Towards Efficient Data Communication in Vehicular NDN: The Superiority of Adaptive SRTT-Based Forwarding (ASF)

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***Abstract*—Vehicular Named Data Networking (V-NDN) is a promising solution for improving data communication in high-mobility vehicular environments. This study compares three forwarding strategies—Best-route, Multicast-VANET, and Adaptive Strategy Forwarding (ASF)—and implements Best-route and ASF in a V-NDN network. Performance is evaluated based on Satisfied Interests, CS Hit Ratio, Unsolicited Data, and Incoming Data Matching. Simulations show that ASF outperforms the other two methods. It achieves the maximum Interest fulfilment ratio with no Unsatisfied Interests, the highest CS Hit Ratio (0.74), and the lowest CS Miss Ratio (0.28), indicating optimal caching efficiency. ASF also handles up to 10,146 Interests per maximum period, far surpassing Best-route (2,978) and Multicast-VANET (2,946). ASF further demonstrates superiority in Incoming Data Matching, achieving the highest total (2,749) among the three methods. Based on these findings, ASF is concluded to be the most effective forwarding strategy for V-NDN networks, particularly in high-density and complex network scenarios. These findings have significant implications for the design and deployment of efficient and reliable vehicular communication systems, paving the way for advanced applications such as autonomous driving and connected vehicles.**

***Keywords*—Vehicular Named Data Networking (V-NDN), forwarding strategies, adaptive forwarding strategy, forwarding pipeline, interest and data measurement**

I. Introduction

Significant efforts have been made to enhance traffic efficiency and safety using vehicular communication systems [1]. Modern transportation systems face increasing demands for real-time data exchange to support automated driving, improve road safety, and enable smart car systems through peer-to-peer data sharing. However, traditional Vehicular Ad-Hoc Network (VANET) architectures, which rely on vehicle identification via IP or MAC addresses to establish connections between data producers and consumers, struggle to meet these demands [2].

The dynamic nature of vehicular environments—characterized by high mobility, rapid topology changes, and intermittent connectivity—makes the establishment and maintenance of these connections challenging. This often results in delays, inefficient content retrieval, and degraded system performance. These limitations highlight the need for innovative solutions that can adapt to vehicular networks' unique characteristics.

This approach aligns well with the requirements of vehicular networks, where content-centric communication can significantly enhance data acquisition efficiency. For instance, Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), and Vehicle-to-Everything (V2X) communications can be facilitated by NDN, offering a future-proof solution for vehicle networking [3]. To address these challenges, researchers have proposed leveraging Named Data Networking (NDN), a promising paradigm shift from traditional IP-based architectures. NDN simplifies communication processes by focusing on data naming rather than location identification, enabling direct data retrieval without the need to establish explicit connections [4]. Despite its potential, Vehicular NDN (V-NDN) faces significant challenges, particularly in identifying the most suitable interface to meet user demands amidst rapid topology changes [5]. To address this, V-NDN introduces three main data structures—Content Store (CS), Pending Interest Table (PIT), and Forwarding Information Base (FIB)—to facilitate the delivery of interest and data packets [6].

The limitations of traditional TCP/IP-based architectures in enabling efficient vehicle data exchange have led researchers to explore the integration of NDN into connected vehicle networks [7, 8]. While prior studies have demonstrated the potential of NDN to improve content delivery efficiency and reduce latency, several technical issues remain unresolved. For example, the high mobility of vehicles in V-NDN environments can lead to frequent communication link breaks, increased latency, and packet loss, all of which hinder the timely delivery of critical information such as traffic

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updates or collision warnings. These challenges underscore the importance of developing robust forwarding strategies that can optimize data dissemination in highly dynamic vehicular networks.

This study presents a novel approach to evaluating forwarding strategies in V-NDN by segmenting results into maximum and minimum periods. This segmentation provides granular insights into the performance dynamics of each strategy, enabling a deeper understanding of their strengths and weaknesses. By incorporating multiple forwarding strategies into the NDNSim source code and analyzing experimental results, this research aims to contribute new recommendations for optimizing V-NDN performance. Specifically, this paper makes the following important contributions:

- The integration of the source code of the best route forwarding strategy algorithm and ASF into a vehicular network framework has been completed;
- Performance measurements of forwarding strategy algorithms are performed using Network Forwarding Daemon (NFD) forwarding path parameters on interest and data packets;
- Changes to data packets and interests are analyzed using NFD forwarding pipes;
- A performance measurement method for forwarding strategies is proposed by measuring interest and data flows in the maximum and minimum periods for each test parameter.

This paper is organized into several parts, as follows: Previous research related to forwarding strategies that support NDN networks in vehicular environments, NDN forwarding strategies, and processing paths in NDN are discussed in Section II; Issues in vehicular networks that are the focus of this work are discussed in Section III. The methodology and techniques used to conduct NDN experiments on vehicular networks, along with the proposed measurement methods, are discussed in Section IV. The results of the experiments are discussed in Section V in several stages, starting with interest and data measurements and the analysis of the performance of forwarding strategies. In Section VI, conclusions on the work, recommendations for forwarding strategies, and future research directions on vehicular networks in NDN are provided.

II. Related Works

A. NDN Architecture

The NDN architecture is recognized as a change in the current communication paradigm, where it is stated that internet users only need content and applications based on data naming rather than location (IP address), and data will be converted into entity form by NDN [9]. The receiving ends control NDN communication, i.e., data consumers. To receive data, data must be requested in the form of an interest packet and a data packet. Both types of packets carry names that identify pieces of data that can be transmitted in one data packet. To receive data, the desired data name must be placed into the interest packet by the consumer [4]. The Router will identify the interface of the incoming request, and the interest packet will be forwarded by looking at the name in the Forwarding Information Base (FIB) and then forwarding the interest to the data producer [10, 11].

The content name in the NDN architecture is used as an address. Three components are identified in the NDN model, namely: the Producer is regarded as a server, the Consumer is regarded as a client, and the middle node is regarded as a router. Three data structures are present in NDN nodes, namely: (1) Content Store (CS), which is used as a temporary cache of received packets; (2) Pending Interest Table (PIT), which is used to record interest packets that have been sent but not yet satisfied; and (3) Forwarding Information Base (FIB), which is used to route data packets [12]. Communication on NDN starts with interest packets being sent upstream by the Consumer. As shown in Fig. 1, an arbitrary name is assigned to the interest packet by the Consumer before it is forwarded to the network. The name is used by the NDN outgoing face (Interface) node to send the reset packet to the Producer. When the interest packet reaches the node that has the requested data, the data packet is sent to the Consumer.

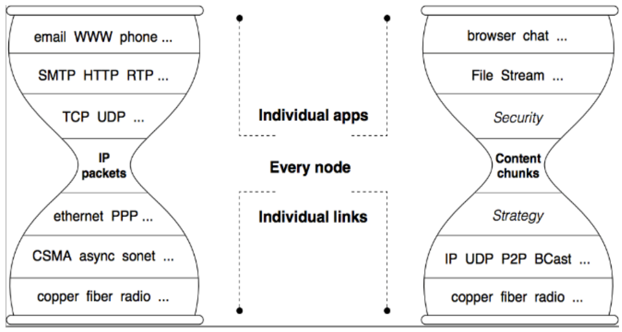


Fig. 1. Hourglas architecture.

When the intended interest packet arrives at a node, the CS is first checked by the node. If the appropriate data packet is available in the CS, it is returned by the node on the same face that the interest packet was received on. Otherwise, the name of the content will be looked for by the node in its PIT. Then, suppose the corresponding interest package entry is available in the PIT. In that case, it means that the same interest has been recorded previously, and the input face packet interest with its arrival time is updated and aggregated in the PIT.

If the entry does not match the PIT, the interest packet is forwarded to the FIB in order to find a path to the producer. If the path already exists in the FIB, the interest packet will be forwarded using a Strategy Forwarding. Otherwise, a negative acknowledgement (NACK) will be returned by the FIB to the consumer who issued the interest package.

B. NDN Forwarding Strategy

The forwarding strategy is responsible for selecting among several best output interface options. Changes in the network environment and the results of the FIB lookup can affect the decision for NDN packet forwarding. The NDN forwarding plane supports three main functions of NDN components: CS, PIT, and FIB [12].

The NFD is a forwarding mechanism that is implemented together with the NDN protocol. The primary purpose of NFD is to support experiments on the NDN architecture by emphasizing modularity and extensibility with protocols, algorithms, and application features. The primary function of NFD is to forward interest and data packets to be forwarded [13]. The challenge in developing forwarding strategies is how an interface that is capable of serving requests with high precision can be found.

C. NDN Vehicular

NDN has the potential to help improve the efficiency of data acquisition in the vehicle environment, so NDN is introduced into the vehicle network, namely vehicular NDN (V-NDN). Message forwarding carried out by vehicles with high mobility will be difficult to achieve request aggregation; V-NDN can provide a solution in reducing data acquisition delays [13].

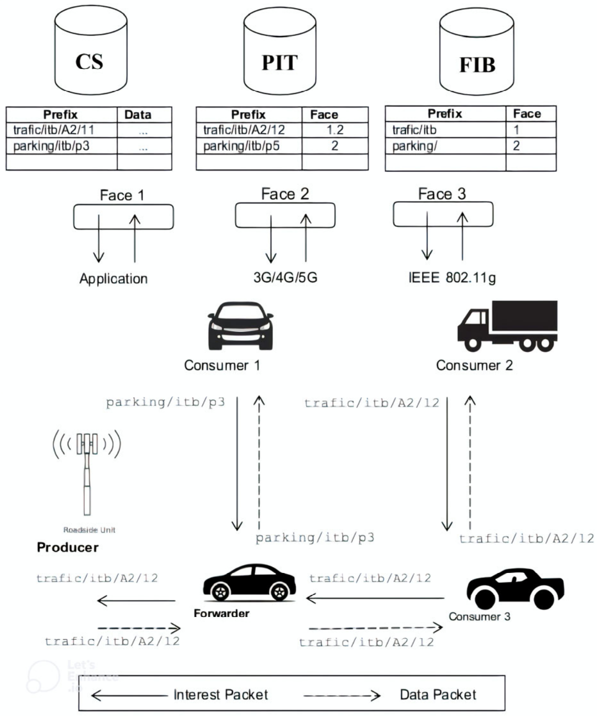


Fig. 2. Vehicle NDN communications [3].

The NDN-based VANET architecture, as shown in Fig. 2, states that to process packets, three main data structures, namely CS, PIT, and FIB, will be included by each node, which are used by NDN routers to store copies of data packets temporarily. Newly forwarded data packets will be stored in the CS to serve future requests [14]. Vehicular NDN is formed by the integration of Named Data Networks (NDN) with Vehicular Ad-Hoc Networks (VANETS). However, communication link breaks can also be caused by the high mobility of vehicles in V-NDN, which has the potential for data transmission failure [15].

Although advantages such as increased content delivery efficiency and built-in security are offered by NDN, significant challenges remain. These challenges are comprised of rapid network topology dynamics, the need for adaptive data forwarding mechanisms, and integration with existing network infrastructure [16].

Authors of Refs. [7, 8, 17] conducted to compare multicast and multicast-VANET in urban and highway mobility scenarios using NS3, ndnsim, and SUMO. The results indicate that multicast-VANET is more efficient in terms of packet count and average travel time. Research [18] has been carried out to evaluate multicast strategies in urban networks based on delay, packet loss, overload, and trip duration. The results reveal that NDN excels in throughput, latency, and packet delivery.

A geolocation-based forwarding strategy has been proposed in Ref. [19] to enhance NDN data dissemination in urban VANETS. Evaluations using Interest Packets, Data Packets, and Cache Delay demonstrate improved efficiency. Zhou *et al.* [20] compared multicast, best-route, and ASF in urban networks using ndnSIM. As a result, ASF has been found to improve the CS Hit ratio and reduce request delay compared to other strategies.

In this study, NDN4IVC (NS3, SUMO) has been used to compare multicast-VANET, best-route, and ASF with broader parameters, such as Satisfied Interest, Unsatisfied Interest, CS Hit, CS Miss, Data Unsolicited, and Data Matching.

Geolocation-based multicast and forwarding were evaluated in previous studies without considering parameters such as cache efficiency, unsolicited data, and matching interest. These limitations are addressed in the current study with a more comprehensive approach. The details are presented in Table I.

