IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 4 June 2025, accepted 22 June 2025, date of publication 25 June 2025, date of current version 3 July 2025.

Digital Object Identifier 10.1109/ACCESS.2025.3583030

RESEARCH ARTICLE

Graph Based Cooperative Forwarding in Information Centric Vehicular Networks

BERI SURYA SAMANTHA[1], (Student Member, IEEE), NITUL DUTTA[2], (Senior Member, IEEE), RAJESH MAHADEVA[3], (Member, IEEE), SHASHIKANT P. PATOLE[4], (Member, IEEE), AND GHEORGHITA GHINEA[5], (Member, IEEE)

[1]Department of Computer Science and Engineering, SRM University, Amaravathi, Andhra Pradesh 522502, India
[2]Department of Computer Science and Engineering, Ecole Centrale School of Engineering, Mahindra University, Hyderabad 500043, India
[3]Department of Computer Science and Engineering, Manipal Institute of Technology, MAHE, Manipal, Karnataka 576104, India
[4]Department of Physics, Khalifa University of Science and Technology, Abu Dhabi 127788, United Arab Emirates
[5]Department of Computer Science, Brunel University, UB8 3PH London, U.K.

Corresponding author: Shashikant P. Patole (shashikant.patole@ku.ac.ae)

ABSTRACT The rise of data intensive applications reveal the limitations of IP-based networking, particularly in dynamic vehicular environment. Transitioning to Information Centric Network (ICN) addresses these limitations by focusing on content retrieval from any suitable location rather than completely relying on content server or host-to-host communication. The content based communication uses an interest packet to seek named data. The interest packets are forwarded through the network to locate and retrieve content. In general the ICN uses Forwarding Information Base (FIB) tables for efficient forwarding of interest. However, in wireless environment like Vehicular Network (V-Net), use of FIB is expensive due to high bandwidth demand for maintenance. Hence, interest forwarding approach without FIB is much popular. In this paper, an interest forwarding technique for Information Centric Vehicular Networks (ICVNs) is proposed without the use of FIB. The prime objective of the algorithm is to reduce content retrieval time and optimize network overhead and throughput. For that purpose the network is modeled as a graph and partitioned into groups where each group is managed by a group leader. The group members cooperate with leader and share local information. The leaders, on the other hand cooperate with other group leaders and share information in the global level. Interest packets are forwarded by leaders on behalf of a group there by accelerating the content retrieval process. The proposed algorithm is named as GCF (Graph based Cooperative Forwarding) and is simulated in *ndnSim*-2.0. The performance of GCF is compared with the other two contemporary protocols, and observation shows better performance of the new approach, specifically in a densely populated scenario, compared to other benchmark algorithms. Various parameters used in the comparison are end-to-end latency, interest loss rate, network overhead, throughput, and server hit ratio. Quantitatively, the proposed protocol shows nearly 10% improvement in latency, 40% improvement in interest packet loss, and 60% improvement in network overhead.

INDEX TERMS ICN based vehicular network, ICVN, interest forwarding, graph theory in ICVN.

I. INTRODUCTION

The applications of current time is highly data intensive. Furthermore, in traditional IP network [1] every content request traverses to the server to fulfill the clients need. Even if multiple nodes in the same locality access the same content, the IP do not have the provision of sharing data among nodes and hence all the request propagates to a distant server. This generates a large traffic which is possible to avoid by sharing data among nodes [2]. Hence, the current Internet architecture is not efficient considering the data hungry applications of current era [3]. Furthermore, TCP/IP based networking has exposed several challenges which is primarily arises due to its host-centric and location dependent data retrieval architecture. Hence, a transition from this host centric model to content centric approach is desirable.

The associate editor coordinating the review of this manuscript and approving it for publication was Tariq Umer.

This new model emphasizes on distributing named objects rather than facilitating host-to-host communication.This shift in communication paradigm is referred as Information Centric Network (ICN) [4]. Looking at the benefits of ICN, researchers are exploring to extend this architecture into various network applications including V-Net. As one of the most widely used data-intensive applications, the V-Net suffer significant challenges when based on IP infrastructure. The dynamic and unpredictable mobility pattern of vehicles, coupled with the lack of consistent roadside infrastructure, maintaining stable end-to-end connections quite difficult [2], [5]. In such conditions, the content centric approach is certainly a better choice as it focuses on retrieving content from any available and reliable source rather than relying on direct host-to-host communication. This paradigm shift makes communication efficient by allowing vehicles to obtain relevant information quickly and reliably. Consequently, this shift has led to the development ICVN, a novel architecture designed specifically to address the unique demands of vehicular communication [6].

In ICN, contents are identified by a unique name. Unlike IP network, where a client sends a request to a content producer to retrieve data, ICN places the request on the network by generating an interest packet. The interest packet carries the name of the requested content. Any intermediate node, on receiving the interest packet, either serves the request if the searched content is with it or forwards the interest to the next node. This way, the interest is moved to a location where the content is found and the client is served. That is why an efficient interest forwarding is crucial for successful content retrieval and the deployment of ICN and its applications. Typically, ICN nodes utilize a Forwarding Information Base (FIB) table to facilitate interest forwarding [7]. The use of the FIB table offers several advantages, including context-aware data dissemination, mitigation of broadcast storms, and efficient interest routing. These benefits, in turn, enhance network performance by reducing congestion and optimizing content delivery. However, to maintain the up to date FIB table, nodes and RSUs in the network need to exchange FIB table information periodically. Since the size of FIB table is considerably large [8], it consumes significant bandwidth. Being a resource constrained network, the vehicular communication cannot afford such table exchange mechanism. Hence, use of FIB for interest forwarding is not feasible in ICVN. Additionally, there are unavoidable challenges associated with FIB tables, including scalability, network overhead, and privacy and security concerns [9], [10]. As the network size and content volume increases, the FIB table expands, leading to higher memory requirements and longer processing times, which exacerbate scalability issues. Moreover, the FIB table contains information about content and its locations, which can be exploited by malicious users [11], posing a significant security threat [9]. Subsequently, interest forwarding without intervention of FIB is adopted as a solution for wireless ICN like vehicular ICN [12]. In this approach, a content seeker or intermediate forwarder does not take help of FIB table to forward interest packets. Instead, either it broadcast the interest to all neighbors or selectively pick one or two neighbor to forward the interest. The most intuitive method of this kind is the flooding of interest in all directions [13]. However, it leads to broadcast storm issue which consumes considerable network bandwidth. To resolve this issue, directed and guided interest forwarding approaches are designed [14], [15]. In this approach, the interest packets are forwarded to few neighbors (1 or 2) based on some decisions made by the network entities such as the client or intermediate nodes. Few of such algorithms, such as [15] uses probability of neighbor density to guess the probable location of searched content. The work of [16] suggests sending the interest to a neighbor who has a large number of neighbors. Assuming there is a high chance of finding the content in a congested area. Another few forwarding approaches, such as in [17] suggest to use machine learning approach to select the next neighbor to forward interest. These algorithms improve the performance by guiding the interest packets towards the right full cache store in the network without using the FIB table. Since, there is no FIB table use, hence the cost of periodic table exchange is eliminated. A thorough discussion of few of the recent works in this area are discussed in Related work section.

The aim of this paper is to propose an interest forwarding technique for ICVN with the objective to reduce the content retrieval time and minimize network overhead. In order to achieve the stated goal the ICVN is modeled as a graph of nodes and partitioned them in to groups. Every group selects a leader and all members in the group share local information with the leader. The leader share information in the global level with other leaders to communicate with rest of the network. The algorithm co-operates among the group members to update local information and leaders of various groups to update global information and forward interest packets. Throughout the discussion of the paper, a framework is established in support of the new protocol. For the ease of understanding Table 1 is presented with a list of the abbreviations and acronyms used throughout this paper.

The rest of the paper is organized as follows. In Section II few state of the art approaches are discussed. Section III describes the System model and Section IV describes the caching and replacement policy adopted in this work. Simulation scenario is discussed in Section VI and results are found in Section VII. The paper is concluded in Section VIII.

II. RELATED WORK

The forwarding strategy in an ICN primarily focuses on the efficient management and dissemination of interest packets, rather than the direct handling of data packets. This distinction arises because data chunks inherently follow the reverse path established by the interest propagation. This method stands in stark contrast to traditional IP network routing protocols, where the primary concern is the routing and forwarding of data packets. The objective of this research is to develop and evaluate a robust technique for

TABLE 1. List of abbreviations.

