A Reliable and Efficient Forwarding Strategy in Vehicular Named Data Networking

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Abstract: **Vehicular named data networking (VNDN) has the data-centric and in-network caching advantages that are in line with the requirements of multi-hop content retrieval in vehicular ad hoc networks (VANETs). Some current restrictive forwarding strategies utilize single-path forwarding to mitigate the Interest broadcast storm in VNDN. However, these strategies do not provide any reliable mechanism for Interest and Data forwarding to address the problem of low performance caused by the dynamic and unreliable VANETs communication environment. In this paper, we propose a packet forwarding strategy based on optimal and backup (PFOB) for VNDN. For Interest, PFOB establishes a single-path forwarding with high reliability and reachability by increasing the signal strength and node-degree criterion and retransmission mechanism. For Data, PFOB provides a reliable multi-path backup forwarding mechanism without additional network overhead. Simulation results show that PFOB can effectively improve the Interest satisfaction ratio, reduce the number of application retransmissions, and reduce the Interest satisfaction delay compared to the current strategies.**

Index Terms: **Named data networking, reliable forwarding strategy, vehicular ad hoc networks.**

I. INTRODUCTION

AS a key component of the intelligent transportation system (ITS), vehicular ad hoc networks (VANETs) have been developed rapidly in recent ten years. Wireless access in vehicular environments (WAVE) protocol stack takes into account the characteristics of vehicular radio communication and can realize efficient information transmission under the condition of high speed movement, therefore, it is currently the most promising vehicular radio communication standard [1]. However, WAVE specializes in providing short-distance safety applications, road charge and other similar services without the TCP/IP overhead [2]. In addition to these short-range emergency traffic information, the traffic situation in the moving direction of the vehicle has received more attention to facilitate driving planning. Moreover, some audio, video and other entertainment information are needed for driving comfort. In order to transmit these application information, a multi-hop protocol stack needs to be established. A large number of routing algorithms based on the traditional TCP/IP network architecture are proposed, but the end-to-end and host-centric approach of TCP/IP is obviously inadequate in the highly dynamic VANETs environment [3]. As discussed in [4]–[7], VANETs need a distributed non-center and content-based network architecture.

Named data networking (NDN) is a new design for future network evolution based on a content-driven model [8], [9]. In NDN, the two communicating parties that interact asynchronously do not need to establish and maintain an end-to-end connection, and the location-independent naming makes it unnecessary to assign a host identifier for a mobile node, such as IP address. With in-network caching, when the content consumer sends an Interest packet identified by the data name as a data request, any node in the network that has cached this data can reply with a Data packet identified by the same data name. The feature of NDN that requests data by sending Interest packet provides flexibility to maintain communication in highly dynamic environment [3]. Additionally, in NDN, a security mechanism for digital signature verification of the data itself is used to prevent malicious nodes from forging data instead of relying on the encryption of transmission nodes and channels. More broadly, all these advantages are in line with the requirements of VANETs. The combination of the VANETs and NDN is a good network architecture, such networks are called as vehicular NDN (VNDN) [10].

There are many advantages of applying NDN architecture in VANETs, but there are still many problems to be solved when applying the original NDN, such as naming, caching, forwarding, security and so on. In this paper, we solve the issue of multi-hop forwarding in VNDN. NDN can easily support the movement of content consumers [3], and also can support the movement of providers [2]. However, it is impossible to establish a relatively stable routing for VANETs with all vehicles to be moved at any time, so the original NDN forwarding strategy is not feasible in VNDN. The easiest way is to take advantage of VANETs's wireless broadcast feature, that is, each intermediate node forwards the received Interest packets and Data packets upon they received them. However, this simple flooding mechanism leads to a large amount of packet redundancy and collisions which leads to the severe performance degradation of the network.

In order to mitigate the broadcast storm caused by flooding mechanism, some restrictive forwarding strategies have been proposed at present. In these strategies [11], [12], the Interest packet is forwarded along a single-path formed by designated forwarding nodes, and the Data packet is returned along the reversed path. As shown in Fig. 1, the node beginning with the let-
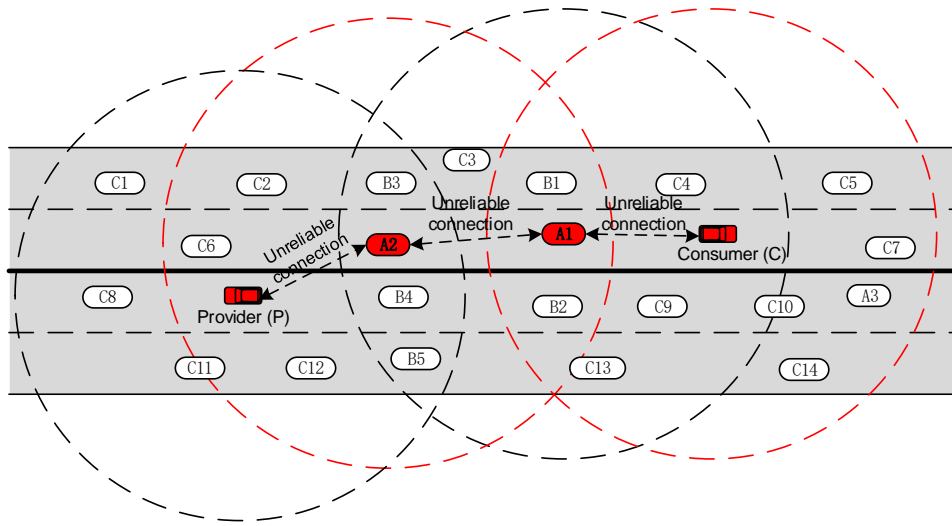
Fig. 1. The nodes beginning with the letter A are the designated forwarding nodes, and the dotted circle is the wireless transmission range. Due to the frequent link disconnection and random packet loss feature of VANETs, transmitting the Interest packet and Data packet in a single-path is unreliable.

ter A is the designated forwarding node per-hop through which the Interest and Data packets are forwarded. However, due to the link disconnection caused by high-speed mobility of vehicle and the random packet loss feature of wireless fading channel, packet loss could also occur at the specified forwarding node [13]. If transmitting the Interest packet in a single-path is unreliable, having the Data packet return along the reversed path of the Interest packet transmission could be even more difficult.

