Data Forwarding Scheme for Vehicle Tracking in Named Data Networking

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***Abstract*—Named data networking (NDN) is one representation and implementation of information-centric networking (ICN) and is considered to be among the most promising designs for the next generation of network architecture. The introduction of NDN into vehicular ad-hoc networks (VANETs) and utilization of its content-centric characteristic to improve data transmission and distribution in VANETs has become a research hotspot in recent years. However, research on mobility support of NDN-based VANETs still faces many challenges. To solve the issue of data transmission path breaking due to *Consumer* mobility in NDN-based VANETs, this article proposes a novel vehicle tracking-based *Data* packet forwarding scheme (VTDF) to improve the successful delivery rate of *Data* packets in mobile environments. In this approach, the urban road structure is divided into complex multi-junction and straight lane scenarios and *Data* packets are forwarded according to vehicle movement information. Simulations indicated that this vehicle tracking scheme provides a lower average data transmission delay, shorter handover delay between roadside units, and higher data delivery rate for *Consumers* compared to the standard methods.**

***Index Terms*—Named data networking, vehicular ad-hoc network, mobility, tracking.**

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I. Introduction

Intelligent transportation systems (ITSs) play a key role in the construction of smart cities, which is becoming increasingly urgent. ITSs enable road monitoring, traffic control, vehicular communication, decision-making for urban transportation management, etc. and constitute a typical example of the integration of wireless sensor networks (WSN) and Internet of things (IoT) techniques [1]. As important components of ITSs, vehicular ad-hoc networks (VANETs) use wireless networking technologies by connecting on-board units (OBUs) and roadside units (RSUs) to provide vehicle-to-vehicle (V2V), vehicle-to-RSU (V2R), and other modes of communication to users [2]. The main functions of RSUs are providing road condition information and data forwarding, and they are important components of VANETs since they undertake most of the data transmission work, e.g., they serve as relay nodes for pairs of vehicles exchanging data [3]. In recent TCP/IP-based VANET structures, vehicles and RSUs have been assigned unique IP addresses, and each packet uses source and destination IP addresses for data forwarding. Such address-based data packet switching and forwarding communication has some intrinsic limitations, e.g., the data transmission path may be broken when the address is changed when the target vehicle enters another local area access network. Therefore, the quality of service (QoS) provided by VANETs cannot be ensured.

To overcome the limitations of recent IP-based networks, a novel network architecture called information-centric networking (ICN) has been proposed. Instead of performing host-centric data exchanging, ICN involves assigning a unique name to each data information object (e.g., a movie with structured hierarchical name /ScienceFictionFilm/Transformers/5.0) and runs name-based data transportation. Such content-centric data information sharing can intrinsically improve the network performance in DNS operation elimination, mobility support, security, etc. Therefore, ICN has been regarded as a clean-slate network architecture for future internetworking. Among recently presented deployments of ICN, named data networking (NDN) is unanimously recognized as one of most promising paradigms by the ICN research community owing to its characteristics of coupled data routing, distributed in-network caching, etc. [4][5]. In NDN, the data requester (*Consumer*) sends a data request packet (*Interest* packet) with the name of the data content into the NDN core network to explore its intended data information object, while the data content holder (*Publisher*) creates a

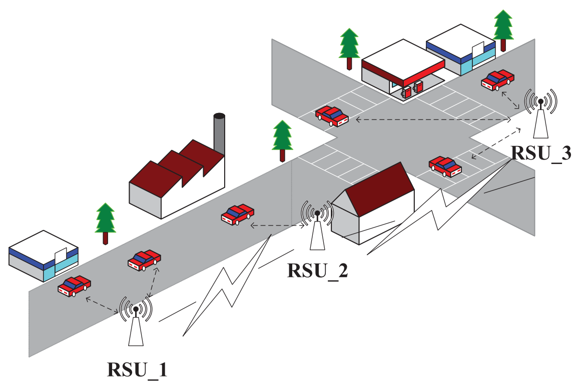

Fig. 1. V2R communication scenarios.

reply packet (*Data* packet) with the name of the data content and sends it back to the *Consumer* along with the path that the *Interest* packet has passed. Since the advantages of NDN enable it to satisfy diverse user demands, it is regarded as an ideal architecture for VANETs, and in recent years, NDN-based VANET research has attracted increasing attention by ICN and ITS researchers [6].

The most significant feature of a VANET is mobility. Generally, in an NDN-based VANET, vehicles are the *Consumers* and they send *Interest* packets into the VANET to explore their intended data content. RSUs located on roadsides forward these *Interest* packets through hop-by-hop data transfer until they find the content *Publishers* (in NDN-based VANETs, the *Publishers* can be content servers, vehicles, or infrastructure elements such as RSUs). Then, the *Publishers* create corresponding *Data* packets that travel along the reverse path of the *Interest* packets and are returned to the *Consumers* to complete the data exchange. In V2V mode, vehicles can use a point-to-point model to complete *Interest* and *Data* exchange, but the involved vehicles should be well within the range of communication; otherwise, they will require assistance from RSUs for relay. Therefore, V2R mode has been primarily applied in VANET communication, in which a *Consumer* sends an *Interest* packet to its adjacent RSU (RSU_1), as shown in Fig. 1. If RSU_1 holds the data content that the *Interest* desired, it creates a corresponding *Data* packet that encapsulates the data content and returns it to the *Consumer*. Otherwise, RSU_1 forwards the *Interest* to the Internet to determine the *Publishers* of the data content. However, due to the mobility of vehicles, the backhaul process of the corresponding *Data* packets always encounters path breaking, which may cause data delivery failure for the *Consumer* (in other words, when the *Data* packet reaches RSU_1, the *Consumer* has moved out from the communication range of RSU_1). Thus, it is important to know the motion status of the *Consumer* and to send the *Data* packet to an RSU that can reliably deliver it the *Consumer* (RSU_2 in Fig. 1). Therefore, it is challenging to provide a reliable *Data* backhaul and delivery scheme in an environment with *Consumer* motion and network topology changes for NDN-based VANETs. In addition, NDN-based VANETs experience a ping-pong handover issue [7], in which a vehicle frequently connects to two adjacent RSUs within a short time interval due to signal instability within the intermediate junction between the RSUs. This issue causes additional data transmission delay, decreases communication quality, and affects user experience [8].