Acronym	Abbreviation
ICN	Information Centric Network
ICVN	Information Centric Vehicular Network
GCF	Graph based Co-operative Forwarding
V-Net	Vehicular Network
FIB	Forwarding Information Base
PIT	Pending Intrest Table
CS	Cache Store
ES	Edge Server
MEDs	Mobile End Devices
RSU	Road Side Unit
CRs	Content Routers

optimizing the forwarding of interest packets within the ICVN framework. This section presents a comprehensive review of several studies that are closely aligned with and contribute to the ongoing work in this domain.

The work in [14] demonstrates an interest forwarding scheme where content names are designed based on the nodes geographic locations. While forwarding interest packets, it looks at the content name and forwards to a zone indicated by the content name. The protocol suggests to build an interest dissemination zone with the requesting node's GPS coordinates and the GPS coordinates of the content. Such dissemination zone eliminates the need of flooding interest requests thereby avoids broadcast storm. The issue with this scheme is the GPS location. Since the nodes are mobile maintaining a stable GPS location of nodes as well as content is a challenging task. A probabilistic forwarding strategy is proposed in [15] as a solution to the broadcast storm with flooding. This technique is specifically designed to cope up with the vehicular density in the network. Each vehicle dynamically computes the probability of content availability considering the number of its neighbors within the communication range. The authors have described a local density approximation method in order to compute the content residence probability. A priority based neighbor selection is adopted to forward the interest in the topology. The success of the algorithm is driven by the accuracy of density approximation. Hence, strongly dependent of the auxiliary algorithm. The authors of [18] have proposed a forwarding algorithm based on optimal content backup. It suggest to establish a single reliable and reachable forwarding path for interest with proper signal strength. On the other hand, for data forwarding the algorithm proposes to have multiple paths as a backup route. As claimed, the protocol effectively improves the interest satisfaction ratio with reduced re-transmissions. However, on principle, the ICN forwards the data in the reverse path of the interest. Hence, implementation of the algorithm may need changes in the core architecture of ICN.

In recent years, the interest forwarding techniques are explored in various directions such as focusing on mobility pattern, road side infrastructures etc. The study by [19] presents a forwarding strategy based on vehicle mobility predictions. It selects the next hop by evaluating neighboring vehicles' speed and direction, predicting future locations. Through simulation, authors has established a reduced content retrieval time and improved interest satisfaction ratio. However, the algorithm highlights performance issues in scenarios with inaccurate mobility prediction. The work described in [20] introduces a forwarding mechanism utilizing roadside edge devices to enhance caching and content retrieval. It optimizes interest forwarding and employs in-network recovery for packet loss. Simulation of the protocol demonstrate its effectiveness though it relies on roadside devices and may incur additional overhead due to re-transmission. As outlined in [21], the proposed algorithm tracks interest and content flow to optimize content retrieval in a content centric V-Net topology. It prioritizes neighbors based on geo-distance closeness between the last forwarder and the current requester. However, this reliance on geo-distance tracking may cause significant computational and communication overhead, particularly in dynamic or large-scale networks. In [22], a distributed lightweight traffic management method for content centric V-Net is described, supported by roadside units in urban areas. The proof-of-concept design highlights that the communication architecture choice greatly affects efficiency and service quality. However, the algorithm performs suboptimally in rural environments due to its reliance on roadside units. The algorithm in [23] outlines a data retrieval scheme for highly dynamic scenario. The dynamic nature of the vehicular network is modeled as a Markov process and employs reinforcement learning to optimize vehicle selection in dynamic environments. In [24], a network architecture for content V-Net compatible with 5G networks is proposed, focusing on autonomous driving by facilitating the exchange of safety information and traffic conditions. The protocol also supports high-definition map validation with trajectory context for vehicle localization and planning. It enables efficient push and pull of map content without overloading the network core. Performance analysis through network simulations highlights the effectiveness of the proposed methods. A clustering approach on content centric peer-to-peer network is proposed in [25]. However, this article emphasizes on clustering of producers and nodes may join in these clusters based on their need. Another work of clustering as reported in [26] is the cluster of vehicles in ICN topology. The work is focused on caching of content in cluster of nodes for better accessibility. By doing so authors shows a better content connectivity in vehicular environment. Unlike [25] which is worked for peer-to-peer overlay network, the proposed approach of this research is based on clean slate ICN implementation. Furthermore, this work is focused on clustering of nodes rather than producers. Compared to [26], this proposed work is concerned in guiding interest packets to rightful nearest content source without following FIB and caching is not explicitly discussed in the process.

The interest forwarding is found to be modeled as game theory in many of the recent research. In [27], an interest forwarding strategy for CCVN, modeled as Public Goods Gaming (PGG) in evolutionary game theory, is proposed. Cooperators forward interest packets towards the content source, while defectors do not. Cooperators are rewarded, aiming to deliver interest packets to the correct content store. Despite its effectiveness, the method's reliance on complex game theory may pose challenges for computationally constrained devices in V-Nets. The work presented in [28] introduces an interest forwarding technique designed to minimize content retrieval time and reduce network overhead. This technique models the interest forwarding process as a bargaining game, where the data seeker acts as the seller and the content provider as the buyer. Intermediate Content Routers (CRs) between the consumer and the actual producer are classified into capable (cCR) and incapable (iCR) routers. Each CR initially holds a currency value based on its attributes. cCRs, which can serve interests, are rewarded with a pre-agreed trading price, while iCRs, unable to serve content, receive a fraction of the trading price based on their role in facilitating the data transmission path.

From the above discussions about the sate of the art protocols in ICVN interest forwarding, it is revealed that an efficient interest forwarding for the technology is highly essential. Researchers are proposing a few approaches in order to address various issues and challenges in the area. However, there is still ample room for improvement with reference to various network conditions in ICN V-Nets. Keeping these in mind, the research problem solved in this research is "to devise an interest forwarding method for Content centric V-Nets governed by clustering of vehicular nodes". The objectives of the work is to

- Model the vehicular network as a graph and partitioning it to form groups among vehicles.
- Design an interest forwarding approach for ICVN taking into consideration the density of vehicles inside a city or relatively congested highways.
- Analysis of the proposed work in simulated environment.
- Comparison of proposed forwarding scheme with few existing state-of-the-art approaches to establish the superiority of the proposed approach.

In view of the above mentioned aim and objectives, the contributions of the work is listed below.

- A clustering algorithm based on the vehicular node characteristics, such as mobility profile and serving probability (Section III-C), is presented.
- A caching technique to support content retrieval in the graph based vehicular network (Section IV) is stated.
- An interest forwarding algorithm considering a group of vehicles as the basis and forwarding among groups (Section V) is proposed.

In the next Section the system architecture for the deployment of proposed algorithm is discussed in detail.

III. SYSTEM MODEL

This paper models the network as a graph with vehicles, road side entities as node. The network entities communicates following ICN architecture that emphasizes on content caching and cooperation in content delivery. Both the underlying ICN architecture and network topology is described in this section.

A. UNDERLYING NETWORK ARCHITECTURE

A typical network topology for the deployment of the proposed interest forwarding technique is depicted in Fig. 1 [29]. The architecture is based on the clean slate implementation of the Named Data Networking (NDN) architecture, as described in [30]. Various network entities, including vehicles or Mobile End Devices (MEDs) and Road Side Units (RSUs), comprises of all key components and data structures of NDN, such as the Cache Store (CS), Pending Interest Table (PIT), and Forwarding Information Base (FIB). There are no modifications made to their core functionalities. Following the NDN paradigm, a client (an MED in an ICVN) generates an interest packet to request specific content by embedding the content's name. When an intermediate node receives the interest packet, it checks its cache for the requested content. If the content is available, it is returned to the requester. If not, the node records the interest packet in its PIT and forwards it to the next hop. Although, FIB table to could be used as a routing table of TCP/IP networks to forward interest, due to the issues in using FIB in an ICVN, as discussed in previous section, in this paper FIB is avoided. The approach described here relies on heuristic knowledge of neighbor information to forward interest. For the purpose, a neighbor table is introduced as an additional data structure in the network entities along with the existing NDN data structures without disturbing the fundamental components of the architecture. The neighbor table is managed by the forwarding module within an ICVN node. A detailed explanation of the neighbor table is provided in the following subsections.

