'(i) + 0.3 * T\_delay'(i)$
        choose a new path with the lowest weight as the update path
    end
    if service 3 s being transmitted **then**
        calculate $weight\_3(i) = 0.3 * loserate'(i) + 0.7 * T\_delay'(i)$
        choose a new path with the lowest weight as the update path
    end
end
Update the routing table

5. Simulation and Analysis

Compared to the AODV protocol, this paper uses MATLAB to simulate the proposed routing algorithm and analyzes the routing discovery overhead, residual link lifetime, packet delivery rate, end-to-end delay, and network throughput.

The simulation network topology in this paper is shown in Figure 1, and the simulation parameters are shown in Table 3. The network runs for 100 rounds. The simulation compares the AODV routing protocol with the dynamic addressing hybrid routing mechanism based on the static configuration proposed in the third part of this article.

Table 3. Parameters of simulation.

Parameter	Value
Tunnel length	2000 m
Tunnel width	3 m
Number of nodes	150
Transmission range	90 m
Transmit power	0 dBm
Receiving sensitivity	−87 dBm
Packet loss rate threshold	1%
Packet length	256 × 8 byes
Train running speed	20 m/s
Bandwidth	2 Mbps

5.1. Improved AODV

5.1.1. Routing Discovery Overhead

This article uses an improved AODV route discovery algorithm. As shown in Figure 5, the simulation results of train location and route discovery overhead are described. For the route discovery part of traditional AODV routing protocols, starting from the source node, each node in the scenario must send RREQ packets to its neighboring nodes. The effective RREQ packets are sent to all nodes adjacent to the node but not adjacent to the previous hop node until a minimum-hop path to the destination node is found. As for the improved routing discovery algorithm, due to the fixed locations of wayside nodes, on the one hand, it only sends RREQ packets to the determined direction and does not need to broadcast throughout the entire network. On the other hand, the improved routing discovery algorithm greatly utilizes existing paths, reducing routing discovery overhead. From Figure 5, it can be seen that the route discovery overhead of the AODV routing protocol increases as the distance from the source node to the destination node increases. This is because the farther the distance is, the larger the flooded area will be. This article sets two destination nodes at stations at both ends. When the train travels from the starting station to the destination station, due to the closer distance between the train and the destination node at the starting station, the train will communicate with the destination node at the starting station, causing the train to be further away from the destination node. When the train travels in the second half of the journey, it will be closer to the destination node of the terminal station, so it will communicate with the destination node of the terminal station, causing the train to become closer to the destination node. Therefore, there will be a trend of increasing and then decreasing routing discovery overhead. The route discovery overhead of the improved route discovery algorithm is significantly smaller than that of traditional AODV routing protocols, highlighting the advantages of the improved route discovery algorithm.

5.1.2. Packet Delivery Rate of Improved AODV

As shown in Figure 6, the simulation results of train location and packet delivery rate are described. The improved AODV route discovery algorithm has a weak advantage in improving the packet delivery rate. As the distance between the train location and the sink node increases, the gap between the two becomes larger because, during route discovery, the improved AODV route discovery algorithm utilizes the routing cost value to select paths with better link quality, and in the subsequent route discovery process, it will use paths with better link quality that have already been found. Compared with the AODV route discovery algorithm, it has been searching for the path with the minimum number of hops. When the source and destination nodes are close, the number of hops is small, and the path difference between the two points is not significant. Therefore, the difference in packet delivery rate is small. When the source and destination nodes are far away, the diversity of paths increases with more hops. The improved AODV routing discovery algorithm makes more use of existing paths with good link quality, while AODV continues to search for the minimum-hop path. Therefore, the improved AODV routing discovery algorithm has advantages.