Therefore, in response to the problem of link interruption caused by high *Consumer* mobility, in this study, we propose a vehicle tracking-based *Data* packet forwarding (VTDF) scheme to adapt NDN-based V2R communication systems for complex urban road environments. In this scheme, urban road structures are divided into multi-junction and straight-lane scenarios; the Tabu search (TS) method is introduced to accurately track the directions of the motion of *Consumers*, thereby increasing the *Data* packet delivery probability.

The main contributions of this study are as follows.

- It introduces the concept of the TS theory and proposes a Tabu node search (TNS) algorithm to effectively track target *Consumers* in mobile situations and complex urban road scenarios for a more timely *Data* packet return.
- A quick handover method (QHM) is presented to provide high efficiency handover during *Data* packet return and effectively alleviate the impact caused by the ping-pong handover problem.
- The proposed VTDF method comprehensively considers the advantages of data caching and data forwarding mechanisms to enhance the successful delivery rate of *Data* packets with low network costs.
- Compared to several related and representative approaches, including data caching, data forwarding, and NDN-based VANET methods, the proposed VTDF can yield a lower average delay, lower handover delay, and higher *Data* packet delivery rate, thereby enhancing the QoS for *Consumers*.

The remainder of this paper is organized as follows. Section II describes related research on NDN mobility issues. Section III presents the design of the proposed system model in detail. Section IV discusses the *Data* packet forwarding process in various road structure scenarios. Section V describes an extensive simulation that was conducted to demonstrate the performance efficiency of proposed scheme. Finally, Section VI concludes the article.

II. Related Work

Each intermediate node in NDN that routes and forwards *Data* packets contains three data structures: content store (CS), pending interest table (PIT), and forwarding information base (FIB) structures [9]. The CS is used for temporary caching of data information received by the node, which can potentially be used to satisfy future *Interest* requests. The PIT records data requests in which the node has forwarded an *Interest* packet but not yet received its corresponding *Data* packet, and it is required to send a *Data* packet to each interface that is listed in the PIT. The FIB acts as a routing table in an IP network to forward *Interest* packets to the subsequent hops based on the longest-prefix strategy according to its holding information [10].

As mentioned before, in NDN-based VANETs, *Data* packet delivery may fail due to path breaking in situations in which the *Consumer* moves or network topology changes. In recent years, two main kinds of schemes have been presented to solve the data communication path breakage problem caused by vehicle movement: data content caching and data forwarding. Regarding the former, Farahat *et al.* [11] proposed a full proactive optimal caching scheme that adopts location and data patterns to perform proactive forecasting to support *Consumer* communication in mobile environments. Deng *et al.* [12] proposed a distributed probabilistic caching scheme based on a clustering algorithm in NDN that mines user needs according to the *Interest* items collected by mobile vehicles and caches data according to the required information and state information of the users to satisfy user requirements. Rao *et al.* [13] proposed a proactive caching method in NDN (PCNDN) that can proactively request and cache data content items that a *Consumer* has not received but has requested before the handover process of an RSU. Similarly, Grewe *et al.* [14] proposed a data packet proactive caching approach for ICN-based VANETs that uses vehicle running information to cache the best data content and forwards it to the access point (RSU) to which the vehicle may switch in the handover process. The above methods are all non-cooperative cache strategies and can improve the delivery rate to a certain extent through data content caching; however, they may also cause frequent caching updates, even excessive caching. In addition, these methods are mainly focused on the status of each individual node, but not the data caching situations of the other nodes, and thus may lose specific data content information from adjacent nodes.

To make data caching more efficient, cooperative caching strategies have been presented to overcome the limited information capturing abilities of non-cooperative caching strategies. Yu *et al.* [15] proposed a neighborhood-aware *Interest* forwarding scheme that uses the block-based intra-network caching in NDN to address the *Data* packet backhaul path breaking problem caused by vehicle mobility and intermittent connections in mobile ad-hoc networks. Wei *et al.* [16] proposed a layered cooperative cache management strategy in a vehicular content-centric network, which selects single-hop neighbors as cache nodes based on the layer level caching potential so that the content in different layers can be progressively passed on to the *Consumer*. Huang *et al.* [17] proposed a cluster-based selective cooperative caching method involving popularity awareness for vehicular NDN (V-NDN), which uses vehicle motion information to cluster vehicles and data popularity to cache the most popular data. On this basis, the authors further proposed a cooperative caching approach based on mobility prediction [18] that uses mobile prediction to establish communication among vehicles with similar mobility patterns, thereby building stable intra- and inter-cluster communication among vehicle clusters. These cooperative data caching methods can enhance the ability of moving vehicles to obtain information, improving the successful delivery rate of *Data* packets. However, because it is necessary to maintain the relevant information of other nodes or clusters in real time and redundant caches on multiple nodes are required to mitigate the effects of uncertainty in mobile prediction, these approaches may result in additional network consumption.

Regarding data forwarding strategies, Liu *et al.* [19] proposed an improved reliable forwarding strategy based on the degree of concern of a node relative to the content. In this approach, beacon messages are used to obtain relevant state information (e.g., node ID, speed, and position) from neighboring vehicles, so that *Data* packets can find reliable connections before returning through a fixed path. Zhang *et al.* [20] proposed a *Data* packet forwarding strategy based on neighbor awareness (FN) in which each vehicle must maintain the location information of its neighbors and the request information for neighboring vehicles. In the *Data* packet response phase, neighboring vehicles can assist the *Publishers* in forwarding *Data* packets to the target vehicle. Tiennoy *et al.* [21] proposed an RSU-assisted data distribution protocol in which each standalone RSU operates independently and data content is obtained by periodically broadcasting polling messages to adjust routing modes, thereby improving network connectivity and data distribution in mobile environments. Lin *et al.* [22] proposed a data packet forwarding method in NDN that selects the next hop forwarding node (vehicle) in the data return process based on the relevant information about the neighboring vehicles that is obtained by beacon broadcasting, so as to establish reliable end-to-end communication in a VANET. Chowdhury *et al.* [23] presented a data content connection and location-aware forwarding strategy with the objective of improving the *Data* packet delivery rate by considering vehicle location information and content-based connectivity information to make a forwarding decision. Deng *et al.* [24] proposed a hybrid forwarding strategy for use in NDN-based VANETs that introduces opportunistic and probabilistic forwarding for location-related and location-independent information. This method fully utilizes geographic information and the characteristics of named data to reduce the packet transmission delay. Zhang *et al.* [25] presented a user mobility support forwarding scheme called Kite that uses PIT entries in NDN routers to track destinations in order to enhance the communication performance among mobile devices. When a *Data* packet is returned, the transmission link path may be broken due to *Consumer* movement; therefore, the *Consumer* should resend an *Interest* packet to establish a new session for the desired data content. Considering this limitation, Cha *et al.* [26] proposed an NDN-based method supporting *Consumer* mobility, in which a new communication link is established during the *Data* packet backhaul process by introducing a mobile link service for each NDN node (vehicle and/or router). Thus, *Data* delivery can be completed without retransmission of the *Interest*. The above data forwarding methods are effective for solving the communication outage problem caused by vehicle movement, but the real-time maintenance of neighbor information or related information about other nodes and devices causes extra network consumption, and the data communication quality is also affected by the vehicle density and signal quality obtained by position systems. Zhou *et al.* [27] proposed a *Data* packet forwarding scheme that uses information about the direction of motion of vehicles to perform forwarding decisions for RSUs under different road layout conditions. However, the urban road environment considered in this method is simple.