B. MODELING OF NETWORK FOR PROPOSED ALGORITHM

The proposed interest forwarding method implemented in a network topology where vehicles or form groups on the go or travel as a group. This group formation is not intentional however due to their movement pattern they form groups automatically. It is assumed that these vehicles travel at relatively similar speeds and stay within communication range for extended periods. For the mathematical modeling of this forwarding method, the network is represented as a graph, where vehicles are depicted as nodes and the connections between them as edges. The following definitions with respect to the vehicular network graph is made for better interpretation of the new forwarding approach.

Definition 1: A network graph G is defined as G=(V, E), where, V is the set of vehicular nodes (and RSUs) and E is

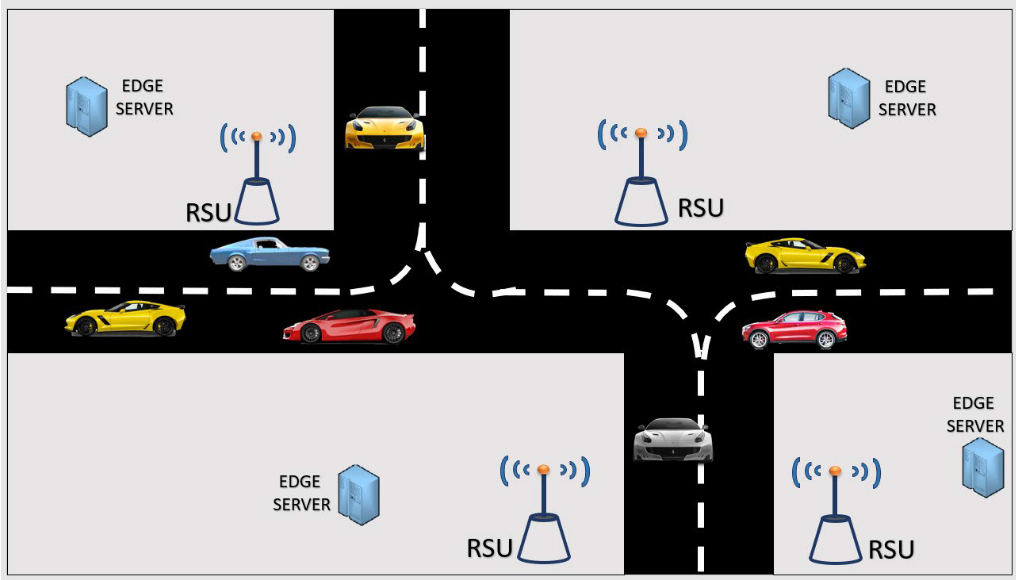

FIGURE 1. A sample vehicular network topology considered for realization of the proposed forwarding scheme.

the set of links connecting two nodes. Further, an edge $e_i \in E$ is defined as a pair of two connected vertices (v_i, v_j) with $v_i, v_j \in V$.

Definition 2: A community $C = (V_c, E_c)$ in G is defined as set of vertices V_c and edges E_c where, $V_c \subset V$ and $E_c \subset E$, and $\forall e_i = (v_i, v_j) \in E_c$ with $v_i, v_j \in V_c$.

Definition 3: A community structure $C = \{C_1, C_2, \cdots C_k\}$ of a network G is a partition of V. In other words, $\sum_{i=1}^{k} C_l V$ and $C_i \cap C_j = \emptyset$ for $i, j = 1, \cdots k$ with $i \neq j$, k refers to the number of communities in C.

The network graph of the topology is logically partitioned into groups based on their connectivity. Each group is recognized as a community as defined in *Definition* 2. On the other hand, few communities together form a community structure as stated in *Definition* 3. Moreover, no two nodes are part of two communities as in Definition 3. To partition the network into community structures of network graph, the Louvain partitioning algorithm as described in [31] is used. The said partitioning algorithm works on heuristic knowledge of the network in order to partition. While forming various communities it uses the modularity optimization algorithm as stated in [32]. The Modularity is a metric used to assess the quality of communities formed during network partitioning. Suppose the network contains n vertices. Let's $s_i = 1$ if i is in group 1 and -1 if in other group 2 say. Further assume that, the number of edges between vertices i and j be A_{ij}, which is normally 0 or 1 considering single edge between two nodes. At the same time, the expected total number of edges between vertices i and j is $\left(\frac{k_i k_j}{2m}\right)$, where k_i and k_j are the degree of the vertices and $m=\frac{1}{2}\sum_i k_i$ is the total number of edges in the network. Thus the modularity can be written

$$Q = \frac{1}{4m} \sum_{ij} \left(A_{ij} - \frac{k_i k_j}{2m} \right) s_i s_j \tag{1}$$

The partitioning algorithm has to identify a set of communities from a network. The first phase of the algorithm is modularity optimization, in which the algorithm attempts to merge every node with its neighbor with a high modularity score in order to form a better community structure. The second phase of the algorithm is known as community aggregation, in which the algorithm creates a new community network by aggregating communities discovered in the first phase. These two phases are iterated until the modularity score is positive. The steps of the algorithm for finding communities are summarized below.

C. LEADER SELECTION

Let us assume that there are k communities formed after partitioning the graph of vehicular nodes. Each of the k communities has to select a leader to communicate among other groups. For the purpose, the node centrality value is considered as the selection parameter. To compute the node centrality, the connectivity degree of a node is considered. A node near to the infrastructure i.e. close to RSUs is more likely to have better connectivity. Moreover, node close to there leaders is to be considered as it helps in communication with the topology. So, the centrality value of a node is considered with maximum weight to calculate the score. It is assumed that if centrality of a node is high then it has more neighbors. Possibly the node is moving with a group in the same direction with relatively same speed for which they are in the communication range. Furthermore, the connectivity to RSU and other group leaders can contribute to the stability of the leader. At the same time it is intended to consider a node which is preferably not a selfish type of node which is not interested in participating in the interest forwarding. So, the S_p is considered as part of the score computation. The existing equation is modified in order to reflect all the above

Algorithm 1 Partition Algorithm

Start
Initialize: Every node v in G forms its own community. Hence, initially, the number of communities $k = |V|$.
Compute modularity Q using the formula stated in Eqn. (1)

$$Q = \frac{1}{4m} \sum_{ij} \left(A_{ij} - \frac{k_i k_j}{2m} \right) s_i s_j$$

for all communities C_i and C_j **do**
  Select a node v_i from community C_i and check its neighbor v_j in community C_j
  if merging v_i and v_j improves modularity ($Q(C_i) \geq Q(C_j)$) **then**
    Move node v_j from community C_j to community C_i
  else
    Keep v_j in community C_j
  end if
end for
while modularity increases with further node movements **do**
  Repeat the process of recalculating modularity and reevaluating nodes.
end while
End when no more new communities can be detected.

mentioned attributes. The equation is stated below.

$$n_R = a \times t_{BC} + b \times (t_{RSU} + t_{OL}) + c \times S_p$$

where, t_{BC} betweenness centrality value, t_{RSU} is the RSU in range, t_{OL} is the other leaders in range. The constants $a + b + c = 1$ and typical values considered are $a = 0.5$, $b = 0.3$ and $c = 0.2$. By taking highest weight of a, the centrality value of node considered as on top priority for selecting as a leader. The leader selection is distributed in nature. All nodes compute their rank and broadcast to all their neighbors. Every node maintains the information about the rank of other nodes and node with highest score is considered as leader. Then the leader announces its leadership to its neighbors as well as the fellow group leaders. The diagram in Fig. 2 shows the selection of leaders and communication among various groups.

Once the leader is selected, it becomes the in-charge of the group. All members get connected to the leader and pass few vital information such as their list of contents stored in the cache, their individual serving etc. These information is used by the leader to forward interest for serving request. If a node leaves a group, at the time of leaving the group it sends an intimation to the leader about its exit. If a leader leaves a group then other suitable node in the group is selected as a new leader.

