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Thesis for the Degree of Ph.D.

Robust Content Retrieval in Future Vehicular Networks

School of Computer Science and Engineering
The Graduate School

Syed Hassan Ahmed

June 2017

The Graduate School
Kyungpook National University
Robust Content Retrieval in Future Vehicular Networks

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School of Computer Science and Engineering
The Graduate School

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International Research Contributions

International Book


Relevant International Journal Publications


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<td>CR</td>
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<td>DSRC</td>
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<td>DONA</td>
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<td>DR</td>
<td>Data Retrieval Rate</td>
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<td>FVN</td>
<td>Future Vehicular Networks</td>
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<tr>
<td>FIB</td>
<td>Forwarding Information Base</td>
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<td>IoT</td>
<td>Internet of Things</td>
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<td>ISP</td>
<td>Internet Service Providers</td>
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<td>ITS</td>
<td>Intelligent Transportation System</td>
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<td>ISR</td>
<td>Interest Satisfaction Rate</td>
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<td>LFBL</td>
<td>Listen First Broadcast Later</td>
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<td>LAL</td>
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<td>MAC</td>
<td>Medium Access Control Protocol</td>
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<td>MGRS</td>
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<td>QoE</td>
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<td>WAVE Short Messaging Protocol</td>
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I. Introduction

Information and communications technologies (ICT) started with the simple concept of communications and became a necessity and part of our everyday lives. ICT has a vital role in enabling ubiquitous connectivity to users with services as well as the things around them. These services include health, transportation, emergency response, shopping, utilities, economy, weather, and so on, and are referred as smart services in this article. Information related to smart services is ubiquitously made available to citizens through varying underlying technologies that make these citizens and services smart to proactively deal with any forthcoming situations. One of the examples of the smart services is the Intelligent Transportation System (ITS) that is mostly investigated for improving the drivers and passengers’ lives on roads and resulted by the ICT involvement in vehicular communications [2].

During the past two decades, researchers from both the academia and the industries have widely explored the applicability, usefulness, and benefits of ICT in the vehicular communications. The prime objective behind those collaborative efforts in the area of vehicular communications is to
make road experience more exciting and safer for both the drivers and as well as the passengers. Initially designed for safety applications like collision avoidance, auto breaking, road condition warning, etc., the vehicular communications scope also covers the non-safety applications as well. For instance, access to the Internet, multimedia sharing, weather forecasting, online gaming, inter-vehicle messaging, the point of interest related advertisements, road congestion information, and infotainment are few examples. Succinctly, these advancements in vehicular communications system meant to alleviate the hazardous situations for people that commute, less hectic, and more entertaining [3]. Before describing the details of vehicular communications, it wouldn’t be unfair to put a bird’s eye view on the relevant communication technologies such as mobile ad hoc networking.

1. Mobile Ad Hoc Networking (MANETs)

The wireless arena has been increasingly investigated during the past decades. We have witnessed a tremendous growth in network infrastructures, availability of wireless applications, and the emergence of wireless communications technologies. Similarly, ad hoc networks have been at-
tenuating a massive amount of attention from researchers, users, and producers’ perspective. Having said that, mobility is an important instinct and need of the ad hoc support of networks. A variety of portable devices such as handheld computers (laptops), cell phones, music players, bluetooth devices, and many more are now an unavoidable part of our lives. To mention few examples, travelers with laptop can surf the Internet from airports and even airplanes, mobile users can cell phone to check email and browse various connected oriented applications, tourists can use GPS installed on the rental cars to smartly move around the new surroundings, and finally we the users can produce our own contents live and post it on the Internet through a number of front end applications like YouTube, Facebook, etc.

For all this, Mobile Ad hoc Networking (MANET) is one of the innovative and challenging areas of wireless networking. As a key step in the evolution of wireless networking, MANET inherits the traditional problems of network such as bandwidth optimization, power control, and transmission quality enhancements.
Table 1-1: MANETs and VNs Characteristics

<table>
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<th>Characteristic</th>
<th>Mobile Ad hoc Network</th>
<th>Vehicular Network</th>
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<tr>
<td>Dynamic Topology</td>
<td>High</td>
<td>Limited to Roads</td>
</tr>
<tr>
<td>Frequently disconnection</td>
<td>High</td>
<td>Very High</td>
</tr>
<tr>
<td>Sufficient Energy</td>
<td>Low, Constraint</td>
<td>Unlimited</td>
</tr>
<tr>
<td>Sufficient Storage</td>
<td>Low, Constraint</td>
<td>Unlimited</td>
</tr>
<tr>
<td>Geographical Support</td>
<td>Limited, costs Energy</td>
<td>Easily Available</td>
</tr>
<tr>
<td>Delay Constraints</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Mobility Prediction</td>
<td>Very Difficult</td>
<td>GPS Assisted Available</td>
</tr>
</tbody>
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2. Vehicular Networks (VNs): A Sub Domain of MANETs