TABLE I. COMPARISON OF FORWARDING STRATEGIES IN V-NDN: SIMULATION, MOBILITY, AND PERFORMANCE

Ref.	Strategi Forwarding	Simulation	Mobility	Measurement Parameter	Result
[7, 8, 17]	Multicast dan multicast-vanet	NS3, ndnsim, SUMO	Urban Network, Highway	Number of packages, average travel time.	Multicast-vanet is more efficient than standard multicast
[18]	Multicast	NS3, ndnsim, SUMO	Urban Network	delay, packet loss, overload, trip duration	Demonstrates NDN's advantages in throughput, latency, and packet delivery.
[19]	Geo-based forwarding strategy	NS3, ndnsim, SUMO	Urban Network	Number Interest packages, Data Packet, Cache Delay	A forwarding strategy improves NDN data dissemination.
[20]	Multicast, best-route, ASF	ndnsim	Urban Network	number of interest, CS Hit Ratio, request delay	increases cache hit ratio, and reduces request delay.
This Research	Multicast-Vanet, Best-route, ASF	NDN4IVC (NS3, SUMO)	Urban Network	Satisfied, Unsatisfied, CS Hit, CS Miss, Data Unsolicited, Data Matching	ASF enhances request satisfaction and caching efficiency with high Satisfied Interest and CS Hit Rates.

III. Problem Definition

As in-vehicle communication technology advances, vehicle networks have been introduced with NDN, creating the concept of V-NDN. Great potential in improving the efficiency of data acquisition in high-mobility environments, such as vehicles, is offered by V-NDN. With the NDN approach, three main data structures—CS, PIT, and FIB—are utilized by each node in the network to store and manage data packets dynamically. This allows for request aggregation and reduces data delivery delay. However, several challenges are faced in the implementation of V-NDN. One of the main problems is the high mobility of vehicles in the network, which causes rapid topology changes, communication link breaks, and potential data transmission failures. This condition complicates the message forwarding process, making it difficult for communication efficiency to be achieved, especially in meeting real-time data requests. In addition, the lack of a robust mechanism to manage network dynamics can worsen network performance, resulting in increased latency and packet loss. These issues highlight the need for practical solutions to address the challenges posed by high mobility in V-NDN.

An approach that can optimize the message forwarding mechanism, ensure communication continuity, and reduce data transmission failures is needed to improve the performance of NDN-based vehicle networks. Therefore, a strategy that can overcome these problems in high-mobility vehicle scenarios need to be developed. The forwarding strategy is one of the primary keys that can effectively find an interface capable of serving requests effectively; in addition, the breaking of communication links on the V-NDN network can also be considered a potential failure in the data transmission process in V-NDN.

Experiments on forwarding strategies were carried out to test performance on the vehicular network so that optimal results can be obtained from forwarding strategy recommendations. Simulations on vehicular networks in NDN networks were conducted using three forwarding strategies: best-route, multicast-VANET, and ASF.

The purpose of the experiment is to obtain test results that are used as recommendations for optimal forwarding strategies by evaluating forwarding strategies that are utilized in various vehicular network scenarios. Three forwarding strategies, namely best-route, multicast-VANET, and ASF, are involved to be tested using vehicular network scenarios. Then, the test result data are analysed to obtain the best forwarding strategy recommendations based on NFD forwarding flow parameters related to interest and data packet flow.

IV. Proposed Solution

V-NDN experiments are conducted specifically for moving vehicles on the NDN architecture using the V-NDN framework based on NDNSim [7, 8], which is a framework utilized for simulating Intelligent Transportation Systems (ITS) and V-NDN applications by combining two simulators, NS-3 and Sumo. The Sumo simulator is utilized as a road traffic simulator for urban mobility. The simulation scenarios are presented in Table II.

TABLE II. Simulation Parameters

Item	Value
Sim_Time	100s
Interest	1000
Cs_Size	1000
SynchInterval	0.1
SumoPort	3400
Forwarding Strategy	best-route multicast-VANET ASF
RSU	2
Nodes Vehicles	61

The V-NDN simulations are run using a V2V. The Use of Roadside Units (RSUs) is implemented to enable vehicles to communicate with other infrastructure (e.g., cloud, edge, etc.), which is known as V2I. The modified intersection topology, as shown in Fig. 3, is utilized in the simulations. This topology is adopted in previous papers [21–23].

The Sumo feature is characterized by a different function compared to the NS-3 simulator, which is not able to handle dynamic node insertion in the network. The appearance of cars during the simulation period is allowed by Sumo, making the simulation more dynamic. In the case of a Traffic Management System (TMS), communication with other vehicles can be facilitated, retransmission on the network can be performed, and actions as consumers can be taken by vehicles. It is considered that vehicles have no problems with computing and storage capacity, unlike other mobile devices.

A. 2X Mechanism with Two RSUs in V-NDN

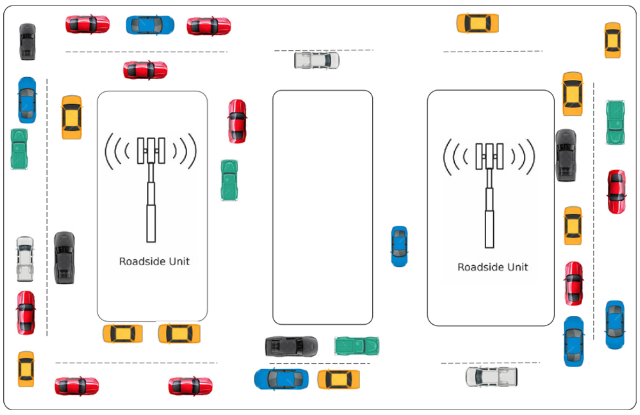


Fig. 3. TMS scenario vehicle NDN communications [17].

RSUs are used as communication access points to facilitate the efficient exchange of information among vehicles in the NDN network. In the context of NDN, RSUs are utilized as caches to store frequently requested Interest and Data packets. Additionally, RSUs are employed as data traffic managers, ensuring that vehicles receive the required information with lower latency. RSUs are also used to coordinate Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications. The implementation of the Vehicle-to-Everything (V2X) communication scenario with two Roadside Units (RSUs) in the V-NDN network is presented in Fig. 3. The V2X mechanism applied in this scenario is described as follows:

1) Interest and data packet forwarding

Vehicles send Interest Packets when information is needed (e.g., traffic maps, accident warnings, or weather data). These packets, labelled with a specific Name Prefix, are forwarded to the nearest RSU or nearby vehicles. Then, the RSU acts as a connector and data cache. If the requested Data Packet is in its cache, the RSU sends it directly to the vehicle. Otherwise, the RSU forwards the Interest Packet to another RSU or vehicle that may have the data. Data Packet Distribution: Once a Data Packet is found (either from the RSU or another vehicle), it is returned along the same path as the Interest Packet. The Data Packet can also be stored by the RSU for future requests to reduce latency and improve network efficiency.

2) RSU-to-RSU communication

Data can be exchanged between RSUs to update the cache and distribute important information to vehicles in different areas. If the data requested by a vehicle is not available in an RSU, a Flower Packet can be sent to another RSU to locate the required data.

3) Benefits of NDN in V2X wih RSUs

The implementation of NDN in V2X provides several benefits, such as: (1) Caching Efficiency: Frequently requested data can be stored in the RSU, allowing for reduced latency and network load; (2) Natural Multicast Mechanism: Data transmitted via NDN can be shared with multiple vehicles simultaneously without requiring point-to-point connections; (3) Better Security: In NDN, a digital signature is attached to transmitted data, ensuring greater security compared to traditional IP-based schemes.

In this scenario, two RSUs are used as data distribution points in the NDN-V2X network, enabling information to be shared among vehicles without always relying on a direct connection to a central server. Data can be stored locally by the RSUs, allowing vehicle requests to be responded to more quickly and enhancing communication between vehicles over a wider area.

The scenario in Fig. 3 is simulated to represent NDN communication in a VANET environment using various forwarding strategies to analyses the efficiency of data distribution. Parameters such as the number of vehicles, RSUs, forwarding methods, and cache sizes are considered to evaluate the performance of NDN in a high-mobility urban scenario.

The simulation is conducted on a road network where 61 vehicles participate in an urban environment. Communication is established between vehicles and Roadside Units (RSUs), of which there are two. Three forwarding strategies are applied: best-route, multicast-VANET, and ASF.

Best-route: The best path is selected based on specific metrics. Multicast-VANET: The multicast mechanism is utilized to distribute data to multiple receivers in the vehicular network. ASF (Adaptive Forwarding Strategy): The packet forwarding method is adjusted according to network conditions and vehicle mobility, see Table II.

The simulation is executed for 100 seconds (Sim_Time = 100 s), and 1000 requests (Interest) are sent. The Content Store size (CS_Size) is set to 1000, determining the cache capacity on each vehicle. The synchronisation interval (SynchInterval) is set to 0.1, allowing for fast network status updates. SUMO is used as a mobility simulator, with port 3400 (SumoPort) facilitating communication between NS-3 and SUMO.

The RSU's role is utilized to strengthen the network and assist in data distribution. RSUs act as data sources and communication intermediaries between vehicles that are not directly connected. With two RSUs, data distribution efficiency is expected to increase, while communication latency is expected to decrease.

The TMS scenario in Fig. 3 is designed with a naming scheme to facilitate the exchange of information in the format: / service/traffic / <road-id> / <time-window>. The naming scheme is used to distinguish the service name, the road of interest, and the time window that represents the traffic conditions in that interval.

B. Measurement of Interest and Data

Interest processing in NFD is separated into several pipelines, which have been explained in the previous section [18]. In this section, the process of sending and receiving interest that is carried out by each vehicle communicating with the next vehicle is explained. Interest processing consists of several parameters that are used, namely satisfied interest, unsatisfied interest, CS hit, and CS miss.

The satisfied interest parameter in the NDN network is considered one of the important indicators that serves as a benchmark for how much a request or interest from a node has been successfully fulfilled by the data requested being returned by the network. The request made by a node can be detected by other nodes in the network that have a copy of the requested data, and they can send a response by forwarding the request. A request is considered satisfied when the network successfully fulfils the interest and the requested data is returned to the node that initiated the request.

The expiration of the time limit causes the unsatisfied interest parameter, while the interest sent to the destination has not received the requested data before the time expires. The timer will end when all In Records in the PIT entry expire. Unsatisfied interest is implemented using the Forwarder: on Interest Unsatisfied method based on the unsatisfiable time setting and when the interest lifetime expires. In addition, PIT entries are also managed by the forwarding strategy through the use of the find effective strategy algorithm in the strategy choice table.

The CS hit parameter is implemented by NFD through the Forwarder: on Content Store Hit method and is entered after the interest is received. Then, the algorithm searches the CS, and a match is found. The input parameters of the channel are included as the interest packet, incoming face, PIT entry, and matching data packet (data matching). The straggler timer needs to be set on the satisfied interest during this processing. Then the matching data is forwarded to the outgoing data processing in the next stage, after which the processing for the interest is considered complete.

Parameter processing in the CS miss interest pipeline is implemented using the Forwarder: on Content Store Miss method and is initiated after an interest has been received. The algorithm then searches the CS, and if no data match is found, the input parameters to the channel are included as interest packets, incoming faces, and PIT entries. CS processes valid interests that cached data cannot meet, so the interest needs to be forwarded to another location.

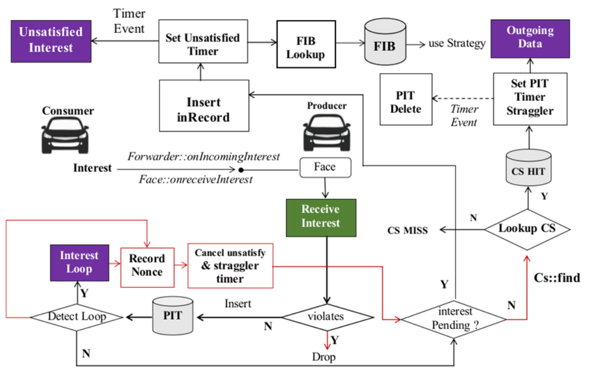


Fig. 4. Processing of interest packets on NDN vehicular networks.

The process is started with the interest being sent by the consumer to the producer through the Face: on Receive Interest pipeline, as shown in Fig. 4. The process is then further processed until the data is sent according to the consumer's request, which will be explained in the detailed discussion section regarding the function of the parameters in interest and data processing. Each interest-sending process carried out by the consumer is compared with different forwarding strategy scenarios. Then, the amount of interest sent according to the scenario set in Table II is measured.

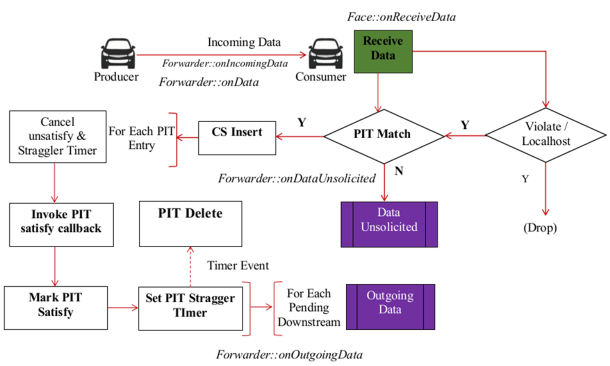


Fig. 5. Processing of data packets on NDN vehicular networks.