In this paper, we propose a packet forwarding strategy based on optimal and backup (PFOB) for the highway scenario in VNDN. In PFOB, the Interest packet is reliably transmitted in both directions of highway along the single-path formed by optimal forwarding nodes, and the Data packet is returned along the backup multi-path. It aims not only to solve the redundancy caused by flooding, but also to achieve reliable and effective Interest and Data forwarding. The main contributions of our work are threefold.

- When selecting the optimal forwarding node, PFOB not only uses distance and link duration as selection criteria like other restrictive forwarding strategies to provide a relatively stable and efficient connection, but also uses signal strength and node-degree as selection criteria to improve link reliability and reachability.
- When Interest packet loss occurs at the selected optimal node, we adopt a lightweight retransmission mechanism, which increases the reliability of the Interest packet transmission without incurring additional control messages.
- As the optimal Interest packet forwarding node is specified, some backup nodes for the return of the Data packet are specified at the same time. The backup node with higher link stability has the higher priority to forward Data packet. This backup mechanism provides reliable multi-path forwarding of Data packets without additional network overhead.

With the combination of optimal based Interest forwarding, lightweight Interest retransmission and backup based Data

multi-path forwarding, PFOB can significantly improve the content retrieval ratio, and reduce the content retrieval delay with low overhead.

The remainder of this paper is organized as follows. In Section II, we introduce the background of VANETs and NDN and review the related work of forwarding mechanism in VNDN. In Section III, we give a detailed description of PFOB. In Section IV, simulation results and analysis are presented. Finally, the conclusions are drawn in Section V.

II. BACKGROUND AND RELATED WORK

A. *Vehicular Ad Hoc Networks*

As a special kind of mobile ad hoc network, VANETs inherit the characteristics of decentralized control, equal status of nodes with independent routing and distributed self-organizing management. Besides these, it also has some unique characteristics.

- Highly dynamic network topology: Due to the high-speed mobility of the vehicle and the frequent departure and entry of vehicles into the network, the topology of the vehicle network changes very rapidly.
- Unstable link connection: High dynamic topology, limited wireless communication range and surrounding environment such as building blockage, wireless interference, etc., make the communication between vehicles unstable and unreliable.
- Non-random movement: Behavior information such as the speed, direction, and position of the vehicle can be obtained through auxiliary equipment such as GPS, sensors, etc. Due to the restrictions of roads, traffic rules and other vehicles, vehicle has a certain moving model instead of random movement.
- Unlimited energy and storage space: In VANETs, communication equipment is generally mounted on the vehicle. As its energy and storage space is provided by the vehicle, energy, storage space, and computing power are not major
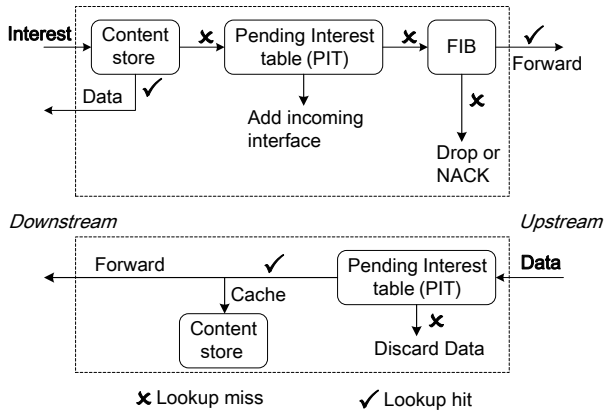
Fig. 2. Forwarding process at an NDN node [9].

problems.

VANETs have attracted lots of attention from both the academia and the industry. The related multi-hop routing protocols are mainly based on the traditional TCP/IP architecture, and the two basic routing protocols are topology-based and position-based routing. However, due to these characteristics of VANETs, the traditional TCP/IP architecture cannot adapt to the rapid network changes, so a new VNDN architecture was introduced, as discussed in Section I.

B. Named Data Networking

NDN uses a pull-based model to retrieve content. There are two types of packets in NDN, namely Interest packets (abbreviated Interest) and Data packets (abbreviated Data). Both types of packets carry a name identifier to identify the content. Consumer sends the Interest which contains the name of the requested content, and any node in the network that has cached the requested content can return the Data according to the reverse path of the Interest forwarded.

Each NDN node maintains three data structures, namely forwarding information base (FIB), pending interest table (PIT) and content store (CS). The function of the FIB is similar to that of the routing table in the TCP/IP architecture. Unlike the routing table in TCP/IP, it allows packets to be forwarded through multiple interfaces. The PIT records information of Interest that has been forwarded, including the name prefix of the Interest and the corresponding interface. The CS is used to store data generated by a node itself or retrieved from other nodes.

Fig. 2 shows the forwarding process of the Interest and Data. The NDN router nodes process the received Interest as follows: 1) It checks its CS first. If CS has content that matches the name in the Interest, the corresponding Data is sent from the incoming face. 2) If no matching content is found in CS, the PIT is checked. If a record exists in the PIT entry, the current incoming face is added to the PIT entry and the Interest is discarded. 3) If there are no records in the PIT entry, it looks for FIB. If there is a corresponding face in the FIB entry, the Interest is forwarded from the face, and the corresponding information of the Interest are recorded in the PIT. 4) If no corresponding entry is found in the FIB, the Interest is discarded. The NDN router nodes process the received Data as follows: 1) It finds whether there is a corresponding entry in the PIT. If there is, the Data is cached in the CS and the Data is forwarded according to all incoming face recorded in the PIT entry. 2) If not, the Data is discarded.