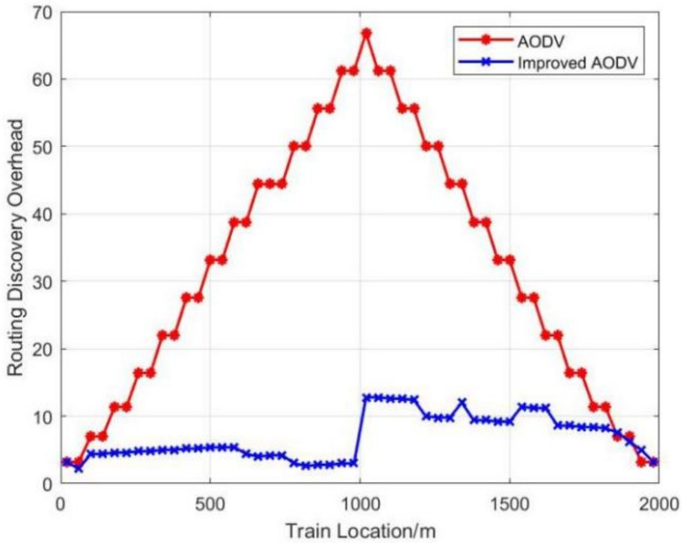

Figure 5. Routing discovery overhead comparison of different locations.

5.2. Residual Link Lifetime

As shown in Figure 7, the simulation results of the train location's residual link lifetime are shown. As can be seen from Figure 7, for nodes selected without considering the residual link lifetime, the residual link lifetime between them and the train is smaller; that is, the link lifetime is shorter and does not have good stability.

Figure 8 shows the relationship between the residual link lifetime and the train speed. It shows that the residual link lifetime between the train and the fixed node reduces when the train speed increases because, as the train speed increases, the distance between the fixed node and the train will change faster and faster until it exceeds the communication range. It also shows that a static configuration that considers the residual link lifetime has a better life. The following two simulation diagrams reflect the advantages of static configuration considering the residual link lifetime.

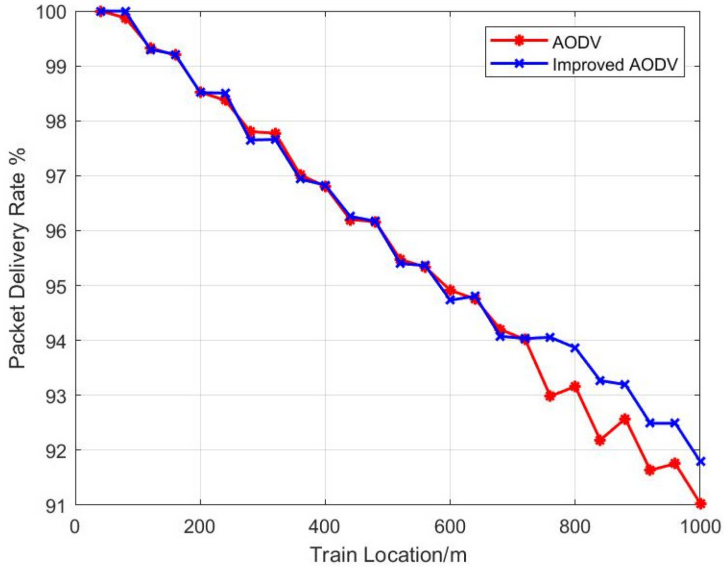

Figure 6. Packet delivery rate comparison of improved AODV and AODV.

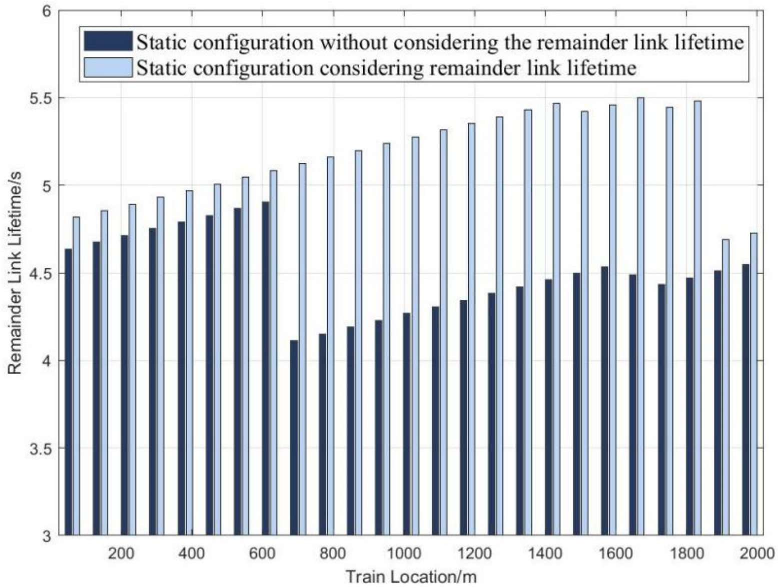

Figure 7. Residual link lifetime comparison of different locations.