There is another critical issue that should be considered thoroughly and addressed in V2R communication systems, called handover (or handoff). Handover is caused by vehicle movement, where a vehicle forms frequent and alternating connections with different RSUs along its path, which may interrupt data communication between the vehicle and RSUs. Jiang *et al.* [28] proposed a location-based multiple-input-multiple-output assisted handoff method to resolve the handover issue in railway systems. In this method, train position information is used to trigger the handover procedure; then, handover signaling and *Data* packets to be sent by different train antennas are set, so that the handover procedures can be performed without interrupting normal data transmission. Chen *et al.* [8] proposed a direction-oriented handover mechanism in an NDN-based railway networking environment that makes handover decisions based on the basic service set identifiers of routers detected by a train to ensure that the train can switch to the next hop router as soon as possible. These methods can improve the handover performance in mobile communication scenarios for railway systems, but the railway environment is relatively simple compared to the urban road network since the direction of motion is explicit and the form of data communication between trains and RSUs is simple; consequently, it is difficult to adopt these methods to complex urban road scenes. To enhance the handover performance in complex mobile environments such as urban road networks, Poolnisai *et al.* [7] proposed a handover delay time estimation method for mobile networks. This approach can be utilized to determine the dynamic handover threshold through the received signal strength (RSS) measured by the Doppler effect technique, vehicle speed, and handover time latency; thus, it can make handover decisions at the appropriate time. Kustiawan *et al.* [29] proposed a Kalman filtering and fuzzy logic-based handover approach that uses the RSS, data rate, mobile terminal velocity, and traffic load as handover-determining factors between mobile nodes and network devices and applies Mamdani fuzzy logic to make handover decisions. Wang *et al.* [30] proposed a road domain (RD) architecture-based mobility management scheme for vehicular networks that provides different solutions for intra-RD and inter-RD handover scenarios. Although these methods can be well adopted to urban road systems and improve the handover performance to a certain degree, they ignore a critical issue in the handover process, called ping-pong handover. This issue is caused by a vehicle connecting frequently and alternatively to different RSUs along its path, interrupting data communication between the vehicle and RSUs and increasing the handover time delay. Ping-pong handover is caused by overlap between the physical communication signal coverage regions of different RSUs (especially for two adjacent RSUs). Recently, researchers have paid increasing attention to the ping-pong handover issue in V2R communication systems. Kang *et al.* [31] proposed an active handover triggering mechanism in which a RSU, such as a base station, sends a handover invitation to vehicles intending to pass through the handover area; then, the vehicle predicts the approximate time required to reach the area in which the signal coverage of the base stations overlaps, according to its current speed, and makes the hangover decision. Although this method can alleviate the impact caused by the ping-pong handover problem, it is only applicable to scenarios in which the vehicle route is relatively fixed. Cao *et al.* [32] proposed a joint handover algorithm in which the target device obtains the related information of the auxiliary devices (vehicles, RSUs) connected to it, then uses the Bayesian model to calculate the handover probability of the target vehicle to make the handover decision. Although this method can effectively alleviate the impact of the ping-pong handover problem, it increases the system complexity.

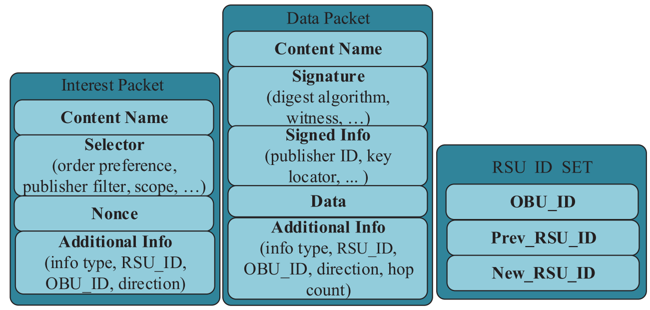

Fig. 2. Structures of *Interest* packet, *Data* packet, and RSU_ID SET table.

For further improvement in the successful delivery rate of *Data* packets to *Consumers* in mobile environments, and to address the handover issue efficiently, this paper proposes a *Data* packet forwarding scheme based on vehicle tracking, and uses TNS to quickly find *Consumers* in a complex intersection environment to improve the *Data* packet forwarding efficiency and successful delivery rate in mobile environments. At the same time, the QHM is used to alleviate the impact of the ping-pong problem caused by the V2R communication during the high-speed movement of the vehicle.

III. VTDF Design

This section presents the VTDF framework design and explains it in detail. The objective of the proposed VTDF is to promote the success rate of *Data* packet delivery in mobile environments. It includes a modified packet format, a tabu node search algorithm, a fast and reliable handover scheme for mobile vehicles, and an in-network caching method. The VTDF design is mainly intended for use in V2R communication systems, in which vehicles generally act as *Consumers*, while RSUs always serve as *Publishers* or data forwarders.