C. Related Work of Forwarding Strategy in VNDN

According to whether the transmitted information is urgent traffic information or not, the applications of VANETs can be divided into two categories: Safety and unsafety. For the safety application, we can use DSRC to transmit some emergent traffic information in the range of one hop; for the unsafety application, it can be further divided into two types: One is location-dependent, such as the traffic situation of some roads, the other is location-independent, such as entertainment information. Bian et al. [14] proposed a forwarding strategy that can select the geographically nearest and intersection nodes to forward the Interest according to the geographical location of requested content. However, this strategy [14] cannot address the content retrieval problem of location-independent application. Grassi et al. [15] proposed Navigo which maps data names to data locations and forwards the Interest along the shortest geographical path. However, for location-dependent application, Navigo can append the geographic location of data to the prefix of the name before sending the Interest. For location-independent application, Navigo needs to discover the geographic location of the data through initial flooding procedure. In addition, Navigo needs an additional mechanism for mapping data names to data locations.

In VANETs, proactive and reactive forwarding are the most commonly used strategies. Yu et al. [16] developed a proactive routing protocol in which a node proactive sends advertisements to form a routing table. Bloom filters are used to reduce the larger overhead. However, this management faces some challenges such as data source mobility, dynamic data catalogues and frequency of updates. Varvello et al. [17] proved that the cost of maintaining routing information may overwhelm the benefits of proactive solutions in content-centric MANETs. Amadeo et al. [3] argued that the dynamics of connectivity among moving vehicles makes it difficult, if not completely infeasible, to run a routing protocol to build and maintain the FIB. These studies [3], [17] have illustrated that it is not feasible to form FIB in VNDN by exchanging name-prefixes announcements among routers. The routing and forwarding in NDN are smart, so each node can perform hop-by-hop intelligent forwarding of the Interest and Data according to the decision of the policy layer in VNDN.

Due to the absence of FIB table, flooding is the simplest forwarding strategy in the native VNDN. However, Flooding forwarding leads to a lot of conflicts, packet loss and retransmission, and the network performance will deteriorate quickly or even not provide services. There have been some restrictive mechanisms to reduce the redundant forwarding. These restrictive forwarding strategies can be divided into two categories: The competitive forwarding strategy of receiver-oriented and the initiative assignment strategy of sender-oriented.

In the sender-oriented strategy, each node periodically sends its own status information through the hello packet. According to the received status information of neighbors, a sender node

specifies the best node to forward packet. Ahmed *et al.* [11] proposed a scheme named robust forwarder selection (RUFS) to mitigate the Interest broadcast storm. RUFS selects a single forwarder for each hop on the basis of multiple criteria, i.e., relative velocity, the Interest satisfaction rate, and the minimum number of hops that Interest is satisfied. However, the biggest shortcoming of RUFS is that the selected forwarding node may be in the opposite direction of the content provider.

In receiver-oriented strategy, when an intermediate node receives an Interest or a Data, it can decide either to forward it or not. Wang *et al.* [18] proposed a mechanism in which each receiver node calculates its distance with the sender, and the farthest one has the smallest waiting time for forwarding packets. However, due to the fading feature of wireless channels, the farther the node is, the more likely the packet will be lost. Moreover, this strategy [18] cannot support location-independent applications, the geo-location information of the requested content is embedded into Interest. Ahmed *et al.* [12] proposed a distributed interest forwarder selection (DIFS) scheme that mitigates the Interest broadcast storm. In DIFS, according to multiple criteria, the Interest is forwarded in a single-path in both directions. DIFS can be applied to location-independent and location-dependent applications, and solves RUFS's shortcoming of single-direction selection of forwarding nodes. However, an important issue is that DIFS does not provide any reliability guarantee mechanism for Interest and Data forwarding in the dynamic and unreliable VANETs environment.

III. PROPOSED STRATEGY: PFOB

A. Strategy Overview

PFOB specifies optimal node to forward Interest by jointly considering distance, relative velocity, link duration, signal strength and node-degree. The non-optimal node does not forward the received Interest. These optimal Interest forwarding (OIF) nodes are abbreviated as OIF nodes. The consumer specifies the left and right OIF nodes in the Interest to be forwarded. When the right OIF node receives the Interest, it continues to specify a next-hop OIF node in the direction where the abscissa is greater than its own. For the left OIF node, it continues to specify a next-hop OIF node in the direction where the abscissa is less than its own. This process continues until the content provider is found. For vertical highway, it will not be repeated here.

These selected OIF nodes have better stability and reliability than their neighbors. However, due to the mobility of the vehicles and the wireless random packet loss characteristics, the transmission of Interest through OIF nodes is still unreliable. For the Interest, we adopt a lightweight retransmission mechanism to improve the reliability of the transmission without increasing the ACK control packet overhead.

The use of unreliable Interest single-path reverse transmission of Data is even more unreliable, and Data packets are large and retransmission costs are too high. In PFOB, while selecting OIF node for each hop, we select some nodes with relatively stable link status as backup Data forwarding nodes. These backup Data forwarding (BDF) nodes are abbreviated as BDF nodes. These BDF nodes form multiple backup paths so that when the Data

NT (Neighbor table)

ID	Position	Velocity	Direction	Node-degree (|RNT|, |LNT|)	Signal strength

Fig. 3. The format of neighbor table.

Interest packet

Name
Selectors (Order preference, publisher filter, exclude filter, ...)
Nonce
Guiders (Scope, Interest lifetime)
Forwarder position
Next-hop OIF ID
BDF list

Fig. 4. Extensions on Interest packet format. Interest packets contain three additional fields to store the forwarder position, Next-hop OIF ID and BDF list.

cannot be successfully forwarded through the OIF nodes, these backup paths provide reliable multi-path forwarding.