5.3. Packet Delivery Rate

Figure 9 shows that the packet delivery rates of transmission Services 1, 2, and 3 in the dynamic addressing hybrid routing mechanism algorithm based on the static configuration in this article are higher than those of traditional AODV routing algorithms. As the distance between the train location and the sink node increases, the gap between the two becomes larger because when the state of a link is not good, the traditional AODV protocol does not replace links and will continue to deteriorate until the link state is broken. However, the improved algorithm will dynamically monitor links and replace links when the link state is not good.

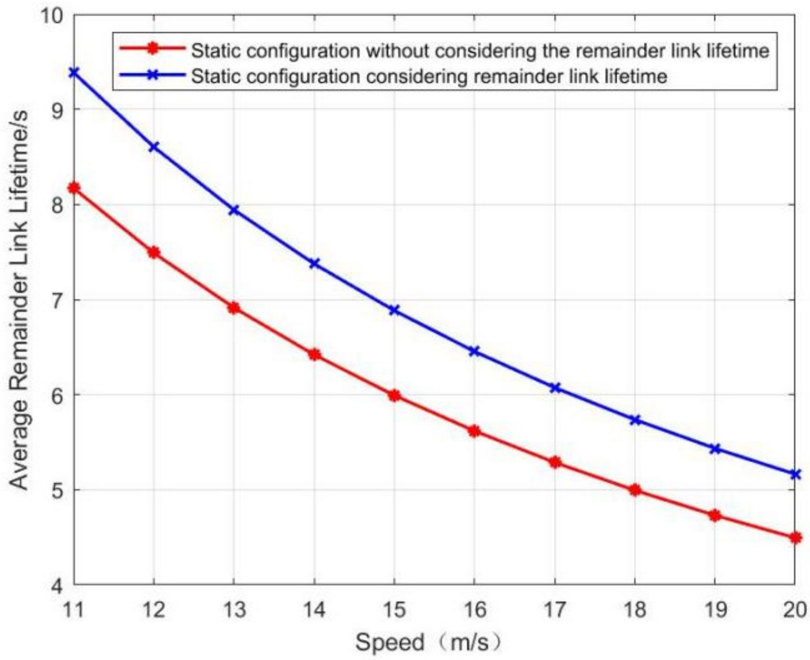

Figure 8. Average residual link lifetime comparison of different speeds.