A. Packet Design

To make data transmission more efficient using the VTDF approach, it was necessary to modify and extend the formats of the *Interest* and *Data* packets, as shown in Fig. 2. For the *Interest* packets, an Additional Info field is added with Info type, RSU_ID, OBU_ID, and direction functions. “Info type” denotes the type of the data item in the current Additional Info of an *Interest* packet, “RSU_ID” records the identity of the RSU that firstly receives the *Interest* request by a *Consumer*, “OBU_ID” is the identity of the *Consumer*, and “direction” is the direction of motion of the *Consumer* after it sends an *Interest* request. For the *Data* packets, an Additional Info field is also added, which includes Info type, RSU_ID, OBU_ID, direction, and hop count functions. Here, “Info type” denotes the type of data item in the current Additional Info of a *Data* packet; the meanings of “RSU_ID”, “OBU_ID”, and “direction” are the same as for the *Interest* packets; and “hop count” records the number of hops from the first-hop RSU to the *Consumer* during the *Data* packet tracking process, where the "first-hop RSU" means the first RSU to receive the *Interest* packet sent by a *Consumer*.

In VTDF, each vehicle must maintain an RSU_ID SET table, which includes the items OBU_ID, Prev_RSU_ID, and New_RSU_ID. Here, "OBU_ID" is the identity of the current vehicle, "Prev_RSU_ID" is the identity of the previous hop RSU that the vehicle has passed, and "New_RSU_ID" is the identity of the RSU connected to the current vehicle.

B. TNS Algorithm for VTDF

When the target vehicle (*Consumer*) must be searched in an urban road environment with interleaved roads and complex network topology, it is easy to cause repeated searching of vehicles due to the random movement of vehicles, thereby affecting the efficiency of *Data* packet delivery. To forward *Data* packets to *Consumers* more quickly and accurately in complex network environments, such as multi-junction areas with large numbers of vehicles, we introduce the TS concept [33][34] and propose a TNS algorithm to search *Consumers*, to enhance the effectiveness of data delivery. Further, the communication signal coverage areas of multiple RSUs are set at each complex multi-junction as the "intersection network". The proposed TNS design is as follows.

(1) Acquisition of the initial solution: At the initial moment, a random vehicle is selected as the initial solution within the communication range of the intersection network.
(2) Solution selection: The neighbor vehicle that is farthest from the current solution is selected as the optimal solution of the next search within the communication range of the intersection network.
(3) Neighborhood search: The current solution iteratively searches all neighboring vehicles that are not in the tabu list.
(4) Determination of tabu objects: The non-*Consumer* vehicles obtained in each search process are called tabu objects and will be added to the tabu list.
(5) Determination of the tabu list length: The tabu length is the maximum number of the tabu objects allowed to be saved in the tabu list. The length of the tabu list is set to the number of vehicles in the intersection network area at the initial moment.
(6) Termination criteria: The search is terminated when the *Consumer* is found or the tabu list is full.

Algorithm I describes the process of using TNS to find the *Consumer*. Firstly, the length of the tabu list is set according to the number of the vehicle in the intersection network. Then, a vehicle is randomly selected as the initial solution in the communication range of the intersection network. If this vehicle is the *Consumer*, the search is terminated. Otherwise its neighboring vehicles will be searched. If the *Consumer* is found among the neighboring vehicles, a *Data* packet is sent to it. Otherwise, the neighboring vehicle furthest from the initial solution is selected as the current optimal solution within the communication range of the intersection network, and the OBU_ID of the neighboring vehicles searched for the initial solution are added to the tabu list to avoid roundabout searching. Finally, the vehicles neighboring the optimal solution are searched iteratively, and the search is terminated when the *Consumer* is found or the tabu list is full. The TNS mainly includes operations such as generating an initial solution, generating a neighborhood, judging the tabu objects, and selecting an optimal solution. The time complexity of the initial solution is O(1), that of generating the neighborhood is O(C_n^2) (the neighborhood mapping is defined as 2-opt), that of the judging tabu objects is O($n * l$), and that of the optimal solution selection is O(n). After analysis, the time complexity of the TNS is O(n^2), where n is the problem size and l is the length of the tabu list.

Algorithm 1: TNS.

```
Input:
T, The initial moment at which the algorithm starts;
Con_ID, The identification of target vehicle (Consumer);
Range, The communication range of the intersection network;
Initialize:
Clear up the tabu list;
Nei_OBU: The vehicles neighboring the current solution;
A vehicle that is randomly selected in Range is the initial solution
while detect Nei_OBU in Range which are not in the tabu list do
  if identification of the Nei_OBU = Con_ID then
    Consumer is found
    the search is terminated
  else
    add the neighboring vehicles to the tabu list
    if the tabu list is full then
      the search is terminated
    end if
    the farthest Nei_OBU is the next optimal solution
  end if
end while
```

C. QHM in VTDF

In V2R communication mode, vehicle movement may lead to frequent network handover, which will increase the delivery delay and degrade the network communication quality. In an urban road environment, the overlapping area covered by the signals of every two adjacent RSUs is called the signal overlap zone. In Fig. 3, the signal overlap zone of RSU2 and RSU3 is region A. When a vehicle switches between RSU networks in area A, the ping-pong handover problem may occur. As shown in Fig. 4, PRSU is the RSU that is currently connected to the vehicle, NRSU is the next-hop RSU in the direction of vehicle movement, and Lv(PRSU) and Lv(NRSU) are the signal strengths of the PRSU and NRSU, respectively, that are received by the vehicle. When the vehicle passes point A, the signal it receives from NRSU is stronger than that from PRSU, and the vehicle is disconnected from PRSU and connected to

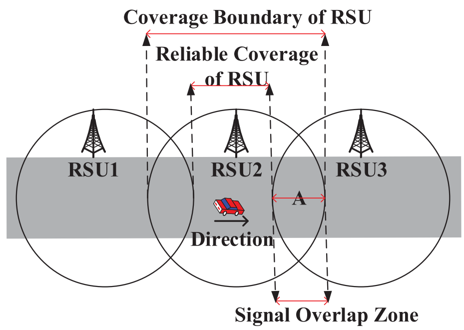

Fig. 3. Classification of RSU signal distribution.