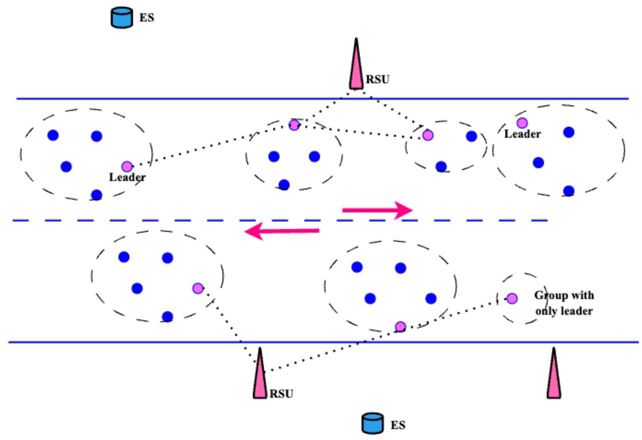

FIGURE 2. Groups among the vehicles are formed based on the partitioning algorithm. A leader from the group is selected to coordinate among the group. Leaders also communicate with other leaders on behalf of the group.

IV. CONTENT CACHING AND REPLACEMENT

The caching technique used in the implementation is a content popularity based approach. The content popularity is driven by Zipf's law [33]. Every producer, RSU and MEDs compute the popularity of its content when it receives an interest packet for the content [34] and keeps the content popularity updated. The popularity is computed as follows.

Following Zipf's law, the content access frequency determines the rank of a content. The skewness α on the other hand determines the popularity distribution. The universal popularity of content C_i with rank R_i is computed as

$$popu(C_i) = \frac{\Omega}{R_i^{\alpha}} \tag{2}$$

where

$$\Omega = \sum_{n=1}^{N} \left(\frac{1}{\alpha} \right)^{-1}$$

and, N is the content count that is being requested by different consumers and $0 < \alpha < 1.2$ considering a broader distribution. The popularity driven by Eqn. (2) is universal assessment and may change due to dynamism in content requests. To addressed this issue, every time a device receives an update on the popularity of content C_i it records the same in a popularity table. The table keeps recent m (an arbitrary count) finite (let say 5) popularity seen for the said content. Based on this information, the device models the expected popularity as a continuous random variable (X) with density function $f(x)$. The $f(x)$ is expressed as

$$f(x) = \lambda_i e^{-\lambda_{ix}}, x > 0 \tag{3}$$

λ_i is the average access request of the content C_i. Hence, the Expected popularity of the content C_i is computed as

$$E[X_i] = \int x f(x) dx = \int x \lambda_i e^{-\lambda_i x} dx \tag{4}$$

Considering $u = \lambda_i x, du = \lambda_i dx$ in the equation 4, it is rewritten as,

$$E[X_i] = \frac{1}{\lambda_i} \int ue^u du \tag{5}$$

The expected popularity of Eqn. (5) is used to store content in various devices like RSUs, ESs and MEDs. There is no restriction on devices to store content and any device with available cache space can store popular data with popularity score greater than P_{thresh} and calls cache replacement algorithms to create space for new contents if necessary.

If content cache is full and there is a need of caching new popular content, then the old caches are evicted to make room for the new content. In this paper, the second chance content replacement algorithm is used. In this technique the evicted cache is re-placed in any other node with free store. This technique employs a hashing technique by a leader to find another node int he group. The use of a hash-based approach allows the leader node to appropriately and efficiently. When content is evicted from a router, a message is sent to the leader node. Upon receiving the message, the leader node computes the hash value h for the evicted content by applying the content name to a function f and a mod operation to determine the new location. Upon receiving the message from the leader node, the router may cache the suggested content on available space. Otherwise, leader again repeat the process till a location is found.

V. PROPOSED INTEREST FORWARDING ALGORITHM

In this section, the working model of the proposed algorithm is discussed. The algorithm works in a hybrid cooperative technique. It cooperates among the nodes in a group and then cooperates among the leaders of various groups. Every node in a group shares local information about cached contents, interest served form their store so far etc. The leaders in the higher level, cooperates with other leaders in its coverage area and communicates parameters such as content ratio, geo-location and serving probability. These parameters are used to compute the score of a node to select it as next level forwarder. Detailed process is discussed next.

Every leader has the information of count of contents stored in the cache of its group members. It broadcast this information to the one hop leader neighbors. When a node needs a content, it forwards the interest packet to its leader. The leader then computes a score of the neighbor as a function of content count, mobility profile and serving probability. The function is defined as given below

$$n_s = f(C_r, M_p, S_p) \tag{6}$$

where, C_r is the content ratio, M_p is the mobility profile and S_p is the serving probability. The parameter C_r is computed as the ratio of total content count (c_t) in a group to the number of members in the group m_t.

$$C_r = \frac{c_t}{m_t} \tag{7}$$

Other parameters, M_p and S_p are calculated as follows.

A. MOBILITY PROFILE (M_P)

The mobility profile specifies the relative speed of a neighbor computed from its known mobility pattern. It is governed by their relative motion and initial positions. It ensures the probability that two neighbor vehicles (say node i and a random neighbor j) stay within the communication range (say in radius R) for a desired duration, let's say, T. We assume that node i has an interest packet and need to search a suitable neighbor. Hence, i is called the candidate node (CN). For a neighbor node j, the CN computes the mobility profile as

$$M_p(T) = \frac{t_{ic}}{T} \tag{8}$$

where t_{ic} signifies the Inter Contact Time (ICT) of node i and j. Larger this time, more is the duration for which they can communicate without disruption. Let's consider that S_i is the speed of the node i and and S_j is the speed of the neighbor vehicle j. The initial distance between both the vehicles is d_0. This distance is calculated by the CN using the goe-location of the neighbor and according to Euclidean distance.

$$t_{ic} = \begin{cases} \dfrac{d_0 - R}{S_i + S_j}, & \text{if moving towards each other} \\ \dfrac{R}{S_i + S_j}, & \text{if moving away from each other} \\ \dfrac{R}{|S_i - S_j|}, & \text{if moving in same direction} \end{cases} \tag{9}$$

Since the movement patterns of vehicles are dynamic in nature, hence the t_{ic} reflects the topological dynamism as stated in Eqn. (8).

B. SERVING PROBABILITY (S_P)

The S_p of a node j is a measure of the possibility that the node j may have the searched content. The CN computes this value to evaluate the score of a node. It is assumed that there are three traffic categories exist in the system, namely, the type 1 ($T1$), type 2 ($T2$) and type 3 ($T3$). The $T1$ includes safety and control traffic, $T2$ includes information and entertainment traffic and $T3$ includes network management traffic. To incorporate serving probability in the model, the interest packet of the NDN architecture is modified to include a field called *traffic_type* that specifies the type of traffic requested. Every node in the network keeps track of all the traffic types that it has served from its cache in the variables $t_{p_{(t)}}$ for $t = 1, 2, 3$. It also stores the total interest packets served so far in the variable t_r. Then, the serving probability of a node in terms of particular traffic type, $S_{p_{(t)}}$ is computed as

$$S_{p_{(t)}} = \frac{t_{p_{(t)}}}{t_r} \tag{10}$$

If the value of $S_{p_{(t)}}$ is high then it implies that the node j has served a considerable quantity of interest packets of the said category traffic and hence, has a higher chance of having the searched content in its cache. So, if such nodes are included in the content search process, the retrieval would be faster.

C. SCORE COMPUTATION

After computing the mobility profile (using Eqn. (8)) and serving probability (using Eqn. (10)) of a neighbor j is computed, the CN computes the rank of the node j using the following equation.

$$r_j = \alpha \times C_r + \beta \times M_p(T) + \gamma \times S_{p(t)} \tag{11}$$

where, α, β and γ are balancing factors and $\alpha + \beta + \gamma = 1$. The content ratio indicates the volume of contents in a group of vehicles. The mobility profile in computing the score of a node ensures the longer connectivity whereas the higher serving probability ensures content availability. The larger amount of storage makes higher possibility of finding the content. Hence, the α value set to 0.4 to give higher importance to C_r. For traffic category $T1$ where both connectivity and availability are is of high importance, both α and β value is kept equal (i.e. 0.3). It implies that neighbors with longer connectivity with the CN and higher probability of finding the contents are preferred. On the other hand, for categories $T2$ and $T3$, β value kept higher (0.4), where the nodes with higher service rates are preferred. a flowchart of the proposed approach is depicted in Fig. 3.