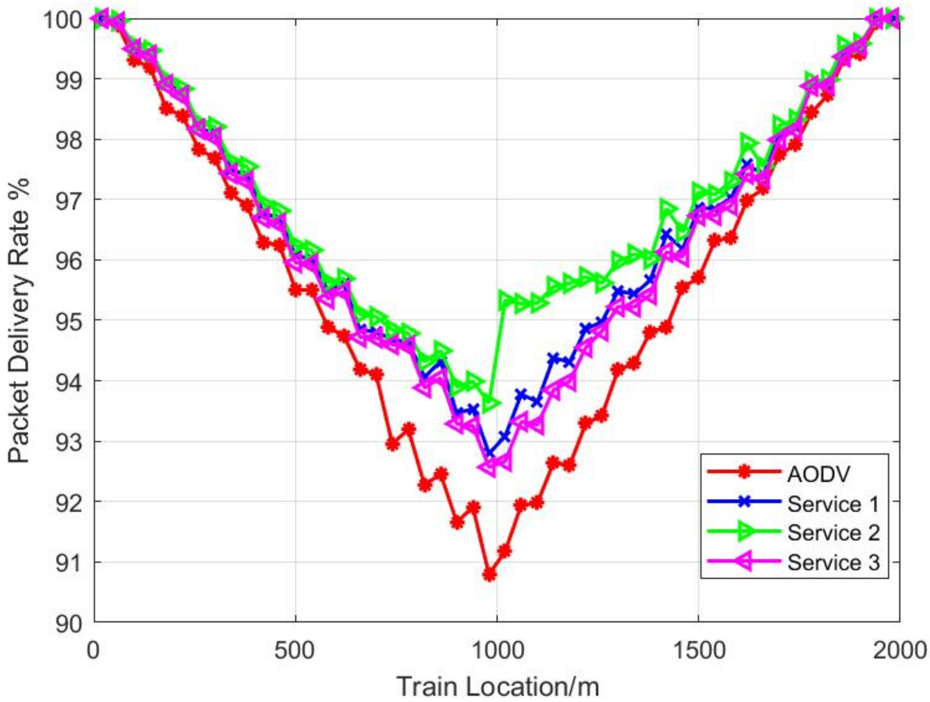

Figure 9. Packet delivery rate comparison of different locations.

Because Service 2 has high requirements for packet loss rate when calculating the link state weight to select a path, the path with the best packet loss rate is selected. Therefore, Figure 9 shows it has the highest packet delivery rate. Correspondingly, Service 3 pays more attention to delay and has low requirements for packet loss rate, so its packet delivery rate is relatively lower. Due to the same emphasis on delay and packet loss rate in Service 1, the packet delivery rate value in Service 1 is in the middle.

The reason why the packet delivery rate of the algorithm in this article can increase is the diversity of the six schemes when updating the path, which ensures that different service types can correspond to the path that best matches the characteristics of the service type, highlighting the overall advantage of dynamic addressing.

Overall, this article takes the convergence node as the destination node and sets it at the stations at both ends. The train travels from the starting station to the destination station. When the train travels in the first half of the journey, it will communicate with the destination node of the closer starting station, and the distance between the train and the destination node will increase; When the train travels in the second half of the journey, it will communicate with the destination node at the destination station, and the distance between the train and the destination node will decrease. Therefore, the packet delivery rate will first decrease and then increase as the distance between the source node and the destination node changes.

Assuming that each node has 1000 packets of data to be sent within each operation cycle and the network runs 100 rounds, the packet loss rate is calculated by counting the number of data packets successfully received by the destination node when the train runs to a certain location. Figure 10 shows the change curve of packet loss rates for different rounds of nodes at a certain location, and Table 4 shows a comparison of the average packet loss rate. It can be seen that the AODV routing protocol has the highest packet loss rate.