Data delivery on the NDN network is regulated by the NFD. Two data processing paths are used, namely: Data Unsolicited in (Drop) and Incoming Data Matching. The data processing path is designed to handle matters related to data processing through a pipe that is divided into several parts, as mentioned. Data processing is initiated when data sent by the producer is received by the consumer, as shown in Fig. 5, through the forwarder. The Start Process Data method, which is triggered by the Face: after Receive Data signal, has input parameters for these pipelines that include packet data and incoming faces. Several steps are involved in the incoming data process, which will be discussed in detail in the following explanation.

The unsolicited data parameter is processed by the Forwarder: on Data Unsolicited method for any unsolicited data, and is excluded from processing when the data packet is found to be unsolicited. The input parameters for this flow include the data packet and the incoming face. Any unsolicited data should generally be discarded before it enters the CS, as it poses a security risk to the sender. Currently, unsolicited data can be cached in the CS if it is received via a local face. On the other hand, a rule can be established to store unsolicited data based on non-local faces, allowing it to be stored in the CS; thus, the forwarder: on Data Unsolicited method rule must be updated to include the desired acceptance policy.

The incoming data matching parameter refers to the data that is received by the forwarder. The Start Process Data method is triggered when the Face: after Receive Data signal is emitted; the input parameters for this pipeline include the data packet and the incoming face. Incoming data matching is a data matching parameter in NDN that ensures data packets are delivered to the requester that issued the related interest packet. In this process, the PIT is checked to match the interest, the data is forwarded to the correct interface, the data is cached for future use, and unsolicited data is handled appropriately.

The interest sending process in the NDN network is quite complex, but the communication process has been summarized to make it easier to understand. In Fig. 6, an illustration of the communication process occurring at 30 seconds is provided. Thirty seconds was chosen because the highest satisfied interest value was achieved in each forwarding strategy test. Referring to the results of the forwarding strategy testing, the highest total satisfied interest was recorded in the ASF forwarding strategy, with a total of 11,111 satisfied interests.

In Fig. 6, the method used to achieve maximum interest acquisition at a simulation time of 30 seconds is described. A total of 313 interests is obtained based on interest requests. In this case, the interest requests refer to information about locations represented by road IDs B0A0, C0B0, B0B1, B1B0, B0C0, and B1C1, while the vehicle nodes used as examples are nodes N7, N11, N30, N23, N20, N52, N8, N33, and N60.

Forwarding best-route is used as an example to determine how the total achieved interest is obtained by summing the values based on the desired location information requests and the satisfied values derived from the sent prefix fragments, namely B0A0 (62 interests), C0B0 (40 interests), B0B1 (48 interests), B1B0 (43 interests), B0C0 (58 interests), and B1C1 (62 interests).

Regarding Fig. 6, communication between nodes to obtain traffic information on road ID B0B1 is illustrated in Fig. 7. Traffic in the vehicle network contains information on a collection of road IDs, with a maximum total interest of 313 and a total of 48 satisfied interests in the best-route forwarding strategy. An illustration is also provided, showing that some of the satisfied interests are obtained based on the total satisfied requests for B0B1.

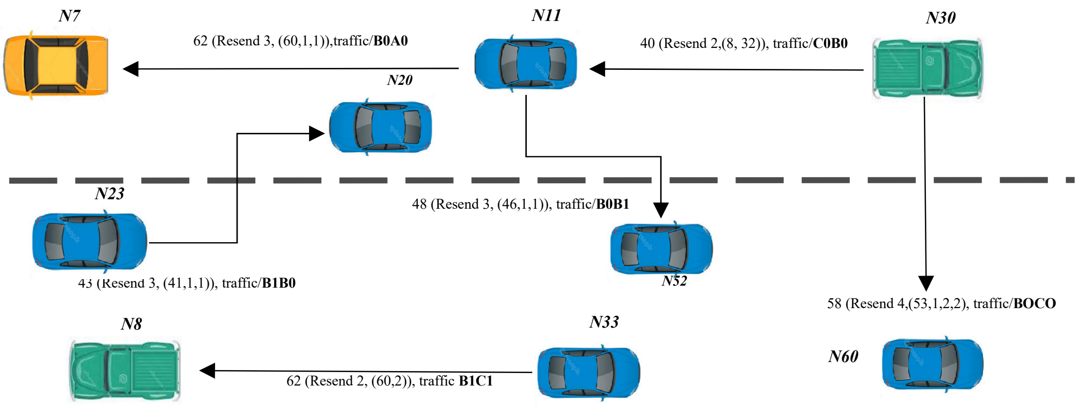


Fig. 6. Hight satisfied interest acquisition in vehicle communication at 30s, 313 satisfied interests.

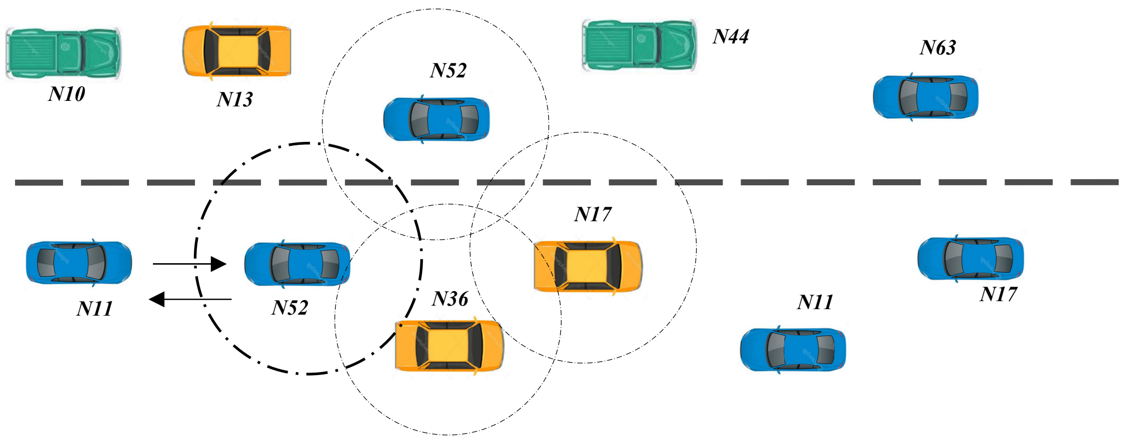


Fig. 7. Communication VID: N11 & N2, Road ID: B0B1, total number of satisfied interests 48.

C. Total Interest and Data

The total interest and data obtained in each test of the forwarding strategy are represented by the total amount of interest or data during the simulation period, based on the specified x parameters, which can be expressed in Eq. (1) and also in Table III.

$$TP_{x(int \vee dat)} = \sum_{t=0}^{n} TP_x^{(int \vee dat)}(t) \quad (1)$$

TABLE III. NOMENCLATURE EQUATION 1

Notation	Meaning
$P_{x(int)}$	Interest based on parameters, x (satisfied, unsatisfied, CS Hit, CS Miss), Example: $P_{x(int)} = P_{x(int,satisfied)}$
$P_{x(dat)}$	Data based on parameters, x (unsolicited, matching). Example: $P_{x(dat)} = P_{x(dat,Dunsolicited)}$
$TP_{x(int)}$	Total amount of interest during the period from the beginning to the end of the simulation, based on parameter x. Example: $TP_{x(int)} = TP_{x(int,Unsatisfied)}$
$TP_{x(dat)}$	Total data from the beginning to the end of the simulation, based on parameter x. Example: $TP_{x(dat)} = TP_{x(dat,DMatching)}$
$\sum_{t=0}^{n}$	Summation of interest or data over the period $t = 0$ to $t = n$

D. Total Interest or Data in Maximum Period

Based on the chosen x parameters, the total amount of interest or data during the maximum period of the simulation is represented as the sum of the interest and data obtained in the maximum period for each test of the forwarding strategy. This can be expressed in Eq. (2) and also in Table IV.

$$TP_{x(int \vee data)}P_{(max)} = \sum_{P_{max}=1}^{n} TP_x^{(int \vee dat)}(P_{max}) \quad (2)$$

TABLE IV. NOMENCLATURE EQUATION 2

Notation	Meaning
$TP_{x(int)}P_{(max)}$	Total interest in the maximum period from the start to the end of the simulation, based on parameter x. (e.g., satisfied). Example: $TP_{x(int)}P_{(max)} = TSatisfied_{(int)}P_{(max)}$
$TP_{x(dat)}P_{(max)}$	Total data in the maximum period from the start to the end of the simulation, based on parameter xx (e.g., unsolicited). Example: $TP_{x(dat)}P_{(max)} = TDUnsolicited_{(dat)}P_{(max)}$
$\sum_{P_{max}=1}^{n}$	Summation of maximum interest or data during the period $P_{max} = 1$ to $t = n$

E. Highest Interest or Data in Maximum Period

The total interest or highest data in the maximum period is stated in Eq. (3) and also in Table V, and the parameters used can be selected based on parameter x.

$$maxTP_{x(int \vee dat)}P_{(max)} = max^{n}_{P_{max}=1}TP_{x}^{(int \vee dat)}(P_{max}) \quad (3)$$

TABLE V. NOMENCLATURE EQUATION 3

Notation	Meaning
$max^{n}_{P_{max}=1}$	Highest value of $TP_x^{(int)}$ acroos all maximum periods P_{max}, from P_{max} =1 to P_{max} = n
$maxTP_{x(int)}P_{(max)}$	Maximum TP_x for interest (int) during P_{max}. The highest CS hit value is given by $maxTP_x^{(int,CSHit)}(P_{max})$
$maxTP_{x(dat)}P_{(max)}$	Maximum TP_x for data(dat) during $P_{max.}$ Period. The highest unsolicited data value is given by: $maxTP_x^{(dat,DUnsolicited)}(P_{max})$

F. Total Interest or Data on Minimum Period

The total interest and data in the minimum period, obtained in each test of the forwarding strategy, are represented by the total amount of interest or data in the minimum period during the simulation period, based on the selectable x parameters, as expressed in Eq. (4) and also in Table VI.

$$TP_{x(int \vee data)}P_{(min)} = \sum_{P_{min}=1}^{n} TP_{x}^{(int \vee dat)}(P_{min}) \quad (4)$$

TABLE VI. NOMENCLATURE EQUATION 4

Notation	Meaning
$TP_{x(int)}P_{(min)}$	Total interest in the minimum period, based on parameter x (e.g., CS Miss). Expressed as: $TP_{x(int)}P_{(min)}= TCSMiss_{(int)}P_{(min)}$
$TP_{x(dat)}P_{(min)}$	Total data in the minimum period, based on parameter x (e.g., data matching). Expressed as: $TP_{x(dat)}P_{(min)}= TDMatching_{(dat)}P_{(min)}$
$\sum^{n}_{P_{min}=1}$	summation of interest or data in the minimum period, from P_{min} = 1 to $t = n$

G. Highest Interest or Data in Minimum Period

The total interest or highest data in the minimum period is stated in Eq. (5) and also in Table VII, and the parameters used can be selected based on parameter x.

$$maxTP_{x(int \vee dat)}P_{(min)} = max^{n}_{P_{min}=1}TP_{x}^{(int \vee dat)}(P_{min}) \quad (5)$$

TABLE VII. NOMENCLATURE EQUATION 5

Notation	Meaning
$max^{n}_{P_{min}=1}$	Highest value of $TP_x^{(int)}$ in all minimum periods P_{min} from 1 to n
$maxTP_{x(int)}P_{(min)}$	MaximumTP_x for interest (int) during $P_{min.}$ The highest CS hit value in the this periode is: $maxTP_x^{(int,CSHit)}(P_{min})$
$maxTP_{x(dat)}P_{(min)}$	Maximum TP_x for data (dat) during $P_{min.}$ The highest data unsolicited value in this period is: $maxTP_x^{(dat,DUnsolicited)}(P_{min})$

V. RESULT AND DISCUSSION

In this section, the measurement of interest and data from several forwarding strategies will be discussed, and the results of the interest change measurements and data analysis will be presented in the form of a change graph.

Interest and data changes will be categorized into two groups: the maximum period group P_{max} and the minimum period group P_{min}, which are distinguished based on the period of interest rate increases and data in each group P_x.

A. Interest and Data Measurement Results

1) Total interest or data during the simulation time

Calculating the total interest or data during the simulation period can be represented by Eq. (1), where the parameter $P_{x(int)}$ refers to the interest value that representing parameter x, including satisfied interest, unsatisfied interest, CS hit, and CS miss.

The total satisfied interest during the simulation period from 0s to 100s can be expressed as $TP_{x(int,satisfied)}$. The total satisfied interest in the best-route strategy is recorded as 4,207. As shown in Table VIII, this also applies to the multicast VANET and ASF strategies. The total unsatisfied interest during the simulation time of 100s is expressed as $TP_{x(int,Unsatisfied)}$ and is obtained based on the total number of unsatisfied interests from the beginning to the end of the simulation period. The total unsatisfied interest for the ASF strategy is recorded as 0, for the best-route strategy as 1,230, and for the multicast-VANET strategy as 226; please refer to Table VIII for more details.