The selection of OIF node, the lightweight retransmission of Interest, the selection of BDF node and the whole forwarding process of PFOB are described in details as follows.

B. OIF Node Selection

In PFOB, each node sends its status information through a one-hop hello packet. The status information includes current position, velocity, driving direction and node-degree represented by (x_n, y_n), v_n, θ_n, and d_n, respectively. According to our experimental scenario, the sending frequency of hello packets is set to 2 Hz.

Each node collects the state information of neighbor nodes and the signal strength of the corresponding hello packet to form a neighbor table (NT). The format of NT is shown in Fig. 3, where node-degree contains two items, |RNT| and |LNT|. |RNT| and |LNT| denote the number of nodes in RNT and LNT respectively. The calculation method of the right neighbor table (RNT) or left neighbor table (LNT) is shown in (1) and (2). For the current right OIF node m, it sorts the nodes in its RNT through a multi-criteria selection method (the same applies to the left OIF node). In other words, the current OIF node only selects the next-hop OIF from the neighbor nodes that are in its forwarding direction. The criteria and methods for OIF node selection are described as below.

$$RNT_m(n) = \{n \in NT_m \,|\, x_n > x_m\} \tag{1}$$

$$LNT_m(n) = \{n \in NT_m \,|\, x_n < x_m\} \tag{2}$$

BL (BDF list)

ID	T_{wait}

Fig. 5. The format of BDF List.

PIT

Name	Nonce	Face	Type	T_{wait}

Fig. 6. Extensions on PIT format. PIT contain two additional fields to store the corresponding type and waiting time.

B.1 Selection Criteria

1) Distance: $D(m, n)$ represents the distance between the current OIF node m and the neighbor node n.

$$D(m,n) = \sqrt{(x_m - x_n)^2 + (y_m - y_n)^2} \quad (3)$$

2) Relative velocity: $V(m, n)$ represents the relative velocity between the current OIF node m and the neighbor node n.

$$V(m,n) = \sqrt{a^2 + c^2}, \quad (4)$$

where, $a = v_m cos\theta_m - v_n cos\theta_n$, $c = v_m sin\theta_m - v_n sin\theta_n$.

3) Link duration: $L(m, n)$ represents the link duration between the current OIF node m and the neighbor node n [19]. R represents the transmission range of node.

$$L(m,n) = \frac{\left(\sqrt{(a^2 + c^2) R^2 - (ad - bc)^2}\right) - (ab + cd)}{a^2 + c^2}, \quad (5)$$

where, $a = v_m cos\theta_m - v_n cos\theta_n$, $b = x_m - x_n$, $c = v_m sin\theta_m - v_n sin\theta_n$, and $d = y_m - y_n$.

4) Signal strength: $S(n)$ represents the exponentially weighted moving average signal strength of neighbor node n [20]. s_n is the received signal strength of neighbor node n, s_{thr} is the threshold value of the signal strength that can be received.

$$S(n) \leftarrow (1 - \alpha) S(n) + \alpha \left(1 - \frac{s_{thr}}{s_n}\right) \quad (6)$$

5) Node-degree: $N(n)$ represents the exponentially weighted moving average node-degree of neighbor node n. nd_n is the node-degree of n as shown in (7), where the current OIF node m selects $|RNT_n|$ or $|LNT_n|$ as the node-degree of n according to its forwarding direction. Each neighbor in the forwarding direction of the current OIF node m has a nd_n value, and $n_{\max}$ is the largest of these values.

$$nd_n = |RNT_n| \vee |LNT_n| \quad (7)$$

$$N(n) \leftarrow (1 - \alpha) N(n) + \alpha \left(\frac{nd_n}{nd_{\max}}\right) \quad (8)$$

In $S(n)$ and $N(n)$, α is a weighting factor whose value is set as 0.8. The smaller the relative velocity and the longer the link

duration, the better the link stability of the nodes. Selecting the node with a larger distance can reduce the number of forwarding hops, but it is not that the greater the distance, the better, because the larger the distance, the greater the signal fading and the greater the possibility of packet loss. More importantly, in PFOB, signal strength is used as a selection criterion, and those nodes with higher signal strength can provide a better packet reception probability. Nodes with higher node-degree have more choices when selecting OIF and BDF nodes, and when the network density is uneven, these nodes have better connectivity and reachability.

B.2 Multi-Criteria Selection Method

Multi criteria decision making (MCDM) method is used to rank neighbors to select the OIF node. TOPSIS [21] method is one of the most commonly used methods in MCDM. An evaluation matrix containing m evaluation objects and n criteria is created. $A = \{A_1, A_2, \cdots, A_m\}$ is the the evaluation object set, that is the neighbor node set. $B = \{B_1, B_2, B_3, B_4, B_5\}$ is the criteria set, that is corresponding to distance, relative velocity, link duration, signal strength and node-degree, respectively. Therefore the decision matrix is $F = [f_{ij}]_{m \times n}$ represents the value of the ith neighbor node at the jth criteria. The ranking method is executed as follows:

1) Construct a normalized decision matrix $H = [h_{ij}]_{m \times n}$

$$h_{ij} = \frac{f_{ij}}{\sqrt{\sum_{i=1}^{m} f_{ij}^2}}, i = 1, 2, \cdots, m; j = 1, 2, \cdots, n \quad (9)$$

2) Construct the weighted normalized decision $O = [o_{ij}]_{m \times n}$. For simplicity, the w_j for all criteria is equally distributed.

$$O_{ij} = w_j h_{ij}, i = 1, 2, \cdots, m; j = 1, 2, \cdots, n \quad (10)$$

3) Determine the positive and negative ideal solution.

$$I^+ = (o_1^+, o_2^+, \cdots, o_n^+), I^- = (o_1^-, o_2^-, \cdots, o_n^-) \quad (11)$$

$$o_j^+ = \max_i o_{ij}, \qquad o_j^- = \min_i o_{ij} \quad (12)$$

B_1, B_3, B_4, and B_5 are the positive criteria, and B_2 is the negative criteria.