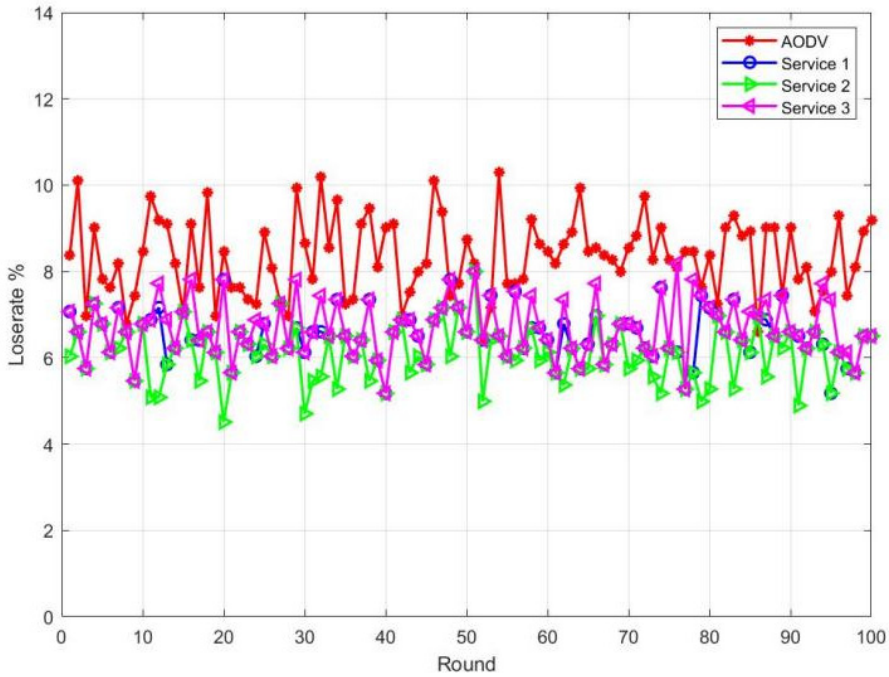

Figure 10. Packet delivery rate comparison of different rounds.

Table 4. Average packet loss rate.

Curve	Value
AODV (red curve)	0.0834
Service 1 (blue curve)	0.0654
Service 2 (green curve)	0.0610
Service 3 (pink curve)	0.0671

5.4. End-to-End Delay

Figure 11 shows the end-to-end delay. In this figure, due to the high requirements for packet loss rate in Service 2, the number of hops will increase in most cases due to the changed path. Data will be forwarded through multiple hops, so the queuing delay will significantly increase. Service 3 has a high requirement for the delay, as the changed path will reduce the number of forwarded hops in most cases, so the probability of the number of hops will not increase, or the overall number of hops will not increase significantly. Therefore, data will be forwarded through fewer hops, greatly reducing the queuing delay. Service 1 has a relatively median delay value due to its equal emphasis on delay and packet loss rate. The above analysis results generally highlight the advantages of static configuration. Moreover, as the arrival rate increases, the queuing delay will continue to increase, leading to an increase in end-to-end delay.

5.5. Throughput

Figure 12 shows the comparison of throughput values for different schemes. It is clear from Figure 12 that the proposed algorithm achieves better throughput values than the AODV routing protocols. Service 1 and Service 3 have the highest throughput because their packet loss rate values are relatively moderate, and the delay values are lower. The throughput value of Service 2 lies between Services 1 and 3 and the AODV routing protocol because its packet loss rate value is relatively small compared to Services 1 and 3, and its delay is larger than Services 1 and 3. The AODV routing protocol has the smallest throughput because of its high packet loss rate and large delay, so the average rate of packets successfully arriving at the destination node from the source node is low. After the above analysis, this algorithm can improve the throughput of the system.

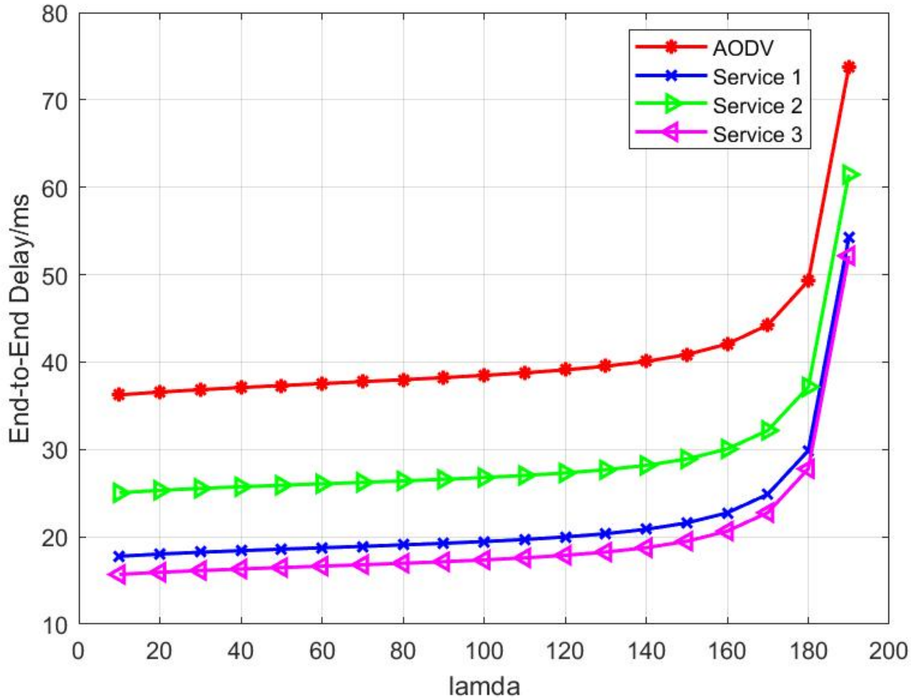

Figure 11. End-to-end delay comparison of different lambda.