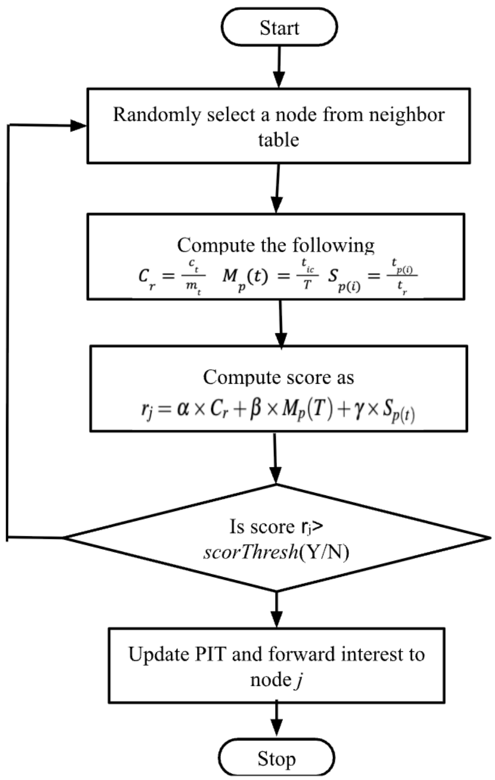

FIGURE 3. Execution flow of proposed GCF algorithm. This algorithm is executed by each of the node in the network that has an interest to forward.

VI. SIMULATED PERFORMANCE EVALUATION

A. SIMULATION TOOLS

During the process of the literature review, there are several simulation tools noticed to be used in designing experimental setup for ICN network specially the ICN based V-Nets. Few of such simulators are briefly discussed in this subsection. The work reported in [35] and many others have used C++ integrated with Matlab to design ICVN network topology. The wireless network simulator module in Matlab supports the design of various wireless network scenarios with different types of nodes. The work discussed in [36] and [37] demonstrates the use of SUMO with *ns*-3. The tool SUMO (Simulation of Urban Mobility) is an open-source tool that models traffic systems, including vehicles, public transport, and pedestrians. It helps in showing traffic flows through a road network and to handle traffic management issues. It offers a comprehensive model for vehicular network. Another popular simulator is Omnet++ as reported in the work of [38] and [39]. It is a C++ based framework and supports various network types, including vehicular networks. There is another tool called 'Veins' as reported in [40] that is found in use for ICN based network. It is another open source framework for running vehicular network simulations under different scenarios. It is based on OMNeT++ and SUMO which supports the traffic management up to a great extent. However, through the review of existing works it is found that the *ns*-3 based *ndnSim* is the highly used simulator for ICN networks. The *ndnSim* is built upon *ns*-3 designed specially to simulate ICN. It also allows researchers and developers to experiment with various ICN forwarding strategies and protocols with tracing and analysis traffic flow. Looking at the popularity of *ndnSim*,the performance of the proposed algorithm is evaluated through a simulation testbed developed in *ndnSim*-2.0. Details of the implementation along with the results, are discussed in this section.

B. SIMULATION SETUP

The smart vehicles are designed following the model presented in [41]. The nodes are integrated with an IEEE 802.11a interface and employ Orthogonal Frequency Division Multiplexing (OFDM) modulation in the physical layer. The data transmission rate is set to 24 Mbps, with a transmission power of 5dBm. Each node has a cache size of maximum 20 named contents with a content size of 5000 bytes each. By default, it uses Least Recently Used (LRU) algorithm as cache replacement policy as defined by *ndnSim*-2.0. The proposed scheme is deployed using 500 uniquely named contents. A total of 50 nodes are placed within an area of 1000x1000 and are allowed to move according to the fluid flow model. The speed and direction of the vehicles vary based on specific experimental conditions as detailed in individual experiment.

To assess the performance of the proposed GCF protocol, it is compared with Bargain Game based forwarding, as described in [28] (labeled as BGF in the graphs), and with Flooding [42]. The study in [28] introduces an interest forwarding approach for ICVN modeled as a Bargain Game (BG). Flooding, on the other hand, is a broadcast method for forwarding interest packets to its many content ICVN implementations. Both BGF and Flooding forwards the interest packet without the help of FIB table. The BGF forwards the interest to a set of selected neighbors based on a Bargain game played between the forwarder node and its neighbor. Depending on the result of the played deal a neighbor is either selected for forwarding interest of rejected. On the other hand, in Flooding, a forwarder node passes the interest packet to all its neighbors. The proposed protocol works in the similar manner and forwards the interest to a cluster head without consulting any FIB table. Comparing the new protocol with flooding helps to highlight the advantages of a guided forwarding approach and comparing with BGF provides an insight about its efficiency with respect to similar solutions.

C. EVALUATION METRICS

For the analysis of the proposed algorithm certain vital parameters are evaluated in a simulation testbed. The definition and relevance of these parameters are briefly discussed below.

1) CACHE HIT RATIO (CHR)

This is a measure of the ratio of the total content request generated (t_{Req}) to the count of retrieving the same from the intermediate cache (s_{ICR}). So, the ratio $\frac{t_{Req}}{s_{ICR}}$ is recorded for various experiments and depicted in concerned graphs. A higher cache hit ratio is desirable and indicates that a better forwarding approach of interest is adopted. However, it is influenced by the caching of contents in the network. Once the contents are sufficiently cached (over time), an efficient interest forwarding technique will significantly improve the performance of the network operation.

2) END-TO-END LATENCY (E2E)

It is the measure of total time taken to receive a content by a consumer since the interest is generated. It is computed as the sum of the time taken for the request to reach the content provider (intermediate source or the content producer) and the content to reach the consumer. The E2E delay includes the computation time of neighbor selection in all the nodes in the path from consumer to the content location. This metric is essential for assessing the performance of a forwarding strategy from the consumer's perspective. Lower the E2E latency better is the performance in terms of user satisfaction.

3) SERVER HIT RATIO (SHR)

This metric denotes the fraction of the content requests (i.e., the interest packets) that reach the content producer or actual server. The success of ICN in general and its applications are determined by the fact that the network is capable to serve user requests from the intermediate cache rather than getting the data from the content server. That is why observation of this metric is important for determining the effectiveness of a caching strategy as well as an interest forwarding strategy from a network efficiency perspective. A lower server workload means less burden on the original content source and less network traffic for content retrieval.

4) LOSS OF INTEREST PACKETS (LIP)

This parameter gives a measure of the amount of interests lost during the content retrieval process. The interests are lost due to the movement of the vehicle from its location at the time of delivery of the content. By observing the said parameter, the impact of mobility on the forwarding technique is examined. If the mobility in not handled adequately, the node (i.e., the vehicles) moves away from the location and data could not be delivered. Hence, the mobility pattern is also to be taken care of in designing the forwarding protocol. It is computed as the ratio or total interests generated to the interests served.

5) PROTOCOL OVERHEAD (POH)

Overhead is the analysis of a forwarding protocol in terms of interest packets. A vehicular node forwards an interest packet to more than one neighbor. Although the proposed protocol restricts the interest forwarding maximum to two neighbors, still few of these interests cannot retrieve content on time. So, these failed interests are considered as network overhead. In the calculation of overhead, the total interest packets including the transmission of unsuccessful are taken into consideration. However, the transmission of the content is not counted in the overhead.

6) NETWORK THROUGHPUT (NTP)

It refers to the amount of content chunks successfully transmitted over the ICVN from the content cache to the consumer in a given period of time. It is measured in terms of bandwidth consumed due to the flow of interest packets as well as the contents in the stipulated time of simulation. The objective of recording this parameter is to examine the effectiveness of the proposed protocol in terms of resource utilization such as bandwidth. It represents the actual performance of a network and is often lower than the network's maximum bandwidth due to protocol overhead. It essentially captures how efficiently a network can handle the flow of data in context of the interest forwarding protocol. An efficient forwarding scheme finds the content in a short distance and hence both the interest and the data travel a shorter distance. It reduces both the bandwidth consumption and network load.

VII. RESULTS AND DISCUSSIONS

Simulated results with reference to the discussions carried out in Section VI are presented in this section along with an analysis of the recorded data. During the analysis, the range of vehicle speed and density is considered rather than specific quantitative values. Table 2.(a) and Table 2.(b) are used for speed and density range of vehicles during various experiments. Individual results are explained below.

TABLE 2. Speed and density range.