TABLE VIII. SF TEST RESULTS (TOTAL INTEREST AND DATA)

Parameter	Strategy Fowarding					
	Best-route		Multicast-V		ASF	
	Total	Avg	Total	Avg	Total	Avg
Satisfied Interest	4,207	41.7	4,085	44.3	11,111	125.6
Unsatisfied Interest	1,230	12.2	226	2.2	0	0
CS Hit Interest	1,821	18.0	1,943	19.2	8,252	81.7
CS Miss Interest	5,447	53.9	2,475	24.5	3,073	30.4
Data Unsolicited in	14,328	141.9	13,689	135.5	82,874	820.5
Incoming Data Matching	2,385	23.6	2,141	21.2	2,749	27.2

The total CS hit interest and CS miss interest are formulated in the same way as the satisfied and unsatisfied interest parameters are calculated. The total CS hit obtained during the 100s simulation period is expressed as $TP_{x(int,CSHit)}$. The total CS miss is represented as $TP_{x(int,CSMiss)}$, as stated in Eq. (1). The total CS hit for the ASF strategy is recorded as 8,252, for the best-route strategy as 1,821, and for the multicast-VANET strategy as 1,943. The total CS miss for the ASF strategy is 3,073, for the best-route strategy is 5,447, and for the multicast-VANET strategy is 5,447. Please refer to Table VIII for more details.

The total unsolicited data and incoming data matching during the 100s simulation period are expressed in $TP_{x(dat,DUnsolicited)}$ and $TP_{x(dat,DMatching)}$, as stated in Eq. (1). Unsolicited data is obtained based on the number of unsolicited data packets, with the total data matching recorded as 82,874 for the ASF strategy, 14,328 for the best-route strategy, and 13,689 for the multicast-VANET strategy; see Table VIII. Meanwhile, data matching is determined based on the successful matching of data packets that can be sent to the requester, with incoming data matching recorded as 2,749 for the ASF strategy, 2,141 for the multicast-VANET strategy, and 2,385 for the best-route strategy.

2) Total interest or data in maximum period

The content requests from consumers that were satisfied during the 100-second simulation period were grouped into two categories: the P_{max} maximum period group and the P_{min} minimum period group. Each P_{max} or P_{min} period group is classified into several changes in interest or data based on parameters P_x. Changes in interest are expressed as $TP_{x(int)}P_{(max)}$, while changes in data are represented as $TP_{x(dat)}P_{(max)}$. Please refer to Eq. (2) for more details.

The total satisfied interest and unsatisfied interest for the maximum period $P_{(max)}$,obtained during the 100s simulation period, are expressed as $TP_{x(int,Satisfied)}P_{(max)}$ and $TP_{x(int,USatisfied)}P_{(max)}$, then segmented at each maximum time period $\sum_{P_{max}=1}^{n}$. The total satisfied interest for the maximum period is recorded as 10,146 for the ASF strategy, 2,946 for the multicast-VANET strategy, and 2,978 for the best-route strategy. Next, the total unsatisfied interest in the maximum period is segmented. The best-route strategy records a total unsatisfied value of 719, the ASF strategy has 0, and the multicast-VANET strategy has 129. Please refer to Table IX for more details. The total CS hit and CS miss for the maximum period, obtained during the 100s simulation period, are expressed in $TP_{x(int,CSHit)}P_{(max)}$ and $TP_{x(int,CSMiss)}P_{(max)}$, then segmented at each maximum time period and represented as $\sum_{P_{max}=1}^{n}$. For more details, refer to Eq. (2). The maximum CS hit is recorded as 7,272 for the ASF strategy, 795 for the multicast-VANET strategy, and 522 for the best-route strategy. The maximum total CS misses are 3,073 for the ASF strategy, 2,475 for the multicast-VANET strategy, and 5,447 for the best-route strategy. Please refer to Table X for more details.

The maximum total unsolicited data for the entire time period is expressed in $TP_{x(int,DUnsolicited)}P_{(max)}$,while incoming data matching is represented as $TP_{x(int,DMatching}P_{(max)}$. The value of $P_{(max)}$ data for each parameter is then calculated over the simulation period of 0−100s. The total unsolicited data in the maximum period is recorded as 22,975 for the ASF strategy, 3,019 for the multicast-VANET strategy, and 2,739 for the best-route strategy. Please refer to Table X for more details. Meanwhile, the total incoming data matching in the maximum period is 1,777 for the ASF strategy, 1,182 for the multicast-VANET strategy, and 1,317 for the best-route strategy. Please refer to Table XI for more details.

TABLE IX. CHANGE IN INTEREST VALUE, AT SIMULATION TIME 100S (SATISFIED AND UNSATISFIED INTEREST)

Strategy Forwarding	Number Satisfied per period		Number UnSatisfied per period		Highest Satisfied per period		Highest UnSatisfied per period		Total Satisfied	Total Unsatisfied	Efficiency Ratio (Satisfied/Unsatisfied)	Efficiency Ratio (Satisfied/Unsatisfied Max)
	Max	Min	Max	Min	Max	Min	Max	Min				
Best-route	2,978	1,537	719	511	871	609	315	307	4,207	1,230	3.4	2.76
Multicast-VANET	2,946	1,139	129	97	1,464	459	63	52	4,085	226	18.08	23.24
ASF	10,146	965	0	0	3,535	319	0	0	11.111	0	∞	∞

TABLE X. CHANGE IN INTEREST VALUE, AT SIMULATION TIME 100 S (CS HIT AND CS MISS)

Strategy Forwarding	Data Unsolicited				Incoming Data Matching				Total Data Unsoliciated	Total Incoming Data Matching
	number per period		highest per period		number per period		highest per period			
	Min	Max	Min	Max	Min	Max	Min	Max		
Best-route	6,867	7,461	2,318	2,739	1068	1,317	444	588	14,328	2,385
Multicast-VANET	6,455	7,234	2,846	3,019	959	1,182	364	498	13,689	2,141
ASF	3,767	79,107	1,068	22,975	972	1,777	385	663	82,874	2,749

3) Total interest or highest data in the maximum period

The highest interest value or data among the maximum periods is recognized as the best period for each parameter. The highest satisfied or unsatisfied interest value in the maximum time period is expressed as $maxTP_{x(int\vee dat)}P_{(max)}$. To determine the highest total interest in the maximum period for the selected parameter, the $maxTP_{x(int)}P_{(max)}$ statement is used, while $maxTP_{x(dat)}P_{(max)}$ is applied for the data. The full expression is provided in the Eq. (3) statement.

The highest satisfied and unsatisfied values in the maximum period $P_{(max)}$, obtained during the 100s simulation period, are expressed as $maxTP_{x(int,Satisfied)}P_{(max)}$ and $maxTP_{x(int,USatisfied)}P_{(max)}$, respectively, and then segmented at each maximum time period $\sum_{P_{max}=1}^{n}$. Please refer to Eq. (2) for more details. The highest satisfied interest value in the maximum period is recorded as 3,535 for the ASF strategy, 1,464 for the multicast-VANET strategy, and 871 for the best-route strategy. Next, the highest total unsatisfied interest in the maximum period is also segmented, with values recorded as 315 for the best-route strategy, 0 for the ASF strategy, and 63 for the multicast-VANET strategy. Please refer to Table IX for more details.

The highest interest value in the maximum period is stated in $maxTP_{x(int)}P_{(max)}$. To determine the highest CS hit value in the maximum period, it is stated in $maxTP_{x(int,CSHit)}P_{(max)}$, while the highest CS miss value in the maximum period is stated in $maxTP_{x(int,CSMiss)}P_{(max)}$, as fully written in the statement of Eq. (3). The highest CS hit value during the maximum period is recorded as 2,655 for the ASF strategy, 657 for multicast-VANET, and 175 for best-route; please refer to Table X for more details. Meanwhile, the highest CS miss value during the maximum period is observed as 926 for the ASF strategy, 611 for multicast-VANET, and 1,697 for the best-route strategy.

The highest data value in the maximum period is stated in $maxTP_{x(dat)}P_{(max)}$. The highest unsolicited data value in the maximum period is indicated in $maxTP_{x(dat,DUnsulicited)}P_{(max)}$, while the incoming data matching value is specified in $maxTP_{x(dat,DMatching)}P_{(max)}$, see Eq. (3). The highest unsolicited data value in the maximum period is recorded for the ASF strategy at 22,975, followed by multicast-VANET at 3,019, and best-route at 2,739. Similarly, the highest incoming data matching value in the maximum period is observed in the ASF strategy at 663, multicast-VANET at 1,182, and best-route at 1,317. Please refer to Table XI for more details.

4) Total interest or data on minimum period

Total satisfied interest and unsatisfied interest at the minimum period $P_{(min)}$, obtained during the 100s simulation time, are expressed in $TP_{x(int,Satisfied)}P_{(min)}$ and $TP_{x(int,USatisfied)}P_{(min)}$, then segmented at each minimum time period $\sum_{P_{min}=1,}^{n}$ see Eq. (4). The total satisfied interest during the minimum period is recorded as 965 for the ASF strategy, 459 for multicast-VANET, and 609 for best-route. Next, segmentation is performed for the total unsatisfied interest during the minimum period; the best-route strategy has the highest total unsatisfied value at 307, while the ASF strategy has 0, and multicast-VANET has 52. Please refer to Table IX for more details.

The total CS hit and CS miss for the minimum period, obtained during the 100-second simulation time, are expressed in $TP_{x(int,CSHit)}P_{(min)}$ and $TP_{x(int,CSMiss)}P_{(min)}$, respectively, and then segmented for each minimum time period $\sum_{P_{min}=1}^{n}$. For further details, refer to Eq. (4). The minimum period CS hit is recorded as 980 for the ASF strategy, 1,148 for the multicast-VANET strategy, and 1,497 for the best-route strategy. Meanwhile, the minimum period CS miss is measured at 918 for the ASF strategy, 1,013 for the multicast-VANET strategy, and 1,176 for the best-route strategy. For more details, please refer to Table X.

To obtain the highest unsolicited data value in the minimum period, it is recorded in $maxTP_{x(dat,DUnsulicited)}P_{(min)}$, while incoming data matching is stated in $maxTP_{x(dat,DMatching)}P_{(min)}$, see Eq. (5). The highest unsolicited data value in the minimum period is recorded for the ASF strategy at 3,767, for multicast-VANET at 6,455, and for best-route at 6,867. The highest incoming data matching value in the minimum period is observed for the ASF strategy at 972, for multicast-VANET at 959, and for best-route at 1,068. Please refer to Table XI for more details.

5) Total interest or highest data in the minimum period

The highest interest value or data in the minimum time period is recorded in $maxTP_{x(int \vee dat)}P_{(min)}$. To determine the highest total interest in the minimum period for the selected parameters, the statement $maxTP_{x(int)}P_{(min)}$ is applied, while the statement for data is expressed in $maxTP_{x(dat)}P_{(min)}$, as fully written in Eq. (5).

The highest satisfied and unsatisfied values in the minimum period $P_{(min)}$ are obtained during the 100s simulation time period, expressed in $maxTP_{x(int,Satisfied)}P_{(min)}$ and $maxTP_{x(int,USatisfied)}P_{(min)}$, and then segmented at each minimum time period $\sum_{P_{min}=1}^{n}$ see Eq. (5). The highest satisfied interest value in the minimum period is 319 for the ASF strategy, 459 for multicast-VANET, and 609 for best-route. Next, a segmentation is also made for the highest total unsatisfied interest in the minimum period: 307 for best-route, 0 for the ASF strategy, and 52 for multicast-VANET. Please refer to Table IX for more details.

The highest CS hit value in the minimum period can be expressed in $maxTP_{x(int,CSHit)}P_{(min)}$, and the highest CS miss value in the minimum period can be expressed in $maxTP_{x(int,CSMiss)}P_{(min)}$, as fully written in the statement of Eq. (5). The highest CS hit value in the minimum period is recorded for the ASF strategy at 305, multicast-VANET at 525, and best-route at 677. Similarly, the highest CS miss value in the minimum period is recorded for the ASF strategy at 385, multicast-VANET at 371, and best-route at 460. For more details, please refer to Table X.

The highest data value in the minimum period is stated in $maxTP_{x(dat)}P_{(min)}$. To determine the highest unsolicited data value in the minimum period, it is stated in $maxTP_{x(dat,DUnsulicited)}P_{(min)}$, and for incoming data matching, it is stated in $maxTP_{x(dat,DMatching)}P_{(min)}$ see Eq. (5) for further information. The highest unsolicited data value in the minimum period is recorded as 1,068 for the ASF strategy, 2,846 for multicast-VANET, and 2,318 for best-route. The highest incoming data matching value in the minimum period is recorded as 385 for the ASF strategy, 364 for multicast-VANET, and 444 for best-route; please refer to Table XI for more details.