Overall, according to the description above, the distance between the source node and the destination node during the train's journey from one end to the other will first increase and then decrease, and the packet delivery rate and end-to-end delay will also show this trend. Throughput represents the volume of data that is delivered to the destination within each time unit, so it will also show a trend of decreasing first and then increasing.

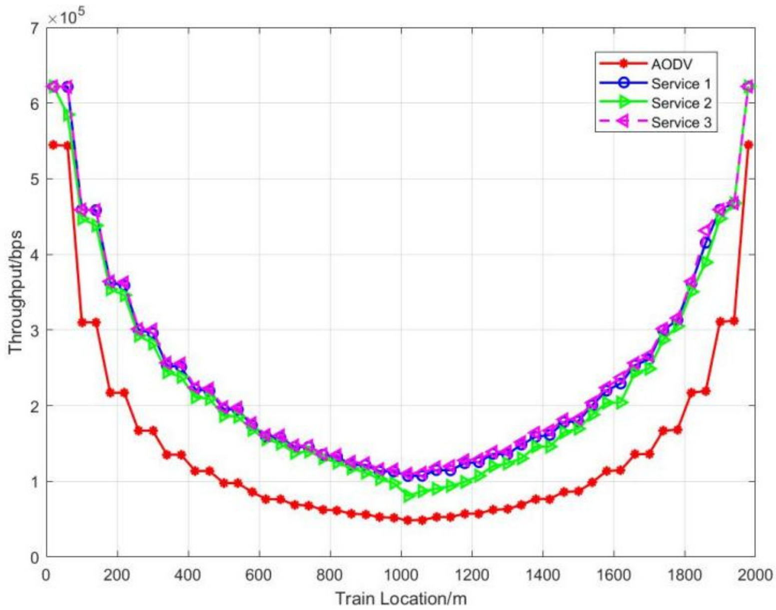

Figure 12. Throughput comparison of different locations.

6. Conclusions

Starting from the wireless communication requirements of urban rail transit, this paper studies routing strategies with low latency and high reliability in rail transit scenarios and proposes DASC from the perspective of route updates. This algorithm utilizes an improved

AODV routing discovery algorithm, selects fixed nodes with a high residual link lifetime to communicate with the train after clustering, and writes the routing table to the router in advance to eliminate the delay caused by routing discovery. The link status of each link is dynamically monitored through detection packets, avoiding the loss caused by replacing the link after the link has been broken during real-time communication. On this basis, different update paths are selected based on the type of communication service. Finally, compared with traditional AODV protocols, simulation results are obtained, verifying the improvement of the proposed algorithm. Compared with traditional AODV, the DASA could reduce the routing discovery overhead by 95% at most, improve the packet delivery rate by 4.6% at most, improve the throughput by 50% at most, and lower the average end-to-end delay by 57% at most.

Author Contributions: Conceptualization, L.L.; Methodology, Z.S.; Software, Z.G.; Validation, S.C.; Investigation, L.S.; Resources, H.H.; Writing—original draft, Z.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Beijing Natural Science Foundation under the grant of [L211002].

Data Availability Statement: Since the data in this paper will continue to be used in the future, participants of this study did not allow data to be publicly shared.

Acknowledgments: The paper was completed entirely by the listed authors and was approved by all authors for publication. Anyone else who contributed to the manuscript but does not qualify for authorship has been acknowledged with their permission.

Conflicts of Interest: The authors declare that there are no conflicts of interest regarding the publication of this paper.