4) Calculate the Euclid distance between each solution and the positive and the negative ideal solution, their values are k_i^+ and k_i^-.

$$k_i^+ = \sqrt{\sum_{j=1}^{m} \left(o_{ij} - o_j^+\right)^2}, k_i^- = \sqrt{\sum_{j=1}^{m} \left(o_{ij} - o_j^-\right)^2} \quad (13)$$

5) Calculate the closeness of each solution to the positive ideal solution.

$$E_i = \frac{k_i^-}{k_i^+ + k_i^-} \quad (14)$$

Finally, the E_i are sorted and the neighbor node with the largest E_i value is selected as the next-hop OIF node.
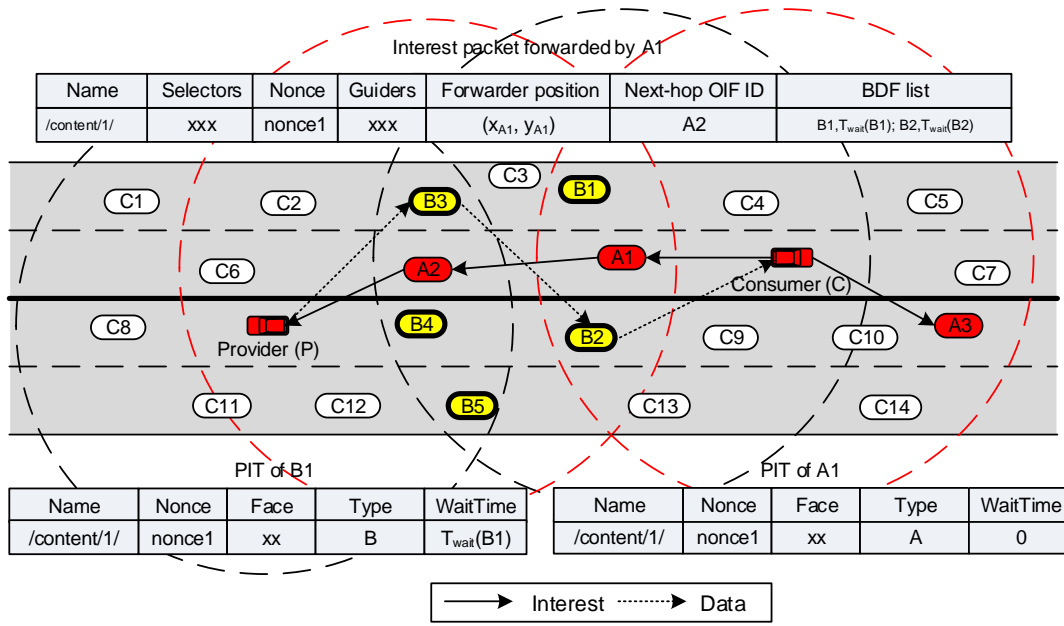
Fig. 7. The node beginning with the letter A is the OIF nodeOIF. According to the extended Interest packet format, the Interest packet is forwarded through the OIF nodes. The node starting with the letter B is the BDF node. According to the extended PIT, the Data packet is forwarded through multiple backup paths formed by BDF nodes.

C. Lightweight Interest Retransmission

The OIF node may not receive the Interest forwarded by the previous-hop OIF node. Due to the loss of Interest, the consumer does not receive a corresponding Data within the application retransmission expiration time, and it will resend the Interest, so the end-to-end delay of the entire request increases. In the MAC layer of IEEE 802.11, there is no confirmation and retransmission mechanism for broadcasting.

Therefore, in order to improve the reliability of Interest transmission, a lightweight acknowledgement retransmission mechanism is adopted in the PFOB, which implements a lightweight retransmission of the Interest without additional acknowledgement information. When an OIF node sends the Interest, it will start the corresponding acknowledgement timer T_{ack}. If the OIF node does not receive the same Interest sent by the upstream OIF node before the timer expires, the OIF node considers the transmission as failed and retransmits this Interest. In PFOB, the expire time of T_{ack} is set to 30 ms by default.

D. BDF Node Selection

When an OIF node receives Interest, it has two important steps to perform. The first step is to specify the next-hop OIF node in the Interest to be forwarded, this step is described in Section III.B above. The second step is to specify BDF nodes in the Interest to be forwarded.

In PFOB, a simple extension is made on Interest packet format. As shown in Fig. 4, Interest packet include Forwarder Position, Next-hop OIF ID and BDF List in additional field. There are two steps for the BDF node selection. One is how to select the BDF nodes, and the other is to determine the waiting timer

T_{wait} for each BDF node. The consumer node does not establish its BDF node. When an OIF node receives the Interest, the following steps are taken to select the BDF node:

1) Find out the corresponding value in the Forwarder Position field of the received Interest, that is, the position of the previous-hop OIF node.

2) Calculate the next-hop OIF node using the method in Section III.B.

3) Find the common neighbors of the previous-hop OIF node and the next-hop OIF node as the BDF nodes. The method of finding common neighbors is shown in (15), where m, x, and y represent the current OIF node, the previous-hop OIF node and the next-hop OIF node, respectively. BL represents the BDF List of m.

$$BL_m(i) = \{i \in NT_m | D(i,x) < R \wedge D(i,y) < R\} \quad (15)$$

4) Calculate the expire time of T_{wait} for each BDF node. For a BDF node i, $L(i,x)$ is the link durations of i and the previous-hop OIF node x, and $L(i,y)$ is the link durations of i and the next-hop OIF node y. The T_{wait} of a BDF node can be computed using (16), where T_{max} is the maximum link duration, and $T_{transmit}$ is a minimum delay for a node that is next to the previous hop. The ID of each BDF node and the corresponding T_{wait} are stored in BL. The format of BL is shown in Fig. 5. At this point, the current OIF node replaces the Forwarder Position, Next-hop OIF ID and BDF List fields of the received Interest, then forwards the new Interest.