Table IX compares three V-NDN methods, namely best-route, multicast-VANET, and ASF, based on satisfied and unsatisfied interests. The analysis includes: (1) satisfied/unsatisfied interests per period, showing the number of interests that receive or fail to receive data packets in each simulation period (Pmin and Pmax); (2)

highest satisfied/unsatisfied interests per period, representing the peak number of fulfilled or unfulfilled interests in a single period; and (3) total satisfied/unsatisfied Interests, indicating the overall fulfilled or unfulfilled interests throughout the simulation.

The Number of Satisfied Interests per Period measures data distribution effectiveness—the higher the value, the better the performance. Conversely, the number of unsatisfied interests per period indicates unfulfilled requests; the lower the value, the more optimal the distribution strategy in the V-NDN network is.

Best-route maintains stable satisfaction levels (1,537–2,978) with a variation of 1,441, ensuring consistent performance. However, its reliance on a fixed path makes it less flexible and unable to handle demand spikes effectively. Despite the increased interest, unsatisfied requests remain high (511–719).

Multicast-VANET adapts better to network changes, achieving a wider satisfaction range (1,139–2,946). Its efficiency depends on vehicle density, making it superior to Best-route, though still limited in highly dynamic traffic. The number of unsatisfied interests (97–129) is much lower than Best-route, indicating higher efficiency.

ASF is the most adaptive, with satisfied interests reaching 10,146—far surpassing Best-route (2,978) and Multicast-VANET (2,946). A variation of 9,181 demonstrates its high flexibility, while optimal path and caching allocation eliminate unsatisfied interests (0), proving its exceptional effectiveness.

Based on Table IX, the analysis is conducted on Total Satisfied Interest, Total Unsatisfied Interest, and the Satisfied-to-Unsatisfied Ratio for Best-route, Multicast-VANET, and ASF. This ratio measures the system's efficiency—the higher the value, the fewer unsatisfied requests. The calculation is performed using Eq. (6).

$$\text{Interest Satisfied Ratio} = \frac{Total\ Satisfied\ Interest}{Total\ Unsatisfied\ Interest} \tag{6}$$

Multicast-VANET perform better than Best-route, as a lower number of unsatisfied Interests is recorded (226 compared to 1,230). This indicates that the multicast mechanism enables more vehicles to receive data in a single transmission, thereby reducing the number of requests that must be forwarded to other sources. With the Highest Satisfied Interest per Period recorded at 1,464, this method is recognized as highly efficient in simultaneously disseminating data to multiple vehicles. The Satisfied Ratio for Multicast-VANET is calculated as 4,085/226 = 18.08, meaning that for every unsatisfied Interest, approximately 18.08 are successfully satisfied. This demonstrates that the efficiency of Multicast-VANET is significantly higher than Best-route. With Total Satisfied Interests (4,085) being significantly greater than Total Unsatisfied Interests (226) and a ratio of 18.08, the system is considered highly efficient, with only 5.24% of requests remaining unsatisfied.

ASF is observed to have the most optimal performance, with 100% of Interests fulfilled and 0% unfulfilled. With the highest Satisfaction per period reaching 3,535, this method can handle large data requests. ASF utilises a highly efficient caching and forwarding mechanism, fulfilling all interests without reliance on a central server. The Satisfied Ratio for ASF is calculated as 11,111/0 = ∞. Since no unsatisfied Interests are recorded, ASF achieves perfect efficiency. Total Satisfied Interests amount to 11,111, while no Unsatisfied Interests (0) are present. The ratio is considered infinite (∞), indicating that all requests are successfully fulfilled without any failures. This demonstrates the best performance compared to other methods.

ASF is recognized as having the best performance, with 100% of requests satisfied, making it ideal for systems that require certainty. Multicast-VANET is found to be more stable than Best-route, with a ratio of 18.08, indicating high efficiency despite the presence of a few unsatisfied requests. Best-route is considered less optimal, with a ratio of 3.42, as many requests remain unfulfilled. If maximum satisfaction is prioritized, ASF should be chosen. For a balance between efficiency and satisfaction, Multicast-VANET is preferred over Best-route, which still requires further optimization.

TABLE XI. CHANGE IN INTEREST VALUE, AT SIMULATION TIME 100 S (DATA UNSOLICITED AND DATA MATCHING)

Strategy Forwarding	CS Hit Interest				CS Miss Interest				Total CS hit	Total CS miss	CS Hit Ratio to Satisfied	CS Miss Ratio to Satisfied
	number per period		highest per period		number per period		highest per period					
	Min	Max	Min	Max	Min	Max	Min	Max				
Best-route	1,497	324	677	175	1,176	4,271	460	1,697	1,821	5,447	0.43	1.29
Multicast-VANET	1,148	795	525	657	1,013	1,462	371	611	1,943	2,475	0.48	0.61
ASF	980	7,272	305	2,655	918	2,155	385	926	8,252	3,072	0.74	0.28

Based on Table X, the number of CS hits per period and CS misses per period are analyzed using the best-route, multicast-VANET, and ASF methods. The number of CS hits per period is defined by the Interest requests served directly by the cache (CS) within one period. A higher value indicates that the strategy's caching mechanism is more efficient.

CS hit is higher in best-route than in multicast-VANET, but is much lower than in ASF. A lower CS hit is observed in multicast-VANET compared to best-route, indicating less effective caching than in ASF. The highest CS miss (4,271) is recorded in best-route, showing that many requests are not found in the cache, leading to increased latency and network load. A lower CS miss (1,462) is observed in multicast-VANET compared to best-route, indicating that multicast helps distribute data and reduce unfulfilled requests. The highest CS hit (7,272) and the lowest CS miss (918) are recorded in ASF, making it the most efficient caching strategy by reducing latency and speeding up data access.

ASF is considered the best caching strategy, with the highest CS hit (7,272) and the lowest CS miss (918), indicating high efficiency and low latency. Best-route is the worst, with the highest CS miss (4,271), increasing network load and latency. Multicast-VANET is positioned in the middle, with a lower CS hit than best-route but a better CS miss. It indicates that while multicast helps with data distribution, its caching remains less effective than ASF.

The highest CS hit and CS miss per period are shown as the highest number of interest requests served directly by the cache (CS) within a period. The greater the efficiency, the more effectively the strategy's caching mechanism operates.

In the highest CS hit per period, the highest value of 677 and the lowest value of 175 are recorded in best-route, indicating a prominent peak but controlled variation. A more stable range of 525–657 is observed in multicast-VANET. A wide range of 305–2,655 in ASF is recorded, indicating large transmissions in specific periods. Among the three, multicast-VANET is the most stable, while ASF shows high but inconsistent performance, and best-route is closer to multicast-VANET than to ASF. In the highest CS miss per period, a range of 460–1,697 is recorded in best-route, indicating high CS miss delivery. A more stable range of 371–611 is observed in multicast-VANET, while ASF, with a range of 385–926, performs better than best-route but remains less stable than multicast-VANET.

Multicast-VANET is observed to be the most stable in preventing CS miss spikes, while the highest spikes are recorded in best-route. ASF performs better than best-route but remains less stable than multicast-VANET. If stability in CS hit and CS miss is prioritized, Multicast-VANET is considered the best choice. If achieving the highest CS hit is the goal, ASF is superior but less stable. Optimization is needed for the best route to reduce CS miss spikes.

Based on Table IX, Total CS hit, CS miss, and their ratio to interest satisfaction will be analyzed for Best-route, Multicast-VANET, and ASF. CS hit is defined as the number of requests served directly from the cache, where a higher value indicates more efficient caching in the network, see Eqs. (7)–(8).

$$\text{CS Hit Ratio to Satisfied} = \frac{Total\ \ CS\,Hit\,Interest}{Total\ \ Satisfied\ Interest} \tag{7}$$

$$\text{CS Miss Ratio to Satisfied} = \frac{Total\ \ CS\,Miss\,Interest}{Total\ \ Satisfied\ Interest} \tag{8}$$

The best-route strategy is observed to have a CS hit ratio of 0.43, meaning that only 43% of satisfied interests are served from the cache, indicating poor caching performance. A CS miss ratio 1.29 is recorded, meaning that for every one satisfied interest, 1.29 cache misses occur, showing that the cache frequently fails to retrieve data. As a result, an increased network load is caused by the number of repeated requests.

The multicast-VANET strategy is observed to have a CS hit ratio of 0.48, which is slightly better than best-route. 48% of satisfied interests are served from the cache, thereby reducing the network load. A CS miss ratio of 0.61 is recorded, indicating that cache miss remains relatively high, although better than best-route, suggesting that cache management should be improved.

The ASF strategy is observed to have a CS hit Ratio of 0.74, indicating an effective cache. 74% of satisfied interests are served from the cache, thereby reducing communication overhead. A CS miss ratio of 0.28 is recorded, meaning that for every one satisfied interest, only 0.28 cache misses occur. This demonstrates that ASF caching is highly efficient, accelerating data access and reducing delay.

It is concluded that ASF has the most optimal caching, with the highest hit ratio (0.74) and the lowest miss ratio (0.28), making it significantly more efficient than best-route and multicast-VANET. Multicast-VANET is considered better than best-route but still has room for improvement, while best-route is identified as having the least effective caching and requires optimization.

Table XI analyses several key parameters related to Data Unsolicited and Incoming Data Matching for the three forwarding strategies: Best-route, Multicast-VANET, and ASF.

The amounts of unsolicited data per period are stable in Best-route and Multicast-VANET. In contrast, ASF exhibits large fluctuations, with low minimum values (3,767) and high maximum values (79,107). This suggests that while Best-route and Multicast-VANET maintain consistency, ASF experiences spikes in unsolicited data during specific periods.

The ranges for Best-route and Multicast-VANET (2.3–3.0) indicate controlled delivery of unsolicited data, whereas ASF has a significantly larger range (1,068–22,975), showing substantial spikes in some periods. This suggests that ASF may be more efficient or less balanced in its forwarding strategy.

Less unsolicited data is observed in Best-route and Multicast-VANET, indicating higher efficiency than ASF. ASF performs superior incoming data matching performance, while Best-route performs better than Multicast-VANET. Multicast-VANET has the lowest data matching efficiency, suggesting weaker performance in data matching.

Regarding the number of incoming data matches per period, Best-route (1,068–1,317) has the highest data matching, indicating better efficiency than Multicast-VANET (959–1,182). ASF exhibits a broader range (972–1,777) with high capacity in specific periods but shows greater variability. Best-route is identified as more consistent, while ASF demonstrates greater flexibility in handling incoming data.

The highest incoming data matching per period is observed in Best-route compared to Multicast-VANET. A wider range of values is recorded in ASF, with a peak reaching 663, indicating greater efficiency under certain conditions. It is argued that data matching in Best-route is superior to that in Multicast-VANET. ASF demonstrates the highest potential for matching data, but with greater variation.

In total incoming data matching, the highest value is recorded in ASF (2,749), followed by Best-route (2,385), while the lowest is observed in Multicast-VANET (2,141). It is argued that ASF has an advantage in total incoming data matching, indicating a more effective forwarding strategy in capturing and processing data. Best-route performs better than Multicast-VANET but remains below ASF.

B. Analysis of Changes in Interest and Data

This section analyses several forwarding strategies based on pipeline forwarding in NFD, specifically the Interest Processing Path (IPP) and Data Processing Path (DPP). The test results for each forwarding strategy in the vehicle network are examined, and changes in interest and data are observed throughout the 100-second simulation period. The results of the analysis of interest and data changes are presented in the form of a change graph. Changes in interest and data are categorised into two groups: the maximum period group P_{max} and the minimum period group P_{min}. These groups are distinguished based on the period during which interest and data increase in each P_x group.

1) Satisfied interest

The satisfied interest parameter is considered an important parameter in NDN communication, as it indicates that the consumer's content request has been successfully found on the producer node. The graph in Fig. 8(a) shows that a high interest flow is observed in the ASF strategy compared to the best-route and multicast-VANET strategies. A high increase in interest value is observed in the ASF strategy, with $maxTP_x^{(int,Satisfied)}(P_{max})$ = 3,535 satisfied at 1s–6s and an average value of 125.6, making ASF highly recommended. The multicast-VANET strategy records an average value of 44.3 satisfied interests. The highest increase in ASF satisfied value is observed at $maxTP_x^{(int,Satisfied)}(P_{max})$ = 1,464 interests during 1s–6s. The ASF value is higher when compared to the best-route strategy, which has the highest satisfied interest of 871 during 2s–4s. The highest satisfied interest value in the minimum period is recorded at 609 interests during 63s-91s. The best-route strategy has an average satisfied value of 41.7 interests. Therefore, the multicast-VANET strategy can be considered an alternative to replace ASF. The highest satisfied value among the maximum periods P_{max} is the best satisfied interest period.