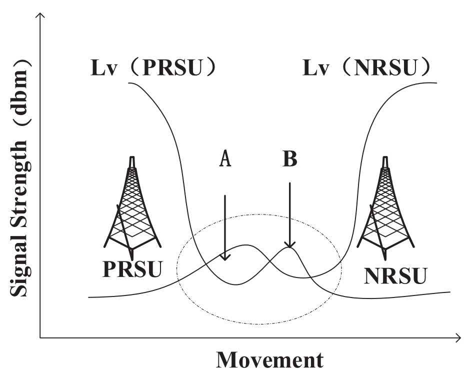

Fig. 4. Ping-pong handover.

Algorithm 2: QHM.

Input:
R, The overlap range of the communication signals from two adjacent RSUs;
SET, RSU_ID sets the table that contains the identities of the last-hop RSU and current RSU;
Initialize:
Vehicle monitors communication signal of RSU in real time;
RSU_ID is the RSU identification;
$CurrentRSU$ is the signal strength of the RSU currently connected to the vehicle;
$NewRSU$ is the next-hop RSU signal strength for vehicle detection;
while monitor the next-hop RSU signal **do**
  if RSU_ID is not in SET and $NewRSU > CurrentRSU$ **then**
    vehicle disassociates from the current RSU;
    vehicle associates with the next-hop RSU;
    update SET
  else
    vehicle stays associated with the current RSU;
  end if
end while

NRSU. When the vehicle passes point B, the signal it receives from PRSU is stronger than that from NRSU, and the vehicle is disconnected from NRSU and connected to PRSU. The above ping-pong handover not only increases the consumption of network resources, but also decreases the communication service quality.

To alleviate the impact caused by the ping-pong handover problem, we designed a QHM that can make vehicles switch quickly between RSUs without interrupting communication. The RSU_ID SET table stored in each vehicle only records the identities of the last-hop RSU connected to the vehicle and the RSU currently connected to the vehicle. As shown in Algorithm II, if a vehicle detects a signal from a new RSU while driving and the identity of the RSU does not exist in the RSU_ID SET table, the vehicle immediately disconnects from the RSU to which it is currently connected and connects to the new RSU. If the identity of the RSU detected by the vehicle already exists in the RSU_ID SET table, network handover does not occur at this time, and the impact of the ping-pong handover problem is alleviated. The QHM is beneficial for improving the accuracy of handover and reducing the handover delay, thereby improving the handover performance and ensuring the QoS and quality of experience (QoE) of user communication.

D. Caching Design

In NDN, the data content is cached in each routing node along the forwarding path. The RSU cache capacity is limited in V2R communication mode. If the RSU caches all forwarded data content, a large amount of unused and expired redundant information will exist in the network cache, wasting valuable storage resources and generating considerable data retrieval delay. To allow the RSU to store the available data content and enable the *Consumer* to obtain the requested data efficiently and quickly, we propose an in-network caching method based on data content popularity. In this approach, the data requested multiple times will be cached in the RSU, and when the *Consumer* near the RSU requests this data again, it will not be necessary to reconnect to the *Publisher* to retrieve the data; rather, the data content only needs to be obtained from the nearest RSU. This method can not only prevent excessive caching, but also effectively reduce the data retrieval delay.

Each RSU needs to maintain a Popularity Table, which includes the content name and requested number for each data item, as well as whether it is popular or not. Here, "content name" refers to the name of the requested data content, "requested number" indicates the times of the data is requested, and "popular or not" indicates whether or not the current requested data content is popular. Each time an RSU receives an *Interest* packet, it matches the content name with the Popularity Table and adds 1 when there exists a corresponding entry; otherwise, a new record is created in the table. A popularity threshold is assigned to each RSU, and when the requested number reaches the popularity threshold in Table I, the data item of "popular or not" is modified to 1 (if the data content is popular) or 0 (if the data content is not popular). When "popular or not" is 1, the *Data* packet can be cached through the following process.

(1) When the RSU has enough cache space, the data content is cached directly.

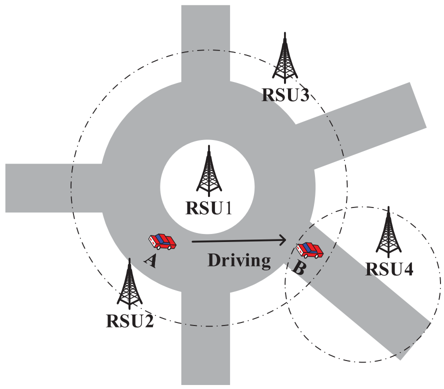

Fig. 5. Complex intersection scene.

(2) If the RSU does not have enough cache space, it is necessary to compare the requested number of data to be cached with the requested number of data already cached in the Popularity Table. If there are entries in the table, and the requested number is less than the requested number of data to be cached, the data with the least requested number in the table will be deleted from the RSU cache until the RSU has enough cache space to store the current data. Otherwise, the data will not be cached.

(3) The popularity of data content changes frequently over time, and many data that were popular in the past may not be popular presently. In order not to waste the RSU cache space, the Popularity Table will be reset periodically in the RSU.

IV. VTDF Mobile Scenarios

In this study, complex multi-junction and straight lane urban road scenarios were considered separately for routing analysis.

A. Complex Multi-Junction

The complex multi-junction environment includes crossroads, three-fork roads, roundabout crossings, and so on. In this paper, we use a complex roundabout crossing as an example to introduce the routing process. As shown in Fig. 5, RSU1, RSU2, and RSU3 are self-organized into an intersection network. The vehicle (*Consumer*) sends an *Interest* packet to the intersection network to request data. If there is data content corresponding to the *Interest* packet in the cache, the intersection network directly encapsulates the data content into the *Data* packet and delivers it to the *Consumer*. Otherwise, the intersection network sends the *Interest* packet to the neighboring RSU until it is forwarded to the *Publisher*. When the *Publisher* replies with a *Data* packet and forwards it to the intersection network along the reversed path of the *Interest* packet, the intersection network uses TNS to search the *Consumer*. If found, that is, if the *Consumer* is still within the coverage of the intersection network signal, the intersection network sends the *Data* packet directly to the *Consumer*. If the *Consumer* is not found, that is, if the *Consumer* has driven out of the intersection network signal coverage range, the network communication link will break. At this time, the *Data* packet returned to the intersection network cannot be successfully sent to the *Consumer*, and it will be sent to the RSU4 in the same direction as the *Consumer* is driving according to the direction specified in the *Data* packet. Then, RSU4 immediately searches for the *Consumer* according to the OBU_ID data item in the *Data* packet. If the *Consumer* is found, the RSU4 will directly send the *Data* packet to it. Otherwise, the *Data* packet will be forwarded to the next-hop neighbor RSU in the same direction.