Vehicular Networking is categorized as a sub domain of MANET due to the similar characteristics such as mobility, disrupted connections, and dynamic topologies (Refer Table. 1-1). Generally, the concept of leveraging wireless communication in vehicles has fascinated researchers since the 1980s [1]. In the last few years, we have witnessed a large increase in research and development in this area. Several factors have led to this development, including the wide adoption (and subsequent drop in cost) of IEEE 802.11 technologies; the embrace of vehicle manufactures of information technology to address the safety, environmental, and comfort issues of their vehicles; and the commitment of large national and regional governments to allocate wireless spectrum for vehicular wireless com-
munications. Although cellular networks enable convenient voice communication and simple infotainment services to drivers and passengers, they are not well-suited for certain direct vehicle-to-vehicle or vehicle-to-infrastructure communications. However, Vehicular Networks (VNs), which offer direct communication between vehicles and to and from roadside units (RSUs), can send and receive hazard warnings or information on the current traffic situation with minimal latency.

With the availability since the late 1990s of low-cost, global-positioning system (GPS) receivers and wireless local area network (WLAN) transceivers, research in the field of inter-vehicular communication gained considerable momentum. The major goals of these activities are to increase road safety and transportation efficiency, as well as to reduce the impact of transportation on the environment. These three classes of applications of VANET technology are not completely orthogonal: for example, reducing the number of accidents can in turn reduce the number of traffic jams, which could reduce the level of environmental impact. Due to the importance of these goals for both the individual and the nation, various projects are underway, or recently were completed, and several consortia were set up to explore the potential of VNs. These consortia projects in-
volve several constituencies, including the automotive industry, the road operators, tolling agencies, and other service providers. These projects are funded substantially by national governments. National governments also contribute licensed spectrum, generally in the 5.8/5.9-GHz band and at least in Japan, the 700-MHz band.

The term VANET was originally adopted to reflect the ad hoc nature of these highly dynamic networks. However, because the term ad hoc network was associated widely with unicast routing-related research, there is currently a debate among the pioneers of this field about redefining the acronym VANET to de-emphasize ad hoc networking. Because this discussion has not yet reached consensus, still it is appropriate to refer to vehicle-to-vehicle and vehicle-to-roadside communication based on wireless local area networking technology as a VNs.

1) Technical Challenges in VNs

A central challenge of VNs is that no communication coordinator can be assumed. Although some applications likely will involve infrastructure (e.g., traffic signal violation warning, toll collection), several applications will be expected to function reliably using decentralized communications.
Because no central coordination or handshaking protocol can be assumed, and given that many applications will be broadcasting information of interest to many surrounding cars, the necessity of a single, shared control channel can be derived (even when multiple channels are available using one or more transceivers, at least one shared control channel is required).

Such a one-channel paradigm, together with the requirement for distributed control, leads to some of the key challenges of VN design. The very well-known problem of hidden and exposed terminals is problematic. Clearly, medium access control (MAC) is a key issue in the design of VANETs. Although time division multiple access (TDMA)- and spatial division multiple access (SDMA)-based approaches were proposed, the main focus today is on using the IEEE 802.11 carrier sense multiple access (CSMA)-based MAC for VNs. This is due to availability and cost considerations and accepts the random elements of such a MAC. The bandwidth of the frequency channels currently assigned or foreseen for VN applications ranges from 10 to 20 MHz. With a high vehicular traffic density, those channels easily could suffer from channel congestion. Making use of more than one channel leads to multichannel synchronization problems, in particular for the case of a single transceiver per vehicle.
and to co-channel interference problems. Other challenges are the dynamic network topology based on the mobility of the vehicles and the environmental impact on the radio propagation. The latter must take into account that the low antenna heights and the attenuation/reflection of all the moving metal vehicle bodies provides for adverse radio channel conditions.

All together, VNs must work properly in a wide range of conditions, including sparse and dense vehicular traffic. There is a strong need for adaptive transmit power and rate control to achieve a reasonable degree of reliable and low latency communication. In addition, there is a challenge in balancing security and privacy needs. On the one hand, the receivers want to make sure that they can trust the source of information. On the other hand, the availability of such trust might contradict the privacy requirements of a sender.