2) Unsatisfied interest

Unsatisfied interest is used as an indicator that the interest has expired or has been sent to the destination but has not received the requested data by the end of the period. It is also considered a benchmark for evaluating the performance of the forwarding strategy. In Fig. 8(b), the ASF strategy is shown to be the best recommendation based on the unsatisfied interest parameter, see Table VIII. The ASF strategy has no unsatisfied interest value. Even in the worst-case scenario, this strategy maintains a lower unsatisfied interest value than the best-route and multicast-VANET strategies. The unsatisfied parameter in the ASF strategy is 0, indicating that all sent interests successfully serve content requests. This result differs significantly from the best-route strategy, which has a total unsatisfied interest of 1,230, with the highest increase of 315 at 32 seconds. The average unsatisfied interest value in the best-route strategy is 12.2. Please refer to Table VII for more details.

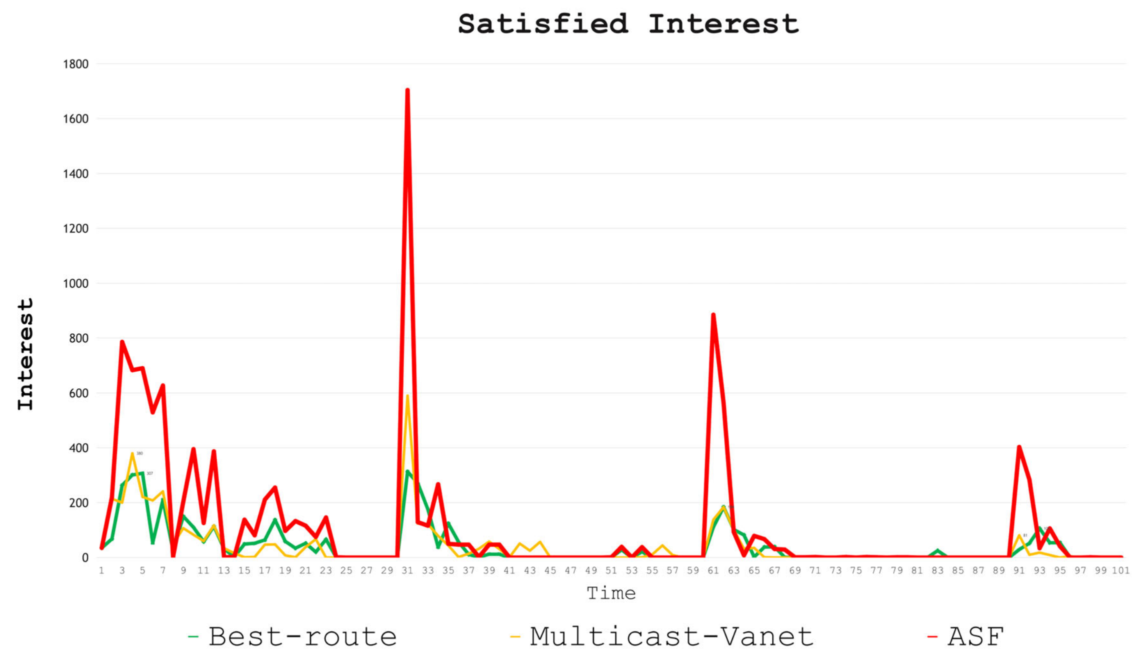
The total unsatisfied interest in the multicast-VANET strategy is lower than that of the best-route strategy. A spike in unsatisfied interest for the multicast-VANET strategy reaches 226, with the highest value, 63, occurring at 32 seconds. The average unsatisfied interest value is 2.2 during the 100-second simulation period. The issue of unsatisfied interest can be addressed by resending interest; however, it is always recorded when the requested interest cannot be found. In vehicular network implementations, unsatisfied interest is an important parameter to consider. The unsatisfied value is calculated using the same method as the satisfied interest parameter.

Fig. 8(a) illustrates the changes in the number of satisfied interests over time for three forwarding strategies: best-route, multicast-VANET, and ASF. X-axis (horizontal–time): The time progression is displayed within a specific interval (1–100). Y-axis (vertical–interest): the number of satisfied interests in each period is represented. Best-route is represented in green, multicast-VANET in yellow, and ASF in red.

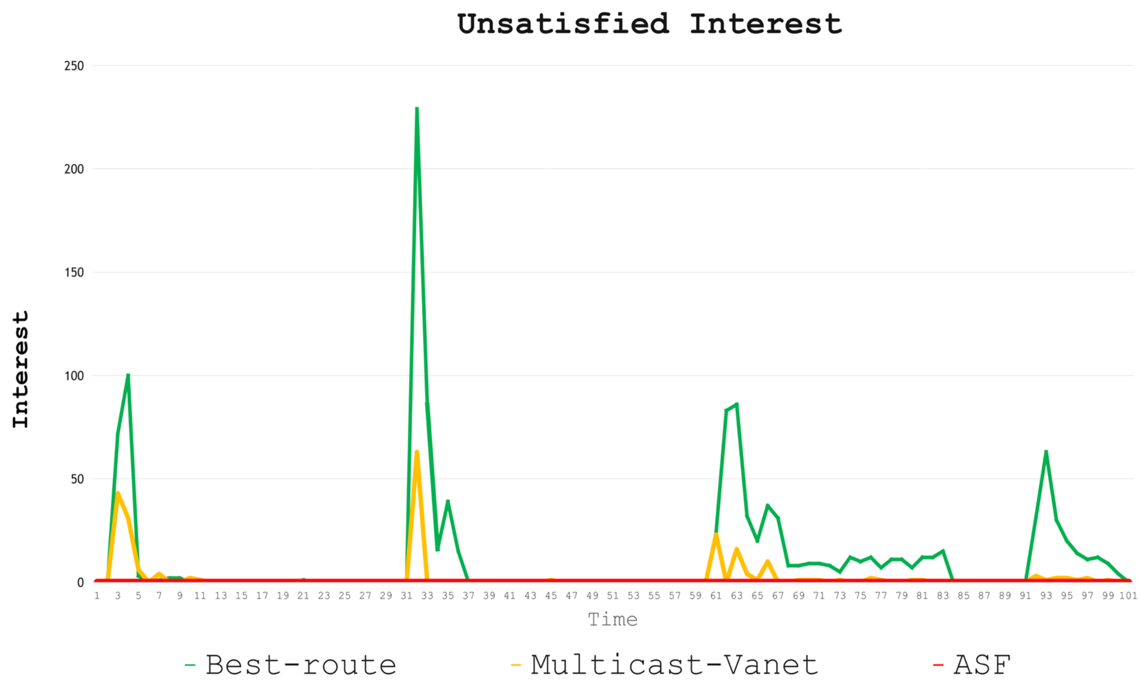
Sharp spikes are observed in ASF (red) at specific time points, particularly around intervals 30, 60, and 90, indicating a drastic increase in satisfied interests. However, after reaching a peak, the number significantly decreases again. A more stable pattern is shown by best-route (green) and multicast-VANET (yellow), with the number of satisfied interests remaining more consistent and not exhibiting large spikes. The number of satisfied interests for best-route and multicast-VANET appears comparable over time, though Multicast-VANET tends to be lower than best-route in specific periods. While ASF demonstrates an advantage in the maximum number of satisfied interests, it also experiences greater fluctuations than the other strategies.

In conclusion, the graph indicates that more Interests can be satisfied by ASF than by best-route and multicast-VANET, though with a lower level of stability.

Fig. 8(b) presents a graph depicting the changes in unsatisfied interests over time for three forwarding strategies: best-route, multicast-VANET, and ASF. The X-axis (horizontal—time) represents the change in time within a certain interval (1–100). The Y-axis (vertical—interest) shows the number of unsatisfied interests that were not successfully satisfied in each time period.



(a)



(b)

Fig. 8. Interest change graph at maximum and minimum periods: (a). Change in satisfied parameters; (b). Change in unsatisfied parameters.

ASF (red) maintains a value close to zero throughout the entire duration, indicating that almost no unsatisfied interests were encountered with this strategy. This suggests that ASF's performance in satisfying Interests is optimal. Best-route (green) exhibits several significant spikes in unsatisfied interests, particularly around intervals 5, 30, 60, and 90, indicating that this strategy struggles during specific periods. Multicast-VANET (yellow) also experiences spikes with lower intensity than best-route, indicating a lower failure rate. Best-route demonstrates inconsistency in satisfying interests, with notable fluctuations at specific intervals, whereas multicast-VANET appears more stable, despite occasional failures. ASF consistently does not experience unsatisfied interests, making it the most efficient strategy in satisfying data requests.

In conclusion, ASF is the most effective in ensuring all Interests are satisfied, while best-route and multicast-VANET still encounter failures at specific periods. Best-route exhibits the highest spikes in unsatisfied interests.

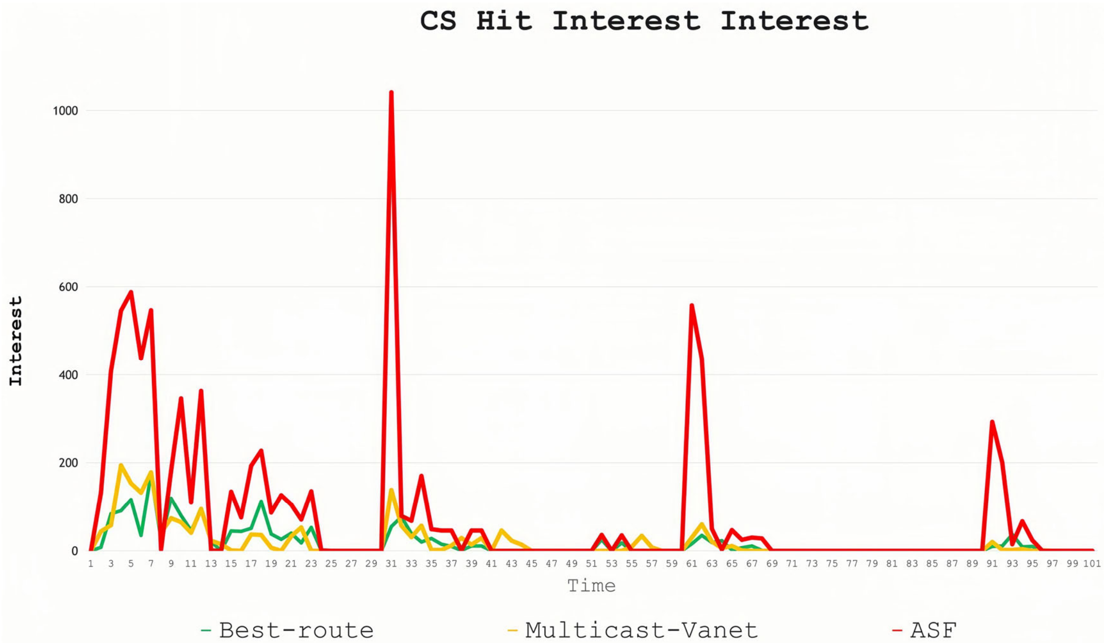
3) CS hit interest

The CS hit interest parameter indicates the data search process in the CS, which uses input parameters such as interest packets, incoming faces, and PIT entries to locate matching data packets. The CS hit value influences the satisfied interest value; if a forwarding strategy results in a high CS hit value, the satisfied interest value will also be high. A high CS hit is observed in the ASF strategy, as shown in Fig. 9(a) and Table IX for further details.

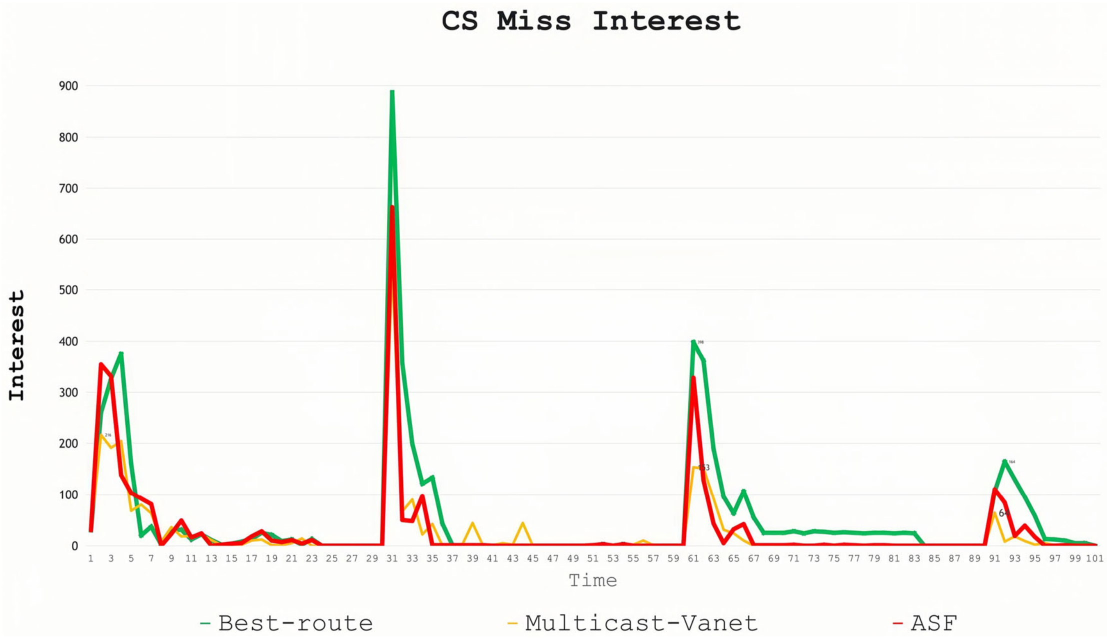
A total CS hit of 8,252 is recorded for the ASF strategy, with an average CS hit value of 81.7. The highest CS hit spike occurs between 1 and 6 seconds, reaching a value of 2,655. The ASF strategy allows the producer's existence to be identified quickly in response to interest requests. The total CS hit values for the best-route and multicast-VANET strategies do not differ significantly, with multicast-VANET recording a total CS hit of 1,943 and best-route recording 1,821. It is concluded that the best-route and multicast-VANET strategies are not recommended based on the CS hit and satisfied interest parameters.