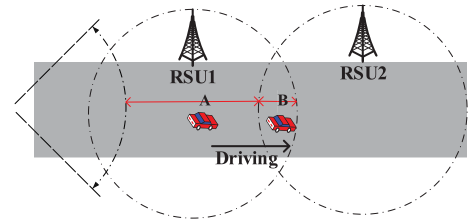

Fig. 6. Straight lane simulation scene.

TABLE I
Popularity Table

Content name	Request number	Popular or not
ScienceFictionFilm/Transformers/5.0	50	1
ScienceFictionFilm/Spiderman/1.0	1	0
...	...	...

B. Straight Lane

As shown in Fig. 6, the *Consumer* sends the *Interest* packet to request data within the communication range of RSU1 in a straight lane. If the requested data exists in the cache of RSU1, RSU1 sends the *Data* packet directly to the *Consumer* to complete the data delivery. Otherwise, the *Interest* packet is forwarded until the *Publisher* is found. When the *Data* packet is returned to the RSU1 along the reversed routing path of the *Interest* packet and the *Consumer* is still in its communication range, RSU1 sends the *Data* packet directly to the *Consumer*. If the *Consumer* has departed from the signal range of RSU1, RSU1 forwards the *Data* packet to the next-hop RSU (RSU2) in the driving direction of the *Consumer* according to the direction specified in the *Data* packet. Then, RSU2 searches for the *Consumer* to complete *Data* packet delivery. If RSU2 still does not find the *Consumer*, the *Data* packet is forwarded to the next-hop RSU in the same direction.

At the same time, every time the *Data* packet passes through an RSU during the data backhaul process, it is necessary to determine whether the data content is popular based on the Popularity Table in the RSU. If it is not popular, the data are not cached, which means that the RSU discards the data content after forwarding the *Data* packet. If it is popular, the RSU detects whether it has sufficient cache space. If there is sufficient cache space, the data are cached in the RSU; otherwise, the RSU retrieves a data entry from the Popularity Table that has fewer requests than the current data. If there is such a data entry, it is replaced with the current data; if not, this data entry is discarded. To avoid the waste of resources caused by the *Data* packet tracking the vehicle indefinitely, we set the maximum number

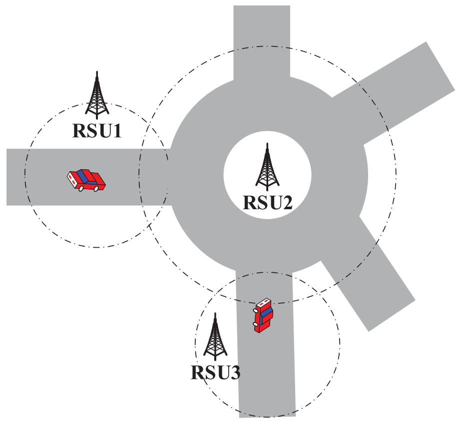

Fig. 7. Special case of complex intersection.

of times *Data* packets can be tracked to three hops. That is, if the *Data* packet fails to find the *Consumer* after being forwarded three hops in the direction in which the *Consumer* is driving, it is discarded. We also set a waiting time T_{wait} for the *Interest* packet to prevent *Consumers* from continuously waiting for data, which would affect the user experience. The timer starts when the *Consumer* sends the *Interest* packet. If the *Data* packet is not received by the time T_{wait} has expired, the *Consumer* resends the *Interest* packet to request the data.

It is worth noting that, as shown in Fig. 7, if the *Data* packet is forwarded to the intersection network within three hops and the *Consumer* still has not been found, then the intersection network broadcasts the *Data* packet to all adjacent next-hop RSUs except the last-hop RSU. For example, the *Data* packet may return to RSU1 along the reverse path of *Interest* packet forwarding. If the *Consumer* still has not been found after searching RSU1 and the intersection network, then the *Data* packet is broadcast to neighboring RSUs in all directions except RSU1. If RSU3 detects the *Consumer*, the *Data* packet is sent to it. This method can not only increase the *Data* packet delivery rate at the intersection, but also prevent excessive extra routing consumption.

V. Simulation

A. Experimental Parameters

To assess the performance of the proposed VTDF, we construct a simulation platform in C++ and use the MATLAB simulation tool for data processing. In the simulation experiment, a road environment with a complex roundabout crossing is constructed as an experimental scenario in which RSUs and vehicles are the main entities in the urban traffic scene. Initially, vehicles are randomly placed on the road following the standard uniform random distribution; the turning operation performed during the arrival of the vehicle at the intersection also uses a standard uniform random distribution. The RSUs are distributed uniformly and in an orderly manner along the road. The data content request was assumed to be Zipf distribution [35], and the Zipf parameter α was set to 0.6. The specific parameter settings are summarized in Table II. We defined the performance metrics as follows and comprehensively compared the performance of VTDF with those of PCNDN [13], which is based on data caching; FN [20], which is based on data forwarding; and V-NDN [36], which is a VANET environment experimentally based on NDN.

TABLE II
Experimental Parameters

Parameter	Value
Simulation area	2800 * 2800 m
MAC protocols	IEEE 802.11p
Number of *Consumers*	10,20,30,40,50,60,70,80,90,100
Vehicle speed	0,5,10,15,20,25,30m/s
Number of RSUs	18
RSU signal range	400 m
Simulation time	500 s
Communication delay between RSUs	10 ms
Reset time for the Popularity Table	30 min
Time of the *Consumer* waits for data (T_{wait})	2 min
Mobility model	Random direction
Node position	Random

(1) Average Delay: The time between the *Interest* packet being sent out and the *Data* packet being returned:

$$AD = \frac{\sum_{i=1}^{N} D_i}{\sum_{i=1}^{N} SD_i}, \tag{1}$$

Where D_i is the delay corresponding to *Consumer* i successfully receiving the *Data* packets, SD_i is the number of *Data* packets successfully received by *Consumer i*, and N is the number of vehicles in the experiment.