References

1. Ning, B.; Liu, C. Technology and application of train operation control system for china rail transit system. *J. China Railw. Soc.* **2017**, *39*, 1–9.
2. Zhao, J.; Liu, J.; Yang, L.; Ai, B.; Ni, S. Future 5G-oriented system for urban rail transit: Opportunities and challenges. *China Commun.* **2021**, *18*, 1–12. [CrossRef]
3. Wu, H.; Li, F.; Du, C.; Li, G.; Meng, Y. City urban rail transit train-ground wireless communication network research based on LTE technology. In Proceedings of the 2020 IEEE International Conference on Information Technology, Big Data and Artificial Intelligence (ICIBA), Chongqing, China, 6–8 November 2020; IEEE: Piscataway, NJ, USA, 2020; Volume 1.
4. Agrawal, R.; Faujdar, N.; Romero, C.A.T.; Sharma, O.; Abdulsahib, G.M.; Khalaf, O.I.; Mansoor, R.F.; Ghoneim, O.A. Classification and comparison of ad hoc networks: A review. *Egypt. Inform. J.* **2022**, *24*, 1–25. [CrossRef]
5. Bruno, R.; Conti, M.; Gregori, E. Mesh networks: Commodity multihop ad hoc networks. *IEEE Commun. Mag.* **2005**, *43*, 123–131. [CrossRef]
6. Johnson, D.B.; Maltz, D.A. Dynamic source routing in ad hoc wireless networks. In *Mobile Computing*; Springer: Berlin/Heidelberg, Germany, 1996; pp. 153–181.
7. Jacquet, P.; Muhlethaler, P.; Clausen, T.; Laouiti, A.; Qayyum, A.; Viennot, L. Optimized link state routing protocol for ad hoc networks. In Proceedings of the IEEE International Multi Topic Conference, 2001, IEEE INMIC 2001, Technology for the 21st Century, Lahore, Pakistan, 30 December 2001; IEEE: Piscataway, NJ, USA, 2001; pp. 62–68.
8. Manjunath, M.; Manjaiah, D.H. Spatial DSDV (S-DSDV) routing algorithm for mobile ad hoc network. In Proceedings of the 2014 International Conference on Contemporary Computing and Informatics (IC3I), Mysore, India, 27–29 November 2014; IEEE: Piscataway, NJ, USA, 2014; pp. 625–629.
9. Shibao, L.I.; Wei, J. AODV route protocol research based on improved ERS algorithm. In Proceedings of the 2010 IEEE International Conference on Wireless Communications, Networking, and Information Security, Beijing, China, 25–27 June 2010; IEEE: Piscataway, NJ, USA, 2010; pp. 102–106.
10. Chavan, A.; Kurule, D.; Dere, P. Performance analysis of AODV and DSDV routing protocol in MANET and modifications in AODV against black hole attack. *Procedia Comput. Sci.* **2016**, *79*, 835–844. [CrossRef]
11. Morshed, M.M.; Ko, F.I.; Lim, D.; Rahman, M.H.; Mazumder, M.R.R.; Ghosh, J. Performance evaluation of DSDV and AODV routing protocols in mobile ad-hoc networks. In Proceedings of the 4th International Conference on New Trends in Information Science and Service Science, Gyeongju, Republic of Korea, 11–13 May 2010; IEEE: Piscataway, NJ, USA, 2010.
12. Liu, S.; Yang, Y.; Wang, W. Research of AODV routing protocol for ad hoc networks1. *AASRI Procedia* **2013**, *5*, 21–31. [CrossRef]
13. Hanashi, A.M.; Siddique, A.; Awan, I.; Woodward, M. Performance evaluation of dynamic probabilistic broadcasting for flooding in mobile ad hoc networks. *Simul. Model. Pract. Theory* **2009**, *17*, 364–375. [CrossRef]