4) CS miss interest

The CS miss interest parameter refers to searching for data in the CS using the input parameters of the interest packet, incoming face, and PIT entry. However, in this process, the interest and data packets requested by the consumer cannot be matched. As a result, the CS processes a valid interest that cannot be fulfilled by the cached data, requiring the interest to be forwarded to another node (router).

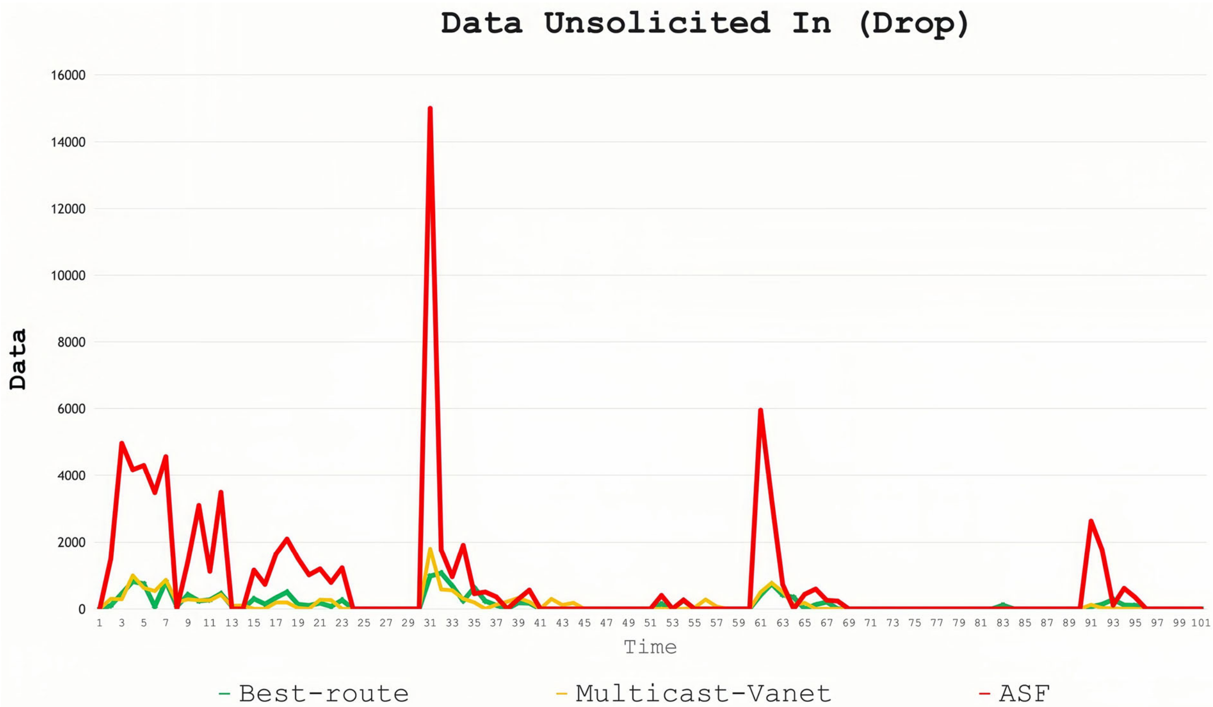


(a)

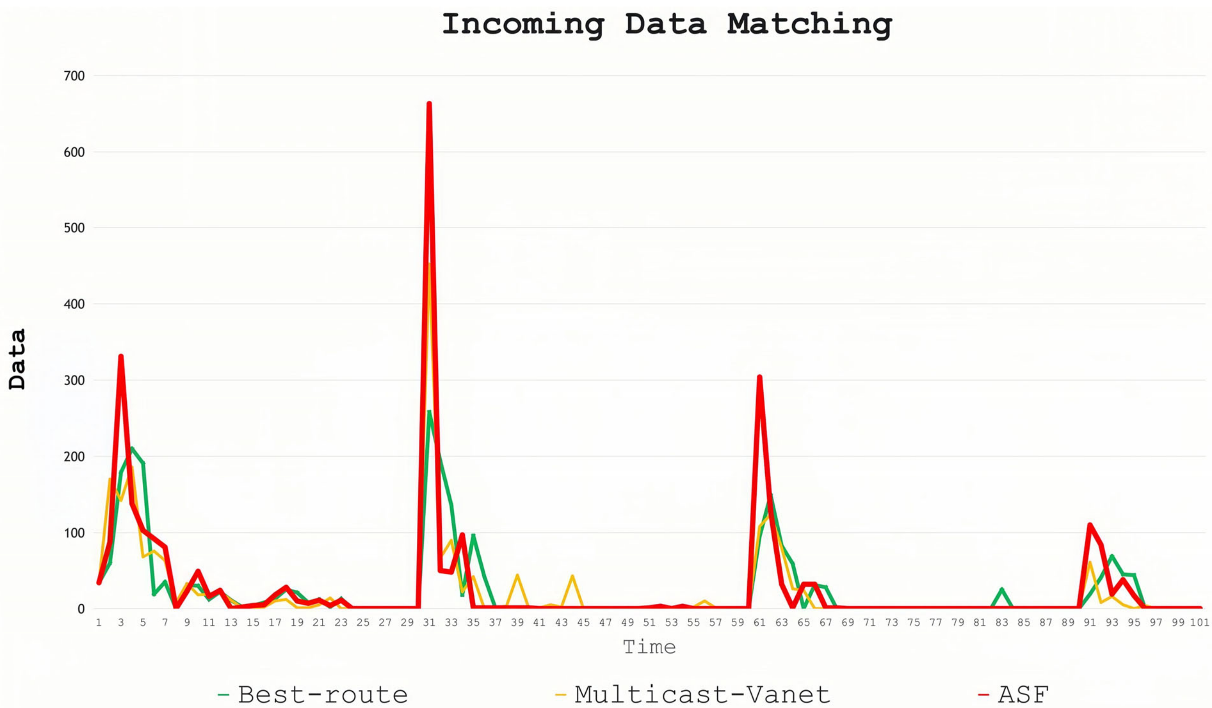


(b)

Fig. 9. Interest change graph at maximum and minimum periods: (a). Change in CS hit parameters; (b). Change in CS miss parameters.



(a)



(b)

Fig. 10. Data change graph at maximum and minimum periods: (a). Change in data unsolicited parameters; (b). Change in incoming data matching parameters.

The ASF strategy is significantly matched with the satisfied interest and CS hit values, supported by a low CS miss value. As illustrated in Fig. 9(b) and Table IX, the ASF strategy exhibits an average CS miss value of 30.4, with the highest increase in CS miss occurring between 1 and 4 seconds of the simulation, totaling 926 interests. Meanwhile, the multicast-VANET strategy has a lower average CS miss value than ASF, at 24.5, with the highest increase in CS miss reaching 611.

The total CS miss for the best-route strategy is recorded at 5,547 interests. Therefore, it is concluded that the best-route strategy is not a suitable recommendation based on the CS miss parameter, as it has a higher number of CS misses compared to the multicast-VANET and ASF strategies.

Fig. 9(a) present a graph illustrating the changes in CS hit interest count over time for three forwarding strategies: best-route, multicast-VANET, and ASF. The X-axis (horizontal—time) represents the change over time within a certain interval (1–100). The Y-axis (vertical—interest) displays the number of CS hit interests that occur in each time period.

A significantly higher number of CS hit interests is recorded for ASF (red) compared to the other strategies. Several large spikes are observed around intervals 5, 30, 60, and 90, indicating that ASF is more effective in utilising the CS to fulfil data requests. Best-route (green) and multicast-VANET (yellow) exhibit lower and relatively stable CS Hit Interest values than ASF. The highest spike for ASF is detected around interval 30, where the number of CS hit interests exceeds 1,000, suggesting that many interests are successfully served directly from the cache. Best-route and multicast-VANET follow similar trends, though with smaller values than ASF.

In conclusion, ASF demonstrates the best performance in CS hit Interest, indicating that this strategy is more effective in utilizing cache to reduce the number of requests forwarded to the source best-route. Multicast-VANET shows lower performance in this aspect.

Fig. 9(b) presents a graph illustrating the changes in the number of CS miss interests over time for three forwarding strategies: best-route, multicast-VANET, and ASF. The X-axis (horizontal—time) represents the change in time within a certain interval (1–100). The Y-axis (vertical—interest) displays the number of CS miss interests occurring in each time period.

Higher CS miss interests are observed in best-route (green) and ASF (red) compared to multicast-VANET (yellow). A significant spike in CS miss Interests is recorded around interval 30, with best-route reaching the highest value (close to 900), followed by ASF slightly below it (~750). Other spikes are detected at 5, 60, and 90 intervals, indicating periods of less effective cache utilization.

A smaller number of CS miss interests is recorded for multicast-VANET overall, suggesting that this strategy is more effective in retrieving content from the cache. After the peak interval, a gradual decrease in CS miss interests is observed across all strategies, indicating that cache efficiency improves over time.

In conclusion, best-route and ASF exhibit many CS miss interests, particularly in the early intervals and around peak periods. Meanwhile, multicast-VANET performs better in reducing CS miss interests, suggesting it is more efficient in utilizing the cache.

C. Data Change Analysis

In this section, the analysis of data changes for each forwarding strategy is presented based on a simulation time of 100 seconds. The data change analysis uses the parameters of incoming unsolicited data, outgoing data, and incoming data matching. The analysis results are also presented through graphs and tables displaying data changes.

Next, each data increase that occurs in each forwarding strategy is compared based on the maximum value of each parameter, namely the highest number of data packets during the data transmission process, referred to as Data (Max), and the lowest number of data packets during the data transmission process, referred to as Data (Min). Each data change is also identified based on variations in the data increase period (Time), the total data sent (Tot) during the transmission period, and the average data value (Avg) during the transmission period.

1) Unsolicited data

Unsolicited data parameters refer to pieces of data that enter the data pipeline and are processed by NFD. However, if the consumer does not request the incoming data, it is handled by NFD using the Forwarder on Data Unsolicited method. These data pieces are labelled unsolicited parameters when the data packets found do not match any requests. Refer to Fig. 10(a) for further information. The ASF strategy indicates unsolicited data has the highest average value of 820.5. The highest increase in unsolicited data within the ASF strategy is observed at 22,975 data pieces during the 1−6 second simulation time. The unsolicited data parameter can be used as a reference to show that the ASF strategy can filter more unsolicited data than other strategies. The multicast-VANET strategy is considered a strong recommendation alongside the ASF strategy, as a significant number of data chunks are filtered, with an average of 135.5 and the highest increase of 3,019 data chunks occurring during the simulation time of 3-6 seconds. Meanwhile, the best-route strategy can only carry data chunks with an average value of 141.9, with the highest number of data chunks reaching 2,739.

The highest total unsolicited data filtered in the minimum period is stated in $MaxTDUnsolicited_{(P_{min})}$ and fully expressed in Eq. (5). The highest unsolicited data value among the minimum periods is achieved by the best-route strategy, recorded at 2,318. This represents the peak performance of the best-route strategy. For further details, please refer to Table XI and Fig. 10(a).

2) Incoming data matching

The incoming data matching parameter ensures that the data packets sent to the consumer correspond to the requested interest. The data matching procedure involves comparing interests in the PIT, forwarding data to the appropriate interface, caching data for future use, and handling unsolicited data. Refer to Fig. 10(b) and Table XI for more details. The ASF strategy demonstrates 2,749 data chunk matches, with the highest increase in incoming data matching occurring at the beginning of the 30-second simulation, reaching a total of 663 data chunks.