(a)

Class	Speed range
Low	20-40 Km/Hr
Medium	40-70 Km/Hr
High	70-120 Km/Hr

(b)

Class	Density range
Sparse	2-3 vehicles in 50m
Moderate	4-8 vehicles in 50m
Dense	8 and above in 50m

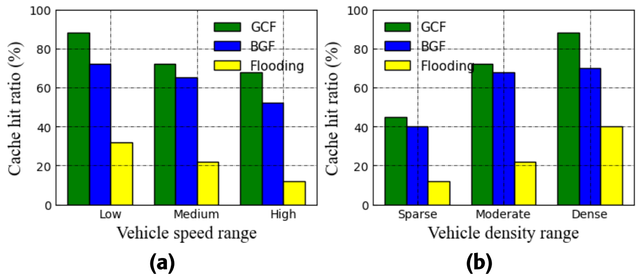

FIGURE 4. Comparison of CHR. (a) For varying vehicle speed. Vehicle density kept in medium 4-8 vehicles per 50 meters. (b) For varying vehicle density. Vehicle speed is kept at medium 40- 70 Km/hr.

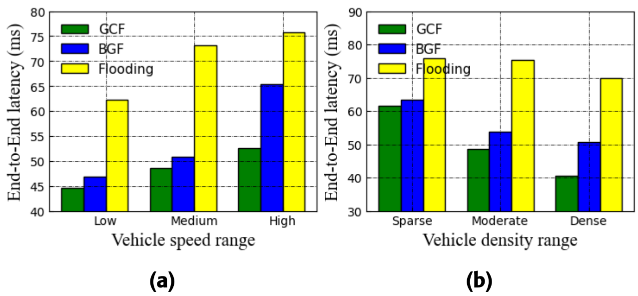

FIGURE 5. Comparison of E2E latency. (a) For varying vehicle speed. Vehicle density kept in medium 4-8 vehicles per 50 meters. (b) For varying vehicle density. Vehicle speed is kept at medium 40- 70 Km/hr.

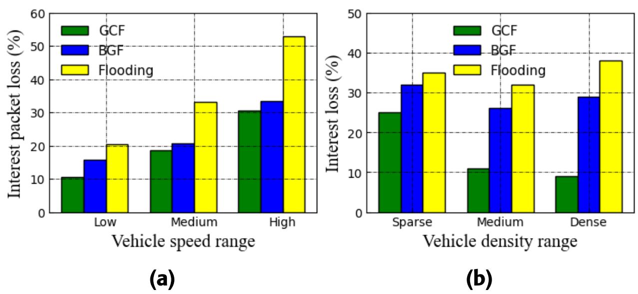

FIGURE 6. Comparison of LIP latency. (a) For varying vehicle speed. Vehicle density kept in medium 4-8 vehicles per 50 meters. (b) For varying vehicle density. Vehicle speed is kept at medium 40-70 Km/hr.

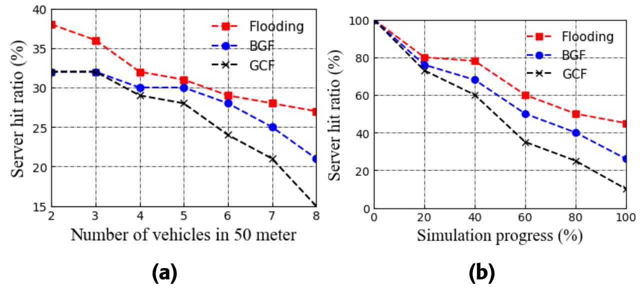

FIGURE 7. Comparison of SHR. (a) For varying vehicle density. Vehicle speed is kept at medium 40-70 Km/hr. (b) For progress in simulation. Vehicle speed is kept at medium 40-70 Km/hr and density at 4-8 vehicles per 50 meter.

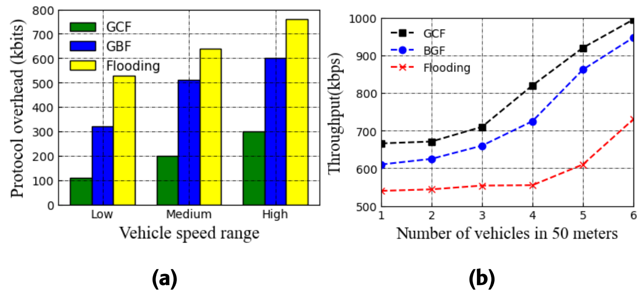

FIGURE 8. Comparison of protocol overhead and throughput. (a) For varying vehicle speed. Vehicle density is kept at 4-6 vehicles in 50 meter range. (b) Against vehicle density. Vehicle speed is kept at medium 40-70 Km/hr.

A. COMPARISON OF CHR

To record the cache hit ratio, 20% of vehicular nodes are modeled as consumers and two RSUs are modeled as content producers. The said parameter is computed by counting the total number of interests initiated and the services made from intermediate nodes other than producer RSUs.Experimental observations are plotted against speed range in Fig. 4(a) and against density range in Fig. 4(b). The recorded data shows that performance is better in low speed and high density. All protocols have high cache hit ratio in this situation. Protocol wise, the new approach, GCF outperforms both BGF and Flooding. The GCF groups the vehicles into clusters and the group leader has information about content cached in the group. Hence, a large range of content space is covered by the GCF and subsequently, more cache hit occurs. The BGF sends the interest to either a single or two neighbors, so sometimes the interest could not find the content in the cache. The Flooding does not use the heuristic of the topology and shows low cache hit ratio.

B. COMPARISON OF E2E LATENCY

The same experimental setup as it is done for cache hit is also used to compute E2E delay. The average time of all the generated interest packets and the delivery of contents to the consumer is recorded. The result of E2E latency is depicted against speed range in Fig. 5(a) and against vehicle density in Fig. 5(b). Overall, both GCF and BGF performs well over Flooding. With the increased speed and decreased density E2E delay increases. Protocol wise, in low and medium range speed, GCF shows nearly 5-7% improvements over BGF. However, with high speed range, the new scheme is showing nearly 18-20% improvement in E2E latency over BGF. Similarly, for sparse and medium density, GCF shows 3-5% better results. However, with high density of vehicles it shows nearly 20-25% improvement. Due to better node management system adopted in the proposed algorithm contents are found in a lesser time. This makes the protocol better in E2E latency.

C. LIP COMPARISON

This parameter is the measure of mobility support by the GCF. For the purpose the speed of the nodes are increased and a limited number of interests are generated. The observation is made on the consumer with a vehicle of higher speed and recorded the content delivery count. The Fig. 6(a) and Fig. 6(b) demonstrates the interest loss in the simulation. Observation depicts that loss decreases in low speed and high density. The GCF performs best followed by BGF. Improvement in low to medium speed is nearly 100% for GCF and 70% for BGF. However, with high speed the improvement is 40% for both the protocols. For low and medium density loss rate dropped by 20% but for high density loss reduces by 5%. Due to the interest delivered to the group leader, many nodes which are not reachable in linear topology is easily connected via the leader. Since, interests which are not replied are considered as loss, in GCF such loss is considerably low as many many of the nodes are reachable through the leader. This is the reason that the GCF shows a better performance.

D. COMPARISON OF SHR

The server hit ratio is computed by allowing nearly 15-20% of vehicular nodes to generate interest packets. Two RSUs are modeled as content producer. The said parameter is computed by counting the total number of interests initiated and the services made from the content producing RSUs. The SHR is plotted against vehicle density in Fig. 7.(a). For the observation the vehicle speed is kept between 70-80Km/hr. Observation states that the SHR decreases with the increase in vehicle density. Among the protocols, proposed GCF performs best. Fig. 7.(b) shows the results against progress in simulation. At the beginning of the simulation the SHR is is 100% for all the protocols as the contents are not cached by nodes. However, with the progress in simulation SHR drops. The GCF shows the best performance after completion of around 80% simulation. Clustering of vehicular nodes in the proposed technique increases the range of contents search space and makes more successful cache hit. Hence less content request reaches the server. Since other benchmark protocols do not employ grouping of nodes hence more server hit ratio is noticed.