As shown in Fig. 6, two fields of Type and T_{wait} are added to the PIT format. When an OIF node receives Interest, the corresponding type in PIT entry is set to A, and the T_{wait} is set to

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Algorithm 1 Received Interest in the Proposed PFOB

1:   Received [Name, Selectors, Nonce, Guiders, Forwarder Position, Next-hop OIF ID, BDF List]
2:   **if** received from Application **then**
3:       Find right and left OIF nodes.
4:       Add [Name, Nonce, Face, Type(A), 0] in PIT.
5:       Replace Forwarder Position and Next-hop OIF ID in received Interest.
6:       Forward Interest.
7:   **else**
8:       **if** Content Not in CS **then**
9:           **if** Name Not in PIT **then**
10:              **if** ID equal Next-hop OIF ID **then**
11:                  Add [Name, Nonce, Face, Type(A), 0] in PIT.
12:                  Calculate new Next-hop OIF ID and BDF List.
13:                  Replace Forwarder Position, Next-hop OIF ID and BDF List in received Interest.
14:                  Forward Interest.
15:              **else**
16:                  **if** ID equal one of ID in BDF List **then**
17:                      Add [Name, Nonce, Face, Type(B), T_{wait}] in PIT.
18:                      Drop Interest.
19:                  **else**
20:                      Drop Interest.
21:                  **end if**
22:              **end if**
23:          **else**
24:              Drop Interest
25:          **end if**
26:      **else**
27:          DATA[Name, MetaInfo, Content, Signature].
28:          Forward Data.
29:      **end if**
30: **end if**

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0. When BDF node receives Interest, the corresponding type in PIT entry is set to B, and its waiting time is recorded in T_{wait} field.

When the Data is returned, some backup path can be provided by the BDF nodes. In order to prevent redundancy and conflicts caused by multiple BDF nodes forwarding the same Data, When a BDF node receives a Data, T_{wait} is started. If a BDF node receives the same Data before the timer expires, the Data forwarding is cancelled, otherwise Data is forwarded. Due to the communication link is easy to disconnect, the node with higher link stability can provide relatively stable services. According to (16) the BDF node with higher link stability has shorter waiting time than a lower one.

$$T_{\text{wait}}(i) = T_{\text{transmit}}\left(1 - \frac{\min\left(L(i,x), L(i,y)\right)}{T_{\max}}\right) \qquad (16)$$

E. Forwarding Process of PFOB

In this subsection, the PFOB strategy is described as a whole in terms of the forwarding process of Interest and Data.

When receiving Interest from the application layer, the consumer specifies OIF nodes in right and left directions respec-

tively in the received Interest, and then new Interest will be forwarded. When an intermediate node receives Interest, it performs the following steps.

1) First, it checks its CS. If there is a matching content, Data will be sent from the incoming face; otherwise, the PIT will be checked.

2) In the PIT, if a matching entry exists, the Interest will be discarded; if not, the ID of this node will be compared with the Next-hop OIF ID in received Interest.

3) If the ID of this node is equal to the Next-hop OIF ID, firstly, a new entry is added to the PIT, where its type is set to A and the waiting time is 0. Then, the node calculates the new Next-hop OIF ID and BDF List and replaces them with the corresponding fields in Interest. Finally, the node forwards this Interest; otherwise, the node checks the BDF List in received Interest.

4) If the node finds itself in BDF List, a new entry is added to the PIT, where its type is B and the waiting time is T_{wait}. The Interest is discarded.

The Interest forwarding process is shown in Algorithm 1. For example, in Fig. 7, the next-hop OIF nodes specified by consumer C are A1 and A3. It needs to be emphasized here that the BDF List field in the Interest sent by the consumer is null. When A1 receives an Interest from C, it first calculates the next-hop OIF node as A2. Then A1 finds the common neighbors of C and A2, such as B1 and B2, and calculates their T_{wait} to form a new BDF List. Then A1 replaces the Forwarder position field with A1's position, the Next-hop OIF ID field with A2 and the BDF list field with (B1, T_{wait}(B1); B2, T_{wait}(B2)) in received Interest. At this point, A1 forms a new Interest and forwards it out. After receiving the Interest from A1, A2 becomes a new next-hop OIF node, and B1, B2 become the BDF node of A1. The same procedure is followed by A2 until the provider receives the Interest.

When a Data arrives, an intermediate node performs the following steps, as shown in Algorithm 2.

1) First, it checks PIT, if a matching entry does not exists, the Data is discarded; otherwise, a further check will be performed in Type field of PIT entry.

2) If the Type is A, Data is immediately forwarded; if not, the node starts T_{wait}.

3) If the same Data is received before T_{wait} expires, the node will not forward Data; otherwise, it will forward Data.

For example, in Fig. 7, when the provider sends Data, because A2 node fails to forward Data, the B3 node will get the priority to forward Data as a BDF node. Similarly, when the next-hop OIF node A1 fails to forward Data, the B2 node will get the priority to forward Data as a BDF node. This process continues until the Data is sent to the consumer.