2) Socio-Economic Challenges in VNs

Market introduction of direct communication between vehicles is suffering from the network effect: the added value for one customer depends on the number of customers in total who have equipped their vehicle
with VN technology. A key question, therefore, is how to convince early-adopters to buy VN equipment for their vehicles. Many options have been discussed, ranging from enforcement by law, preferred insurance premiums, and attractive deployment applications. In general, it seems likely that some installed roadside infrastructure will be used to lure the very first customers. As Pravin Varayia put it in his ACM VANET 2005 keynote address, by analyzing the cost-benefit gap, one can argue that reception of high value safety messages with almost zero probability (during the market introduction period) might be of smaller value than receiving non-safety announcements available from day one. Still, with respect to the infrastructure on the roadside, backhaul connectivity and IT-management issues arise that might affect many parties (various communities, road operators, etc.), a fact that led to troublesome experiences for those who have tried to set up real-world field tests.

3) Working Principles of VNs

In general, a VN consists of fixed infrastructure nodes and wireless mobile nodes. The fixed infrastructure nodes include the Road Side Units (RSUs), back-end systems to manage network operations and traffic in-
formation, etc. The wireless mobile devices include the on-board units (OBUs) installed in the vehicles and the handheld devices carried by the passengers or commuters traveling in those vehicles or nearby the road.

Communication scenarios in the VN depend on the devices that interact with each other. Inter-vehicle communication, also known as vehicle to vehicle (V2V) communication, is helpful to rapidly share the critical information or warning messages between vehicles to assist drivers. The other communication scenario where vehicles communicate with the fixed infrastructure RSUs is Vehicle to Infrastructure (V2I) communication. Weather, infotainment, traffic conditions and other information is communicated using the V2I communication architecture. Communication architecture where information is exchanged between vehicles and pedestrians, called vehicle to pedestrian (V2P) communication. V2P communicates the information between vehicles and pedestrians about their presence and mobility, especially at the blind spots, road crossings, and so on [4].

Like aforementioned, the spontaneous wireless VN scenario is the subtype of mobile ad hoc network that usually involves V2V and to a certain degree the V2I communication. Unlike traditional wireless ad hoc net-
works, VNs have distinct features that include highly dynamic topology, intermittent link condition, unpredictable network density, frequent and dynamic network partitioning, etc. resulted by the high mobility and dynamic device penetration. In result, it is quite challenging for the researcher to support reliable communication in VNs.

Considering the unique nature of VNs, a specialized protocol suite called dedicated short-range communication (DSRC) protocol along with the wireless access in vehicular environments (WAVE) has been proposed. DSRC and WAVE efficiently support safety applications by periodically exchanging the short messages, called beacons. DSRC basically supports data exchange without the Transmission Control Protocol (TCP) / Internet Protocol (IP) overhead caused by the conventional IEEE 802.11 family [5].

DSRC/WAVE uses IEEE 802.11p standard, the variant of IEEE 802.11a, for physical and Medium Access Control (MAC) layers. IEEE 802.11p guarantees the Quality of Service (QoS), i.e., less delay and better throughput because of it employs the multi-channel network. It uses one Control Channel (CCH) and multiple Service Channels (SCH). All vehicles in the network divide time slots into control and data intervals to negotiate and
communicate information in the network. The network critical messages are communicated by vehicles in the network using the WAVE Short Messaging Protocol (WSMP) that works without TCP/IP layer support. On the other hand, in the case of infotainment systems (i.e., non-safety applications), numerous TCP/IP protocols have been proposed to run on top of the DSRC/WAVE in VNs [6].

However, running IP over IEEE 802.11p brings several technical issues. To solve this, there is rich literature and research in the context of ad hoc networking over IP and a number of routing protocols have been proposed; however, a fundamental limitation in their deployment is the infrastructure support requirement for the purpose of global IP address allocations. Due to the dependence on the IP addresses, today’s Internet communications faces several challenges, including extensive packet lost, particularly in the case of highly mobile devices such as vehicles. Moreover, the dynamic vehicular environment also demands that routes to be recalculated and sessions to be re-established at a higher frequency due to the intermittent connectivity, which is also deemed infeasible [7].

Regardless of the non-safety related applications’ motivation, the main purpose of connecting vehicles is to share the data/content to fulfill the
applications’ requirements [8]. However, due to mobility, which is an intrinsic feature of VNs, makes it difficult to communicate data reliably and efficiently using the existing communication standards directly in VNs. The main reason is that the current standards were originally proposed for static and quasi-static environments. Henceforth, the VN specific communication protocols WAVE/DSRC collectively enable efficient emergency communication between vehicles, RSUs, and pedestrians, but not the non-safety-related information. Despite the fact that these standards tend to support mobility and fast data delivery in VNs, still, the applications (especially non-safety related applications) require destination address to communicate data. Hence, the communication is contingent to the vehicle’s identity (IP and/or MAC address). Data delivery to the farthest vehicles in the network also require identities of intermediate nodes to establish the path. Path establishment, maintenance, and identity assignment in dynamic topology-based VNs is challenging and requires much overhead [9]. From the applications’ point of view, it requires data or content, irrespective of the identity and location of the actual provider or producer. The vehicles also require content regardless of the underlying communication technologies. Additionally, the guaran-
teed and secure connectivity in the intermittent VNs is quite difficult.