14. Bhardwaj, A.; El-Ocla, H. Multipath routing protocol using genetic algorithm in mobile ad hoc networks. *IEEE Access* **2020**, *8*, 177534–177548. [CrossRef]
15. HHu, Y.-Z.; Zhang, F.-B.; Tian, T. Dynamic relationship-zone routing protocol for Ad Hoc networks. *Wirel. Pers. Commun.* **2020**, *114.3*, 2461–2476. [CrossRef]
16. Wang, W.; Li, C.; Wang, Y. An Improved AODV Routing Protocol Based on WSN. *Comput. Mod.* **2012**, *1*, 182–185.
17. Kumar, R.; Arya, K.; Shekhar, S.; Agrawal, R. An on demand routing protocol AODV with end to end reliability and backward route information. In Proceedings of the 2014 9th International Conference on Industrial and Information Systems (ICIIS), Gwalior, India, 15–17 December 2014; IEEE: Piscataway, NJ, USA, 2014.
18. Touzene, A.; Al-Yahyai, I. Performance Analysis of a Grid Based Route Discovery in AODV Routing Algorithm for MANET. In Proceedings of the 2014 2nd International Conference on Artificial Intelligence, Modelling and Simulation, Madrid, Spain, 18–20 November 2014; IEEE: Piscataway, NJ, USA, 2014.
19. Noureddine, H.; Ni, Q.; Min, G.; Al-Raweshidy, H. A new link lifetime prediction method for greedy and contention-based routing in mobile ad hoc networks. In Proceedings of the 2010 10th IEEE International Conference on Computer and Information Technology, Bradford, UK, 29 June–1 July 2010; IEEE: Piscataway, NJ, USA, 2010.
20. Wang, E.; Dong, Z. Link Quality and Topology Quality Based Routing Protocol in Mobile Ad hoc Network. *Electron. Technol.* **2010**, *37*, 64–66. (In Chinese)
21. Skold, M. Using location information to reduce the route search in tactical radio networks. In Proceedings of the 2001 MILCOM Proceedings Communications for Network-Centric Operations: Creating the Information Force (Cat. No. 01CH37277), McLean, VA, USA, 28–31 October 2001; IEEE: Piscataway, NJ, USA, 2001; Volume 1.
22. Boudhir, A.; Bouhorma, M.; Ahmed, M.B.; Elbrak, S. New routing protocol "Dicho-AODV" for energy optimization in MANETS. In Proceedings of the 2012 International Conference on Multimedia Computing and Systems, Tangiers, Morocco, 10–12 May 2012; IEEE: Piscataway, NJ, USA, 2012; pp. 444–447.
23. Zhang, J.; Xi, K.; Luo, M.; Chao, H.J. Dynamic hybrid routing: Achieve load balancing for changing traffic demands. In Proceedings of the 2014 IEEE 22nd International Symposium of Quality of Service (IWQoS), Hong Kong, China, 26–27 May 2014; IEEE: Piscataway, NJ, USA, 2014.
24. Kumar, R.; Dave, M. A comparative study of various routing protocols in VANET. *arXiv* **2011**, arXiv:1108.2094.
25. Kushwaha, U.S.; Dixit, M.K.; Singh, A.K. AOMDV Intelligent Decision (AOMDV-ID) to Minimize Routing Delay for Diverse VANETs. In Proceedings of the 2022 International Conference for Advancement in Technology (ICONAT), Goa, India, 21–22 January 2022; IEEE: Piscataway, NJ, USA, 2022.
26. Liu, H.; Yang, L.; Zhang, Y. Improved AODV routing protocol based on restricted broadcasting by communication zones in large-scale VANET. *Arab. J. Sci. Eng.* **2015**, *40*, 857–872. [CrossRef]
27. He, G.; Zhou, S.; Liu, S. A K-hop Based Clustering Algorithm in Ad Hoc Networks. In Proceedings of the 2008 International Conference on Networking, Architecture, and Storage, Chongqing, China, 12–14 June 2008; IEEE: Piscataway, NJ, USA, 2008; pp. 151–152.
28. Yang, Y. Research and Implementation of Improved AODV Routing Protocol for VANET. Master's Thesis, Harbin Engineering University, Harbin, China, 2020. (In Chinese).
29. Xu, Y.; Heidemann, J.; Estrin, D. Geography-informed energy conservation for ad hoc routing. In *Proceedings of the ACM/IEEE International Conference on Mobile Computing and Networking*; Association for Computing Machinery: New York, NY, USA, 2001; pp. 70–84.