(2) Handover Delay: The time between the *Consumer* disassociating with the current RSU and the *Consumer* receiving the *Data* packet in the next-hop RSU:

$$TD = Tn - Tc \tag{2}$$

Where Tc is the moment at which the *Consumer* disconnects from the current RSU and Tn is the moment at which the *Consumer* receives the *Data* packet sent by the next-hop RSU.

(3) Delivery Ratio: The number of *Data* packets successfully received as a percentage of the total number of requested *Data* packets:

$$DR = \frac{\sum_{i=1}^{N} SD_i}{ND}, \tag{3}$$

where ND is the total number of *Data* packets requested by the vehicles.

B. Simulation Results

(1) In Fig. 8, without-QHM is the case in which the VTDF is not added to implement the network handover method and without-TNS is the case in which the VTDF is not added to the node search method. Fig. 8(a) shows the change of the average delay caused by VTDF, without-QHM, and without-TNS as the speed of the *Consumer* changes. It is apparent from Fig. 8(a) that the combined action of the QHM and TNS can reduce the average delay to a certain extent. This reduction occurs because

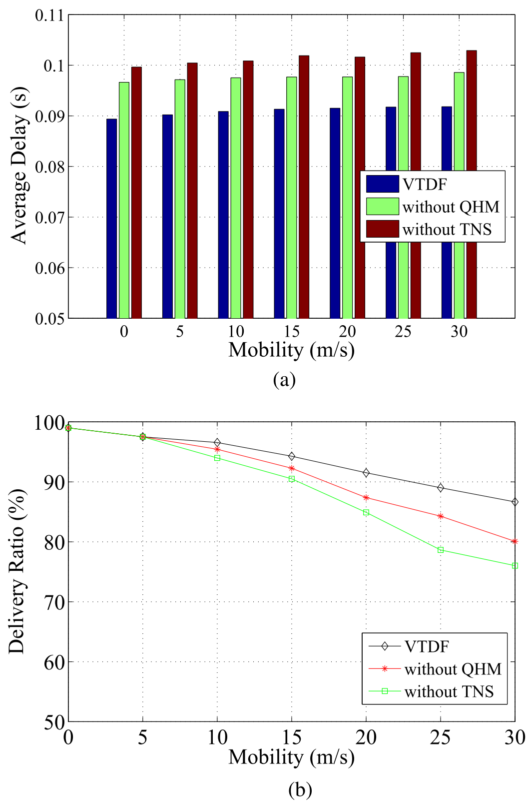

Fig. 8. Effects of the TNS and QHM on the VTDF.

the TNS can quickly search the target vehicle node in complex environments and reduce the delay of data reception, and the QHM can alleviate the impact of the ping-pong problem caused by vehicle handover between two adjacent RSUs, thus reducing the handover delay. As the vehicle speed continues to increase, the average delay of VTDF increases slightly. This increase occurs because *Data* packet tracks the vehicle node through some fixed RSUs, and the speed of vehicle has a relatively small effect on the average delay.

Fig. 8(b) shows the change in the proportion of data successfully received in the VTDF, without-QHM, and without-TNS cases as the speed of the *Consumer* increases. With increasing *Consumer* speed, both the average consumption delay and successful delivery rate of the *Data* packets are better in the VTDF case than in the other two cases. The above experimental results show that both the TNS and QHM can reduce network consumption and improve network performance to a certain extent. In Fig. 8(b), as the vehicle speed increases, the data delivery rate gradually decreases. This tendency exists because the high mobility of the vehicle causes frequent changes in the network topology, which increases the probability that the vehicle disconnects the current communication connection during the data return process. Compared to the other two methods, the VTDF not only uses the TNS approach to search quickly for the target vehicle node, but also uses the QHM to reduce the handover delay between the vehicle and RSUs, thereby increasing the data delivery rate.

(2) In this set of experiments, we evaluated the routing performance by changing the number of *Consumers*. In Fig. 9(a), as the number of *Consumers* increases, the average delay that FN consumes increases significantly, while V-NDN, PCNDN, and VTDF become stable, and the average delay in the VTDF case is the smallest. The reason is that the FN uses the V2V communication mode, and the performance of this method depends on the density of vehicle nodes. The V-NDN, PCNDN, and VTDF techniques use the V2R communication mode, and changes in the number of *Consumers* have relatively little effect on them. The VTDF uses the *Data* packet tracking vehicle route recovery method to reduce the loss of *Data* packets and unnecessary repeated requests for *Interest* packets. Simultaneously, in the process of data forwarding, the VTDF technique also includes a specific cache method to improve the cache hit rate of the data content, making its performance in terms of the average delay is better than the PCNDN, FN and V-NDN.

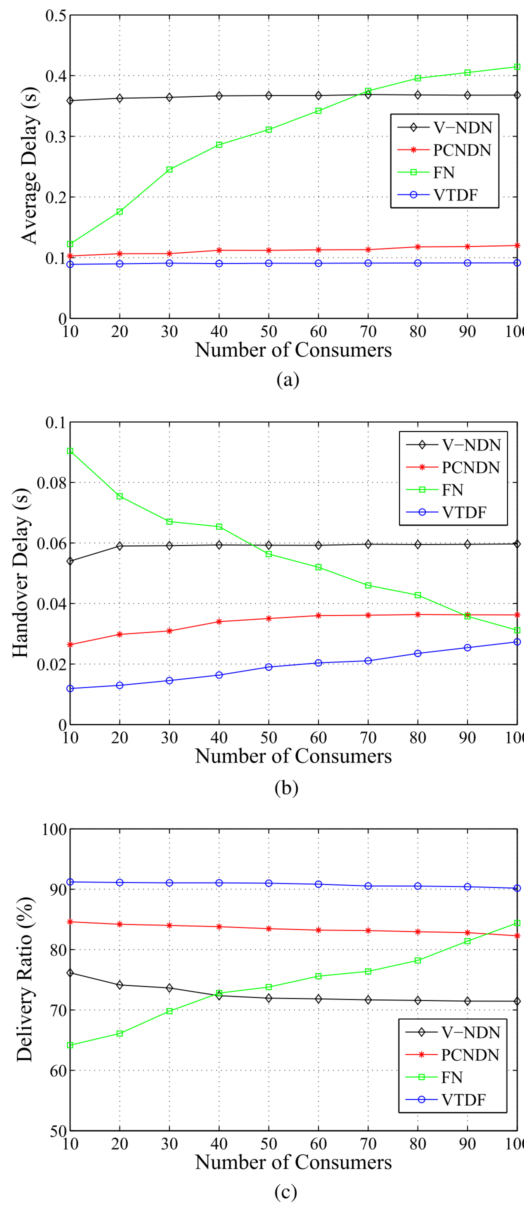

Fig. 9. Effect of the number of *Consumers* on the network performance.