E. COMPARISON OF OVERHEAD AND THROUGHPUT

The overhead is computed by counting the amount of traffic load on the network due to interest packets. The amount of load per second is recorded for the projected results. The same experimental setup is also used for computing the throughput. Protocol overhead is shown for varying vehicle speed in Fig. 8.(a). Observation reveals that the overhead increases with the increase in speed. For GCF shows nearly 60% increase in throughput, however for other protocols it shows more than 100%. Hence, GCF is better than other two. Throughput is plotted against vehicle density in Fig. 8.(b). Throughput increases with the increase in vehicle density. Car density between 3-4 shows nearly 150% improvement in throughput for GCF. Overhead is less in GFC because the group leader handles interest packets for a large number of vehicles and it reduces the cost of propagation. As the rang of content search increases the through put is high.

VIII. CONCLUSION

A Graph based Cooperative Forwarding (GCF) technique is described in this paper. The proposed GCF models the network as a graph, and the graph is partitioned to form a group of vehicles. Every group selects a leader based on their rank to coordinate in global level. Any interest forwarding, or data retrieval in the network takes place through the group leaders. Performance evaluation of the proposed GCF is carried out through simulation in *ndnSim*-2.0 and compared with other benchmark algorithms Bargain Game based Forwarding (BGF), and flooding. Various parameters used in the comparison are end-to-end latency, interest loss rate, network overhead, throughput and server hit ratio. Quantitatively, the proposed GCF shows nearly 10% improvement in end-to-2nd latency, 40% improvement in interest packet loss, and 60% improvement in network overhead. Further it also shows a superior performance in server hit ratio compared to other protocols. The GCF group vehicles into clusters and group leader records the content information within a group. Hence, a large range of content space is covered by the GCF and subsequently better performance in terms of observed parameters such as retrieval time, interest success, cache hit, etc., are noticed. On the other hand, the BGF send the interest to either a single or two neighbors. So, interest loss occurs, and more delay is noticed. Flooding does not use the heuristic of the topology and hence shows lower performance. These improvements indicate that GCF is a promising approach for optimizing data dissemination in vehicular networks, contributing to more responsive and scalable ICVN deployments. In the experimentation of the protocol, the forwarding algorithm along with the subsequent supporting functionalities such as caching and leader selection algorithms are implemented as a part of the mobility class in *ns*-3. The protocol is to be integrated as a forwarding module in NDN architecture for real time deployment supporting intelligent transport systems.

The proposed GCF does not incorporate security provisioning except the one provided by the NDN architecture. Hence, only authenticity and integrity are preserved in the communication of content. However, the privacy of searched content is not ensured in GCF. The security provisioning of GCF in terms of privacy is planned to be addressed in future work. There are new directions of ICN research integrating reinforcement learning [17], [43] is reported recently. The research idea of this paper is planned to extend with this new concept for interest forwarding in an cluster based vehicular environment.

ACKNOWLEDGMENT

Shashikant P. Patole would like to thank Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates, for its financial support through the internal fund for high-quality publications.

REFERENCES

[1] R. Callon, "Use of OSI IS-IS for routing in TCP/IP and dual environments," Digit. Equip. Corp., USA, Tech. Rep. 1195, 1990.

[2] S. Fayyaz, M. A. Ur Rehman, M. S. U. Din, M. I. Biswas, A. K. Bashir, and B.-S. Kim, "Information-centric mobile networks: A survey, discussion, and future research directions," *IEEE Access*, vol. 11, pp. 40328–40372, 2023.

[3] H. Asaeda, K. Matsuzono, Y. Hayamizu, H. H. Hlaing, and A. Ooka, "A survey of information-centric networking: The quest for innovation," *IEICE Trans. Commun.*, no. 1, pp. 139–153, 2024.

[4] M. Amadeo, C. Campolo, and A. Molinaro, "Information-centric networking for connected vehicles: A survey and future perspectives," *IEEE Commun. Mag.*, vol. 54, no. 2, pp. 98–104, Feb. 2016.

[5] M. Royer, A. Pirovano, and F. Garcia, "Survey on context-aware publish/subscribe systems for VANET," in *Proc. Int. Workshop Commun. Technol. Vehicles*, Jan. 2013, pp. 46–58.

[6] Z. Xia, J. Wu, L. Wu, Y. Chen, J. Yang, and P. S. Yu, "A comprehensive survey of the key technologies and challenges surrounding vehicular ad hoc networks," *ACM Trans. Intell. Syst. Technol.*, vol. 12, no. 4, pp. 1–30, Jun. 2021.

[7] N. Dutta, "An approach for FIB construction and interest packet forwarding in information centric network," *Future Gener. Comput. Syst.*, vol. 130, pp. 269–278, May 2022.

[8] L. Wang, A. Hoque, C. Yi, A. Alyyan, and B. Zhang, "OSPFN: An OSPF based routing protocol for named data networking," Univ. Memphis, USA, Tech. Rep. NDN-0003, 2012.

[9] M. Safwat, A. Elgammal, E. G. AbdAllah, and M. A. Azer, "Survey and taxonomy of information-centric vehicular networking security attacks," *Ad Hoc Netw.*, vol. 124, pp. 1–15, Jan. 2022.

[10] N. Dutta, N. Jadav, S. Tanwar, H. Sarma, and P. Emil, *Cyber Security: Issues Current Trends*. Cham, Switzerland: Springer, 2022, pp. 13–174.

[11] N. Dutta, N. Jadav, N. Dutiya, and D. Joshi, *Using Honeypots for ICS Threats Evaluation*. Switzerland: Springer, 2020, pp. 3–25.

[12] H. Khelifi, S. Luo, B. Nour, H. Moungla, Y. Faheem, R. Hussain, and A. Ksentini, "Named data networking in vehicular ad hoc networks: State-of-the-art and challenges," *IEEE Commun. Surveys Tuts.*, vol. 22, no. 1, pp. 320–351, 1st Quart., 2020.

[13] A. Benmoussa, C. A. Kerrache, N. Lagraa, S. Mastorakis, A. Lakas, and A. E. K. Tahari, "Interest flooding attacks in named data networking: Survey of existing solutions, open issues, requirements, and future directions," *ACM Comput. Surv.*, vol. 55, no. 7, pp. 1–37, Jul. 2023.

[14] A. A. Prates, I. V. Bastos, and I. M. Moraes, "GeoZone: An interest-packet forwarding mechanism based on dissemination zone for content-centric vehicular networks," *Comput. Electr. Eng.*, vol. 73, pp. 155–166, Jan. 2019.

[15] R. Tizvar and M. Abbaspour, "A density-aware probabilistic interest forwarding method for content-centric vehicular networks," *Veh. Commun.*, vol. 23, pp. 10–26, Jun. 2020.

[16] F. Gu, Y. Zhang, and H. Zhu, "A congestion-aware interest forwarding scheme for information-centric vehicular networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 21, no. 6, pp. 2280–2291, Jun. 2020.

[17] S. Sharma and S. Garg, "A reinforcement learning based adaptive interest forwarding scheme for information-centric vehicular networks," *IEEE Internet Things J.*, vol. 9, no. 8, pp. 7315–7327, Aug. 2022.

[18] D. Li, T. Song, Y. Yang, and I. R. Ul, "A reliable and efficient forwarding strategy in vehicular named data networking," *J. Commun. Netw.*, vol. 22, no. 4, pp. 348–357, Aug. 2020.

[19] J. Wang, J. Luo, J. Zhou, and Y. Ran, "A Mobility-Predict-based forwarding strategy in vehicular named data networks," in *Proc. GLOBECOM IEEE Global Commun. Conf.*, Dec. 2020, pp. 01–06.

[20] S. Shi, J. Li, H. Wu, Y. Ren, and J. Zhi, "EFM: An edge-computing-oriented forwarding mechanism for information-centric networks," in *Proc. 3rd Int. Conf. Hot Inf.-Centric Netw. (HotICN)*, Dec. 2020, pp. 154–159.

[21] H. Al-Omaisi, E. A. Sundararajan, R. Alsaqour, N. F. Abdullah, K. A. A. Bakar, and M. Abdelhaq, "IDTracS: An interest-data-flow tracking-based forwarding scheme for vehicular named data networks," *J. Supercomput.*, vol. 79, no. 15, pp. 16580–16615, Oct. 2023.

[22] G. Araujo and L. Sampaio, "A scalable, dynamic, and secure traffic management system for vehicular named data networking applications," *Ad Hoc Netw.*, vol. 158, May 2024, Art. no. 103476.