The ASF strategy is proven to deliver more data that matches consumer demand based on interest and data compatibility. The multicast-VANET strategy is also recommended, as it has a higher average data compatibility value than the best-route strategy, with the highest increase in data chunks reaching 588. On the other hand, the best-route strategy has not outperformed ASF but remains superior to multicast-VANET, with the highest spike value recorded at a total data match of 2,385. The highest incoming matching data filtered in the minimum period, stated in $MaxDMatching_{(P_{min})}$, is fully described in the statement of Eq. (5). The highest matching data value among the minimum periods is achieved by the best-route strategy, reaching 444. This represents the highest gain of the best-route strategy. For more details, refer to Table XI and Fig. 10(b).

Fig. 10(a) presents a graph illustrating the changes in the number of unsolicited data drops over time for three forwarding strategies: best-route, multicast-VANET, and ASF. The—axis (horizontal—time) represents the change in time within a specific interval (1–100). The—axis (Vertical—data) displays the number of Data Unsolicited In packets, which are sent without a corresponding request (Interest) and eventually dropped.

Best-route is represented in green, multicast-VANET in yellow, and ASF in red. A significantly higher number of unsolicited data packets is observed in ASF (red) compared to best-route and multicast-VANET. The most significant spike occurs around interval 30, where more than 15,000 dropped packets are recorded for ASF. Additional spikes are observed around intervals 5, 60, and 90, indicating that high volumes of unsolicited data transmission occur at these times.

Overall, a lower number of data unsolicited in packets is recorded for best-route (green) and multicast-VANET (yellow), suggesting that these strategies are more efficient in preventing unnecessary data transmissions. After peak periods, a gradual decrease in the number of unsolicited data packets is observed across all strategies.

In conclusion, ASF records the highest number of unsolicited data packets, indicating that this method is more prone to transmitting data without valid requests. Meanwhile, best-route and multicast-VANET demonstrate better control over unsolicited packet transmissions, making them more efficient in minimizing wasted data.

Fig. 10(b) presents a graph illustrating the changes in the number of incoming data matches over time for three forwarding strategies: best-route, multicast-VANET, and ASF. The X-axis (horizontal—time) represents the change in time within a certain interval (1–100). The Y-axis (vertical—data) displays the number of data packets successfully matched with the request (interest), meaning the data is valid and can be utilized by the receiver.

A higher peak in data matching is observed in ASF (red) compared to best-route and multicast-VANET. A significant spike is recorded around the time interval 30, where ASF exceeds 600 data matches with the request. Additional spikes occur around intervals 5, 60, and 90, indicating high data matching activity periods. Compared to ASF, a more stable trend with lower fluctuations is observed in best-route (green) and multicast-VANET (yellow). After certain peak intervals, a significant decrease in the overall number of data matches is observed.

In conclusion, ASF exhibits more incoming data matches than the other strategies. However, this may be attributed to a larger transmitted data volume than Best-route and Multicast-VANET. Meanwhile, Best-route and Multicast-VANET display a more stable pattern matching data with incoming requests.

D. Performance Issues in Best-route and Multicast-VANET

ASF fulfils Interest requests without failure significantly better than best-route and multicast-VANET. However, weaknesses in this aspect are still observed in best-route and multicast-VANET. Several parameters are considered in the evaluation, including (1) Performance in fulfilling interest requests; (2) Caching efficiency; (3) Handling of unsolicited Data; (4) Handling of data matching; and (5) Performance stability.

1) Performance in fulfilling requests

Only 4,207 interest requests are successfully fulfilled by best-route, while 1,230 requests remain unsatisfied. The satisfied-to-unsatisfied ratio is recorded at only 3.42, meaning that only 3.42 requests are successfully met for every failed request. The highest number of unsatisfied requests per period reaches 315, indicating that this method frequently fails to meet requests, even under optimal conditions.

Multicast-VANET fulfilled 4,085 interest requests, leaving only 226 unsatisfied. Although a higher satisfied-to-unsatisfied ratio of 18.08 is achieved, the total number of satisfied requests remains significantly lower than that of ASF. The highest number of unsatisfied requests per period is recorded at 63, which, while lower than Best-route, still indicates occasional request failures.

A 100% fulfilment rate is achieved by ASF, with no unsatisfied requests and a total of 11,111 satisfied interests. The highest number of satisfied requests per period is 3,535, far exceeding other methods. The absence of unsatisfied request spikes confirms that ASF is highly effective in meeting interest demands.

2) Caching efficiency

Best-route and Multicast-VANET exhibit poor caching performance, causing more requests to be forwarded to other sources. In contrast, ASF utilizes caching much more efficiently, leading to reduced latency and network load.

A low CS hit ratio of 0.43 is achieved by best-route, indicating that only 43% of requests are fulfilled from the cache. A high CS miss ratio of 1.29 is also recorded, meaning that 1.29 requests are not found in the cache for every fulfilled request. Additionally, the highest total CS miss, 5,447, is observed, demonstrating frequent failures in utilizing the cache efficiently.

Multicast-VANET shows a slight improvement over the best route, with a CS Hit Ratio of 0.48, though it remains significantly lower than ASF. Its CS miss ratio of 0.61 is better than that of the best route but still higher than that of ASF. The total CS hits of 1,943 and CS misses of 2,475 further indicate that this method is less effective in leveraging the cache.

ASF achieves the highest CS hit ratio, 0.74, fulfilling 74% of requests directly from the cache. Additionally, the lowest CS Miss ratio, 0.28, is maintained, meaning that only 28% of requests fail to retrieve data from the cache. ASF also records the highest total CS hits, 8,252, and the lowest CS misses, 3,073, outperforming the other methods.

3) Handling unsolicited data

Less flexibility and a more conservative approach are exhibited by best-route and multicast-VANET, making them less optimal in handling spike requests. In contrast, ASF takes a more aggressive data distribution approach, improving efficiency in high-demand scenarios.

Best-route records a lower total amount of unsolicited data (14,328), indicating that this method is less aggressive in data distribution. A more stable range of unsolicited data values (6,867–7,461) is observed, but less flexibility in handling spike requests is demonstrated.

A similar amount of unsolicited data, 13,689, is observed in multicast-VANET compared to best-route, but a more varied range of values (6,455–7,234) is recorded. Although greater stability than ASF is exhibited, this method is less effective in handling spike data.

The highest total amount of unsolicited data 82,874 is recorded by ASF, demonstrating a more aggressive approach in data distribution. Despite experiencing large fluctuations in unsolicited data delivery range: (3,767–79,107), efficient data handling is still achieved by ASF.

4) Handling data matching

Best-route and multicast-VANET demonstrate less efficiency in this regard. In contrast, ASF exhibits superior performance in matching data to requests.

A lower total amount of incoming data, matching 2,385, is recorded by best-route compared to ASF. A more stable range of values (1,068–1,317) is observed, but less flexibility in handling request variations is demonstrated.

Multicast-VANET records the lowest total incoming data, matching 2,141. A narrower range of values (959–1,182) is observed, indicating lower efficiency in matching data to requests.

The highest total incoming data matching 2,749 is achieved by ASF, indicating better performance in data-to-request matching. A wider range of incoming data matching values (972–1,777) is recorded, suggesting greater flexibility in handling request variations.

5) Performance stability

Best-route and multicast-VANET exhibit less flexibility, and failures are often encountered under challenging conditions. In contrast, ASF demonstrates greater adaptability and the ability to handle dynamic network conditions.

Stable performance is maintained by best-route, but limitations are present in its capacity to fulfill interests. A high level of unsatisfied interests is recorded, indicating that less adaptability to changes in network conditions is shown by this method.

ASF shows high performance variation, but optimal results are consistently achieved under the best conditions. No unsatisfied interests are recorded, indicating that this method demonstrates a high reliability level.

Poor performance is exhibited by best-route and multicast-VANET due to the following factors: a high failure rate of unsatisfied interests, low caching efficiency, limited flexibility in handling spike requests, and greater stability but lower efficiency in dynamic conditions. In contrast, excellence is demonstrated by the ASF strategy in all critical aspects, including: (1) Interest request fulfillment (100% of interests are satisfied); (2) Caching efficiency (the highest CS hit ratio and the lowest CS miss ratio); (3) Handling of unsolicited data (more aggressive and flexible); (4) Incoming data matching (greater efficiency in matching data with requests); (5) Adaptability to network conditions (capable of handling spike requests). Therefore, ASF is identified as the most effective strategy for V-NDN networks, while further optimization is required for best-route and multicast-VANET to enhance their performance.

E. Limitations of ASF

Although ASF excels in many aspects, such as request fulfillment (100% Satisfied Interest) and caching efficiency (CS Hit Ratio of 0.74), its weaknesses must be considered to ensure effective implementation in various V-NDN network scenarios. Several major weaknesses are identified in the ASF strategy, including:

1) High variability in performance

Large fluctuations in the number of CS hits per Period (ranging from 305 to 2,655) are observed in the ASF strategy, indicating that its caching performance varies significantly depending on network conditions. Although the highest CS Hit Ratio (0.74) is achieved, this variability may lead to instability in specific periods, particularly when the network encounters unexpected demand spikes. A significant spike in Unsolicited Data is recorded in the ASF strategy, with 82,874, more than five times higher than Best-route and Multicast-VANET. This surge can result in substantial network overhead, as data is sent aggressively even when not explicitly requested.

2) Potential imbalance in data delivery

The ASF strategy observes a wide range of incoming data matching per period (972–1,777), indicating lower consistency in matching data with requests. Although the highest total incoming data matching, 2,749, is recorded compared to other methods, this high variation may lead to an imbalance in data management, particularly in scenarios with dynamic network traffic.

3) Implementation complexity

The ASF strategy is highly adaptive and can handle up to 10,146 satisfied interests per period. However, additional optimization is required to ensure performance stability. In poor network conditions, performance degradation may be experienced if proper optimization is not applied, particularly in managing unsolicited data and incoming data matching.

4) Higher network overhead risk

Due to aggressive data sending in the ASF strategy, 82,874 metric tons of unsolicited data are generated. This may increase network overhead and cause data congestion, particularly in high vehicle density scenarios. While this approach facilitates faster request fulfillment, it can become counterproductive without effective traffic control mechanisms.

5) Risk of instability under certain conditions

Although ASF performs optimally under ideal conditions, its performance can decline drastically in poor network conditions (e.g., during outages or demand spikes). Even though zero unsatisfied interests are recorded, the risk of instability remains if the system fails to adapt to sudden changes in network topology.

To improve ASF performance, several recommendations can be considered: (1) The delivery of unsolicited data should be reduced to minimize network overhead; (2) Consistency in incoming data matching should be increased by optimizing data matching algorithms; (3) Traffic control mechanisms should be added to manage demand spikes under dynamic network conditions.

VI. Conclusion

Based on the experiments and measurement results conducted on the best-route, multicast-VANET, and ASF forwarding strategies, the analysis was performed using measurement data that refers to the NFD forwarding pipeline. From the analysis, several important points can be concluded, indicating that the forwarding strategy with the ASF approach is significantly better than the best-route and multicast-VANET strategies.

The measurement of changes in interest and data using the maximum and minimum periods with four parameters—satisfied interest, unsatisfied interest, CS hit, CS miss, unsolicited data, and incoming data matching—has been conducted and is concluded to indicate that:

- Compared to the best-route and multicast-VANET strategies, the ASF strategy has the highest satisfied interest value during the maximum period. The ASF strategy is recommended as the best option based on the unsatisfied interest parameter, as it has a value of 0, indicating that all sent interests successfully serve content requests.
- The ASF strategy is observed to have a high CS hit and significant conformity with the satisfied interest and CS hit values, while also being supported by a low CS miss value.
- The highest data increase in the ASF strategy within the unsolicited data parameter can indicate that the ASF strategy filters more unsolicited data than other strategies. The multicast-VANET strategy can also be recommended as an alternative to the ASF strategy. Additionally, the ASF strategy has been proven to provide more data matches to consumers based on interest and data compatibility.

This study highlights that the ASF forwarding strategy outperforms others in vehicular NDN environments. Higher satisfied interest rates are achieved, CS utilization is optimized, and unsatisfied interests are reduced, making ASF the most effective strategy for enhancing data acquisition and communication reliability in high-mobility scenarios. These findings have significant implications for designing and deploying efficient and reliable vehicular communication systems, paving the way for advanced applications such as autonomous driving and connected vehicles.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Syaiful Ahdan formulated the research problem, developed the modeling for the proposed solution, conducted model validation, analyzed the results, prepared the research reports, and drafted the manuscript for publication; Iskandar assisted Syaiful Ahdan in guiding and supervising the research process and contributed to building the experimental environment by implementing the system model within the Named Data Networking (NDN) architecture, focusing on vehicle network integration (V-NDN); Nana Rachmana Syambas provided strategic direction, supervised the overall research activities, and coordinated the manuscript writing process by Syaiful Ahdan to ensure alignment with academic standards; all authors had approved the final version.

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