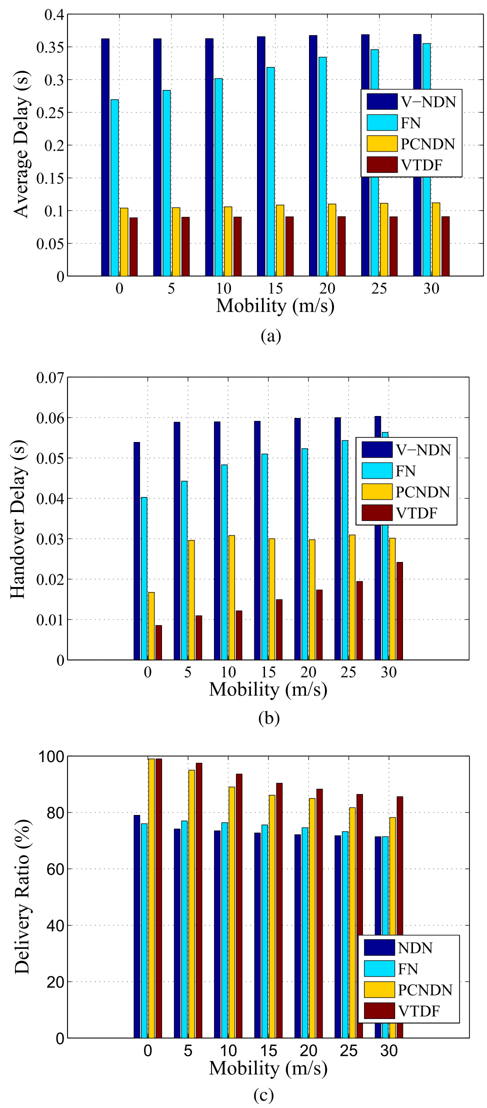

Fig. 10. Effect of vehicle speed on network performance.

As shown in Fig. 9(b), as the number of *Consumers* increases, the handover delays corresponding to V-NDN, FN, PCNDN, and VTDF all increase to some extent. Among them, the V-NDN delay remains stable after the number of *Consumers* reaches 20. Further, when the number of *Consumers* reaches about 90, the handover delay in the FN case exceeds that in the V-NDN case. However, the handover delay corresponding to VTDF is always the lowest, which is due to the use of handover method, which relieves the ping-pong handover problem between the vehicle and RSU and reduces the handover delay.

In Fig. 9(c), the successful data delivery rates in the VTDF and PCNDN cases tend to remain stable as the number of *Consumers* increases. When the number of *Consumers* reaches around 40, delivery rate for V-NDN changes from decreasing slightly to remaining steady. In contrast, the data delivery rate in the FN case increases as the *Consumer* number increases. Overall, the VTDF routing performance is the best. The VTDF method mainly uses the V2R communication mode for data backhaul. With the combined action of target vehicle search algorithm and the caching algorithm based on data popularity, the delivery success rate of *Data* packets is improved.

(3) We verified the effect of the vehicle speed on the routing performance in the next set of experiments. In Fig. 10(a), the delays in the PCNDN and VTDF cases remain stable as the vehicle speed increases, and they are always significantly lower than those corresponding to V-NDN and FN. In the process of using RSUs to assist the *Data* packet tracking *Consumer*, the VTDF uses the search algorithm of the target vehicle node to find the *Consumer* quickly, avoiding the loss of *Data* packets caused by the *Consumer* leaving the communication range of the current RSU and reducing the re-request of *Interest* packets. Meanwhile, the cache algorithm of data popularity is used to maximize the data cache hit rate and to reduce the delay of data transmission and reception.

As shown in Fig. 10(b), as the vehicle speed increases, the handover delays for all of the experimental vehicles change to a certain extent. The V-NDN, FN, and VTDF all show slightly increasing trends when the vehicle speed is low, and the handover delay in the PCNDN case increases but gradually stabilizes when the speed reaches about 10 m/s. However, the VTDF handover delay is always the lowest. This characteristic exists because as the vehicle speed increases, the frequency of network handover between the vehicle and RSUs increases, and the network topology changes frequently. In addition, the VTDF uses a QHM for communication signal strength comparison, which improves the efficiency of handover between the vehicle and RSUs and provides lower handover delay.

As shown in Fig. 10(c), the vehicle speed does not have a particularly significant effect on the data delivery rate in the V-NDN and FN cases, but the data delivery rate is very sensitive to changes in vehicle speed in the VTDF and PCNDN cases. The data delivery rate is significantly reduced in both the VTDF and PCNDN cases, although the former is always higher than the latter. It is precisely because of the node search algorithm TNS and network handover method QHM in the VTDF method that the *Data* packet can find the *Consumer* more quickly and efficiently complete the delivery of the *Data* packet. In this set of experimental data, the routing performance of VTDF is better than those of PCNDN, FN, and V-NDN when the vehicle speed changes.

VI. Conclusion

In this paper, we proposed a vehicle tracking-based data forwarding method for efficient *Consumer* mobile support in NDN-based VANETs. The method of forwarding *Data* packets along the direction of motion of the *Consumer* was adopted, a TNS and QHM were utilized to reduce the communication interruptions caused by user migration as well as the network overhead, and a popular caching approach was used to reduce data retrieval latency. We firstly analyzed the effects of the TNS and QHM on the performance of VTDF, then investigated the network delay, handover delay, and data delivery rate of VTDF and other mobility solutions. The simulation results showed that the VTDF scheme performs better than other mobile support methods. In future research, we will further study the data transmission rules in the case in which both the requester and publisher move and reduce the network consumption as much as possible in the combined V2R and V2V communication mode to improve the network transmission performance.

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