[23] D. M. Doe, D. Chen, K. Han, H. Wang, J. Xie, and Z. Han, "DSORL: Data source optimization with reinforcement learning scheme for vehicular named data networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 24, no. 10, pp. 11225–11237, Oct. 2023.

[24] S. Lee, Y. Jung, Y.-H. Park, and S.-W. Kim, "Design of V2X-based vehicular contents centric networks for autonomous driving," *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 8, pp. 13526–13537, Aug. 2022.

[25] X. Bai, S. Liu, P. Zhang, and R. Kantola, "ICN: Interest-based clustering network," in *Proc. 4th Int. Conf. Peer Peer Comput.*, Aug. 2004, pp. 219–226.

[26] L. C. Fourati, S. Ayed, and M. A. B. Rejeb, "ICN clustering-based approach for VANETs," *Ann. Telecommun.*, vol. 76, nos. 9–10, pp. 745–757, Oct. 2021.

[27] S. S. Beri and N. Dutta, "Evolutionary game based interest forwarding in information centric vehicular networks," *Veh. Commun.*, vol. 47, pp. 1–20, Jun. 2024.

[28] N. Dutta, "A bargain game theory assisted interest packet forwarding strategy for information centric network," *J. Netw. Comput. Appl.*, vol. 209, Jan. 2023, Art. no. 103546.

[29] N. Dutta, "Genetic algorithm-based interest forwarding for information centric vehicular networks," *Int. J. Commun. Syst.*, vol. 38, no. 8, May 2025, Art. no. e70091.

[30] L. Zhang, A. Afanasyev, J. A. Burke, V. Jacobson, K. claffy, P. Crowley, C. Papadopoulos, L. Wang, and B. Zhang, "Named data networking," *ACM Comput. Commun. Rev.*, vol. 44, no. 3, pp. 66–73, Jul. 2014.

[31] V. D. Blondel, J.-L. Guillaume, R. Lambiotte, and E. Lefebvre, "Fast unfolding of communities in large networks," *J. Stat. Mechanics: Theory Exp.*, vol. 2008, no. 10, Oct. 2008, Art. no. P10008.

[32] M. E. J. Newman, "Modularity and community structure in networks," *Proc. Nat. Acad. Sci. USA*, vol. 103, no. 23, pp. 8577–8582, Jun. 2006.

[33] L. Breslau, P. Cao, L. Fan, G. Phillips, and S. Shenker, "Web caching and Zipf-like distributions: Evidence and implications," in *Proc. IEEE INFOCOM Conf. Comput. Commun. 18th Annu. Joint Conf. IEEE Comput. Commun. Societies. Future is Now*, vol. 1, Mar. 1999, pp. 126–134.

[34] N. Dutta, S. K. Patel, O. S. Faragallah, M. Baz, and A. N. Z. Rashed, "Caching scheme for information-centric networks with balanced content distribution," *Int. J. Commun. Syst.*, vol. 35, no. 7, pp. 348–357, May 2022.

[35] R. Hou, S. Zhou, M. Cui, L. Zhou, D. Zeng, J. Luo, and M. Ma, "Data forwarding scheme for vehicle tracking in named data networking," *IEEE Trans. Veh. Technol.*, vol. 70, no. 7, pp. 6684–6695, Jul. 2021.

[36] J. Rabari and A. R. P. Kumar, "FIFA: Fighting against interest flooding attack in NDN-based VANET," *Int. Wireless Commun. Mobile Comput.*, vol. 2021, pp. 1539–1544, Jun. 2021.

[37] K. Fang, B. Yang, H. Zhu, Z. Lin, and Z. Wang, "Two-way reliable forwarding strategy of RIS symbiotic communications for vehicular named data networks," *IEEE Internet Things J.*, vol. 10, no. 22, pp. 19385–19398, Nov. 2023.

[38] S. Zhang, J. Li, H. Luo, J. Gao, L. Zhao, and X. Sherman Shen, "Low-latency and fresh content provision in information-centric vehicular networks," *IEEE Trans. Mobile Comput.*, vol. 21, no. 5, pp. 1723–1738, May 2022.

[39] J. Wang, J. Luo, Y. Ran, J. Yang, K. Liu, and S. Guo, "Towards predictive forwarding strategy in vehicular named data networking," *IEEE Trans. Veh. Technol.*, vol. 72, no. 3, pp. 3751–3763, Mar. 2023.

[40] A. M. de Sousa, F. R. C. Araújo, and L. N. Sampaio, "A link-stability-based interest-forwarding strategy for vehicular named data networks," *IEEE Internet Comput.*, vol. 22, no. 3, pp. 16–26, May 2018.

[41] X. Guo, Y. Chen, L. Cao, D. Zhang, and Y. Jiang, "A smart forwarding scheme for the interest packet in VNDN," in *Proc. 2nd Int. Conf. Hot Inf.-Centric Netw. (HotICN)*, Dec. 2019, pp. 7–12.

[42] A. Ioannou and S. Weber, "Towards exploring the benefits of scope-flooding in information-centric networks," in *Proc. IEEE 40th Conf. Local Comput. Netw. (LCN)*, Oct. 2015, pp. 193–196.

[43] I. V. Bastos and I. M. Moraes, "A forwarding strategy based on reinforcement learning for content-centric networking," in *Proc. 7th Int. Conf. Netw. Future (NOF)*, Nov. 2016, pp. 1–5.

BERI SURYA SAMANTHA (Student Member, IEEE) is currently pursuing the Ph.D. degree with the Department of Computer Science and Engineering, SRM University, Andhra Pradesh. Her research focuses on information centric networks, particularly in routing and forwarding interest packets in information centric vehicular networks (ICVN) and named data networks (NDN), utilizing the ndnSIM simulator.

NITUL DUTTA (Senior Member, IEEE) received the B.E. degree in CSE from Jorhat Engineering College, Assam, the M.Tech. degree in IT from Tezpur University, Assam, and the Ph.D. (Engineering) degree in computer networking from Jadavpur University, West Bengal, in 2012. He worked as a Postdoctoral Fellow (PDF) with Jan Wyzykowski University, Polkowice, Poland. He is currently working as an Associate Professor with the Department of CSE, Mahindra University, Hyderabad, India. He has authored or co-authored more than 35 papers in journals of repute and two reference books in Springer. His current research interests are information centric networks, ipv6-based networks, and cognitive radio networks. He served as the Vice-Chair for the IEEE CIS, Gujarat Section.

RAJESH MAHADEVA (Member, IEEE) received the Ph.D. degree in artificial intelligence from Indian Institute of Technology (IIT) Roorkee, India, in 2022. From 2011 to 2017, he was an Assistant Professor with the Technocrats Institute of Technology (TIT), Bhopal, and Marwadi University (MU), Rajkot, India. From September 2022 to July 2024, he was a Postdoctoral Fellow with Khalifa University, Abu Dhabi, United Arab Emirates. He is currently an Associate Professor with the Department of Computer Science and Engineering, Manipal Institute of Technology, MAHE, Manipal, India. His research interests include applications of data science, artificial intelligence, and machine learning.

SHASHIKANT P. PATOLE (Member, IEEE) received the B.Sc., M.Sc., and M.Phil. degrees in physics from the University of Pune (UoP), India, and the Ph.D. degree in nanoscience and technology from Sungkyunkwan University (SKKU), Suwon, South Korea, in 2010. Since 2017, he has been an Assistant Professor with the Department of Physics, Khalifa University (KU), Abu Dhabi, United Arab Emirates. Before joining KU, he was an Entrepreneur and a Postdoctoral Researcher with the King Abdulla University of Science and Technology (KAUST), Saudi Arabia. In KAUST, he served as a Founding Member of the Laboratory for Carbon Nanostructures and the Co-Founder of a Graphene Crystal Startup Company.

GHEORGHITA GHINEA (Member, IEEE) received the B.Sc. and B.Sc. degrees (Hons.) in computer science and mathematics and the M.Sc. degree in computer science from the University of the Witwatersrand, Johannesburg, South Africa, in 1993, 1994, and 1996, respectively, and the Ph.D. degree in computer science from the University of Reading, Reading, U.K., in 2000. He is a Professor of Mulsemedia Computing with the Computer Science Department, Brunel University London, Uxbridge, U.K. His research activities lie the confluence of computer science, media and psychology, focusing on building adaptable cross-layer end-to-end communication systems incorporating user multisensorial and perceptual requirements.