IV. EVALUATION RESULTS

We used an NDN simulator ndnSIM [22] (version 2.3) to conduct simulations. ndnSIM offers a common, user-friendly, and open-source simulation platform based on the NS-3. Simulation environments of this paper are shown in Table 1. We carry out the traffic vehicle mobility model generated by [23] built over SUMO [24]. The highway consists of two lanes in

Algorithm 2 Received Data in the Proposed PFOB

1:    Received [Name, MetaInfo, Content, Signature]
2:    **if** Name in PIT **then**
3:        **if** Type in PIT entry is A **then**
4:            Forward Data.
5:        **else**
6:            Start T_{wait} in PIT entry
7:            **if** not received the same Data before T_{wait} expires **then**
8:                Forward Data.
9:            **end if**
10:       **end if**
11:       Remove [Name, Nonce, Face, Type, T_{wait}] from PIT.
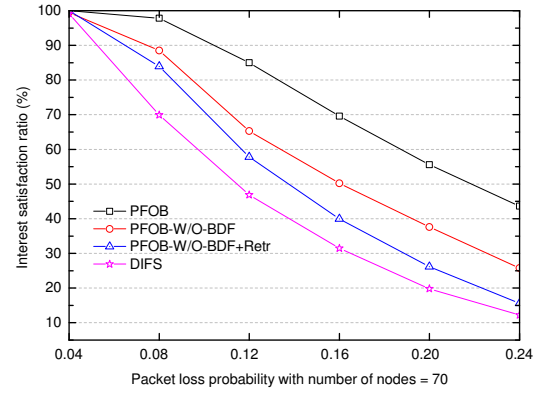12:   **else**
13:       Drop Data.
14:   **end if**

Table 1. Simulation environment.

Parameter	Value
Topology	3000 m, 4 lanes
Average vehicle velocity	20 m/s
Number of Interest	4 packet per consumer
Data packet size	1024 bytes
Communication range	250 m
MAC protocol	IEEE 802.11p
Propagation model	Nakagami model
Simulation duration	500 s

(a)

(b)

Fig. 8. Interest satisfaction ratio for various packet loss probabilities and number of nodes.

each direction, and the length of all lanes is 3000 m. The average vehicle velocity is 20 m/s. The transmission range is 250 m. In the initial state, 10,000 contents are randomly and evenly distributed to all nodes in the network. The Data packet size is 1024 bytes. The simulation duration is 500 s. During the running duration, each node in the network randomly generates 4 Interests. We conducted comparative experiments under different packet loss probabilities and network sizes. The maximum packet loss probability is set as 0.24 because we want to model a moderate fading channel on highway, different from a dramatically fading channel in urban communities [25]. We plotted the graphs from the average value of 50 different simulation runs and the confidence interval is 95%.

Like aforementioned, PFOB has three mechanisms: OIF, lightweight retransmission and BDF. In order to better evaluate each mechanism of PFOB and compare with DIFS [12]. PFOB was compared with "PFOB-W/O-BDF", "PFOB-W/O-BDF+Retr", and DIFS. "PFOB-W/O-BDF" represents PFOB without BDF mechanism. "PFOB-W/O-BDF+Retr" represents PFOB without BDF and lightweight retransmission. In comparison, the following quality metrics were employed:

- Interest satisfaction ratio: The average ratio of satisfied Interests to all requested Interests.
- Interest satisfaction delay: The average delay from the first time the consumer forwards Interest to the corresponding Data response.
- Number of application retransmissions: The average number of application layer retransmission for per satisfied Interest.
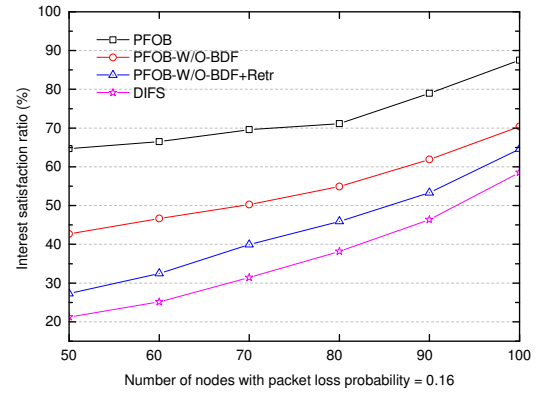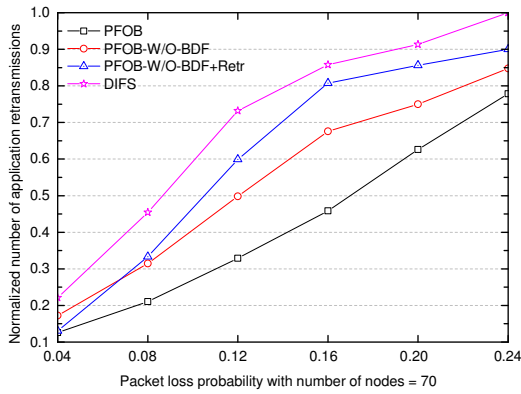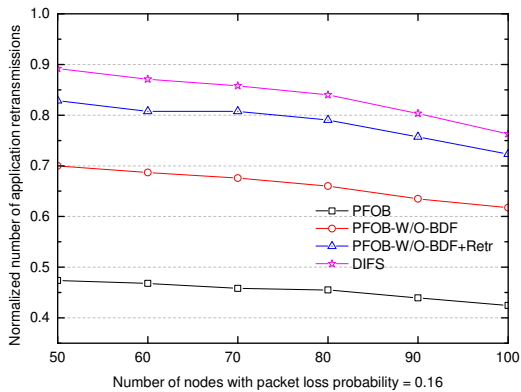
A. Interest Satisfaction Ratio

Figs. 8(a) and 8(b) show the average Interest satisfaction ratio for various packet loss probabilities and number of nodes, respectively. In Fig. 8(a), DIFS shows the lowest satisfaction ratio at different packet loss probabilities. The reason is, DIFS forwards Interest and Data according to the specified single-path. The establishment of this single-path only takes into account the distance and movement factors of the vehicles. There is no mechanism to guarantee transmission reliability, thus causing the failure of a large number of requests. In addition, DIFS is a receiver-oriented strategy, in which each node determines whether to forward or not in an autonomous manner, as a result, redundant broadcasts cannot be eliminated entirely. The PFOB-W/O-BDF+Retr works better than DIFS, because it takes into account not only distance and movement factors, but also signal strength and node-degree. It has relatively high connection reliability and reachability in unreliable networks and in different network sizes. The PFOB-W/O-BDF works better than PFOB-W/O-BDF+Retr, because it adds the retransmission mechanism of Interest on the basis of OIF mechanism, improving the success rate of Interest reaching the provider. PFOB adds the BDF mechanism on the basis of PFOB-W/O-BDF and improves the success rate of Data returning to the consumer. Therefore, PFOB can achieve 33.1%, 72%, and 114.2% higher satisfaction ratio than PFOB-W/O-BDF, PFOB-W/O-BDF+Retr and DIFS respectively in various packet loss probabilities. In Fig. 8(b), the
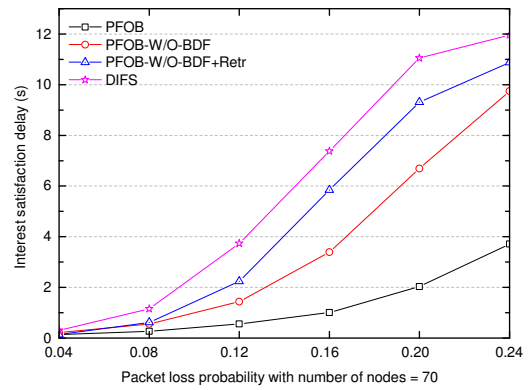
Fig. 9. Number of application retransmissions for various packet loss probabilities and number of nodes.

Fig. 10. Interest satisfaction delay for various packet loss probabilities and number of nodes.
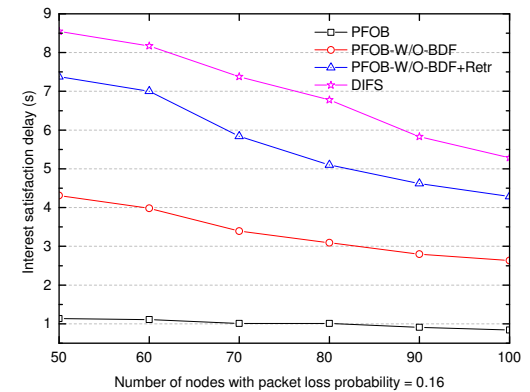
satisfaction ratio of these four methods increases as the number of nodes, and PFOB is better than the other three. It is observed that PFOB achieves 35.7%, 75.7%, and 116% higher satisfaction ratio than other three under different network sizes. This shows that PFOB can still achieve a high Interest satisfaction ratio in the environment with small network size and poor connectivity.

B. Number of Application Retransmissions

Figs. 9(a) and 9(b) show the average number of application retransmissions for various packet loss probabilities and number of nodes, respectively. In ndnSIM, when consumer sends Interest, a retransmission timer is started. If the related Data is not received before retransmission timer expires, consumer will retransmit the Interest. In this experiment, the initial application retransmission timer of consumer is the default value of ndnSIM 2.3. In Fig. 9(a), DIFS shows the highest number, because in the unreliable single-path, each hop transmission failure will lead to the final application layer retransmission. As described in Section IV.A, DIFS has a lower Interest satisfaction ratio, thus increasing the number of retransmissions per request. Under different packet loss probabilities, the number of application retransmissions of PFOB is 25.1%, 28.2%, and 41.9% lower than those of PFOBW/O-BDF, PFOB-W/O-BDF+Retr and DIFS respectively. In Fig. 9(b), when the number of nodes increases, the number of retransmissions of the four methods de-

creases, and PFOB is better than the other three. PFOB achieves 31.5%, 42.3%, and 45.8% less number of application retransmissions than other three in various network sizes.

C. Interest Satisfaction Delay

Figs. 10(a) and 10(b) show the average Interest satisfaction delay for various packet loss probabilities and number of nodes, respectively. In Fig. 10(a), as the packet loss probability increases, PFOB shows the lowest delay. The reasons are as follows: 1) Due to the OIF and lightweight retransmission mechanism of PFOB, the reliability of Interest transmission per hop increases, and the loss of the Interest can be discovered and retransmitted earlier, instead of waiting for the consumer's retransmission timer to expire. Therefore, the delay for Interest to reach the provider is reduced. 2) The BDF node with longer link duration has higher forwarding priority. This mechanism allows the backup path to have better transmission reliability and avoids the simultaneous forwarding of Data, thus reducing the delay due to collisions and retransmission, thus reducing the delay of the entire request. PFOB achieves 58.3%, 59.8%, and 75.5% less delay than other three under different packet loss probabilities. In Fig. 10 (b), we find that when the packet loss probability is fixed and number of nodes decreases, the delay of PFOB does not increase significantly with the decrease of network size as DIFS does, that is to say, PFOB can still maintain a good delay performance when the network size is small. It is observed that

PFOB achieves 69.8%, 82%, and 85.5% less delay than other three in various network sizes.

V. CONCLUSIONS

In this paper, we have identified the redundancy and unreliability challenges faced by VNDN forwarding, and proposed PFOB. In PFOB, by considering the signal strength, node-degree and light retransmission of Interest, the Interest forwarding path with more reliability and accessibility is established. In particular, while establishing the Interest path, some backup multi-path is established to realize the reliable return of Data. Due to the reliable single-path forwarding of Interest and backup multi-path forwarding of Data, PFOB not only solves the flooding problem, but also realizes reliable and effective forwarding of packets in unreliable VANETs environment. Simulation results show that PFOB can significantly improve the content retrieval performance, which achieves 119% higher Interest satisfaction ratio, 46.5% lower number of application retransmissions, and 86% lower Interest satisfaction delay compared with DIFS in the case with moderate wireless reception and network connectivity.

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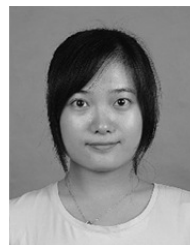
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