To satisfy the information demand of the non-safety VN applications, recently researchers have explored new research direction that employs a simplified domain of future Internet architectures, which is termed as Information-Centric Networking (ICN). ICN is the general class of these new Internet architectures that includes Named Data Networking (NDN) [10], which is one of the famous and widely used ICN architectures. NDN is the extended implementation of another ICN architecture called Content-Centric Networks (CCN) [12] and has been emerged into VNs, called Future Vehicular Network (FVN), as a Future Internet architecture [11][13]. The identity and location of the content generator and/or provider is relinquished and the communication is solely focused on the content itself. In addition to that, NDN does not secure the end-to-end channel but it intrinsically embeds security with the content itself. In result, it avoids additional delays and consumption of network resources to securely and effectively communicate the appropriate content.

Content location independence is achieved by NDN through assigning the unique *names* to the content itself rather than the device(s) and the routing of the content in the network is done using this content *name*. 
A simplified pull-based communication mechanism is used by the NDN to perform communication between the content requesting vehicle or VN device (called \textit{Consumer}) and the vehicle or VN device that holds the copy of the content or generated the content (called, \textit{Provider}). The consumer sends an \textit{Interest} packet containing the name of the desired content and the provider forwards the content to the consumer in a \textit{Data} packet. Along with the content name, the Interest packet also contains NONCE\textsuperscript{1} value to identify the Interest message. On the other hand, the Data message contains the same content name and the embedded security information (signatures) within it. Therefore, instead of securing the connection, the security is inherently augmented with the Data.

Additionally, NDN supports multiple interfaces for a reliable and quick fetching of the required content. Each NDN enabled VN node uses some data structures to perform Interest-Data communication, which includes:

- Content Store (CS) is a cache of Data messages that stores either whole content of chunk(s) of the content that are either generated or received by the vehicle.

- Forward Information Base (FIB) stores the name prefixes and the

\textsuperscript{1}NONCE is a unique identifier used to avoid Interest Looping
corresponding outgoing interface(s) associated with those name pre-
fixes. FIB assists in forwarding process of the Interest packets that
are received from the downstream VN nodes towards the upstream
potential content providers.

- Pending Interest Table (PIT) keeps record of the names and in-
coming interface(s) from where the Interest was received. Each PIT
entry is associated with the holding timer that is used to purge the
PIT entry if the requested content is not received before expiration
of that timer.

It is obvious that all vehicles and RSUs are equipped with wireless in-
terfaces, that are by default of broadcast nature. Therefore, the Interest
and Data are forwarded in a broadcast manner in the FVN. The epi-
demic Interest forwarding in FVN results in traffic congestion due to the
broadcast storm. Recently, there have been several efforts to minimize
the Interest flooding issue, specifically in the mobile environment. Fol-
lowing is the short summary of those schemes, however, they are briefly
discussed in the next section.

Interest broadcast storm in wireless environment can be minimized
when multiple nodes suppress their transmission or only the selected
nodes forward the Interest. Forwarder selection can be distributed or its information is available in the Interest message. One of the Interest broadcast storm mitigation scheme just divides the Interest forwarding region around the Interest forwarder node into four quadrants [14]. It selects the only node in each quadrant to forward the Interest and the same quadrant based phenomenon is used by all those Interest forwarders until the Interest reaches the provider node. Another way to suppress Interest forwarding in VN environment is to select forwarders that have larger Data retrieval rate and distance to the consumer [15]. The alternative method is to select only one vehicle among the immediate neighboring vehicles that have favorable parameters [16]. These parameters can be the number of hops from where the Data was received, current velocity of that vehicle, and the Interest Satisfaction Rate (i.e. data retrieval rate), etc. Another approach is to couple the geo-location of the data with its name in the Interest packet [17]. The fact of the matter is that NDN architecture does not support the geo-location based mapping, thus, additional algorithms for mapping the geo-locations and a namespace is defined to limit the Interest forwarding.

Irrespective of the forwarder selection criteria or selection method,
the prime objective of Interest broadcast storm mitigation schemes is to reduce the number of copies of an Interest forwarded in the network. However, these schemes have to keep track of and consider the updated parameter values in the dynamic and distributed nature VN where the node(s) have unstable and short-term link or obsolete data retrieval rate information. This becomes a more challenging task, whenever there are additional constraints that must be met e.g., QoS requirements of the VN applications.

To mitigate the Interest broadcast storm issue in VNs, a distributed Interest Forwarder selection (DIFS) scheme is presented in this dissertation. DIFS selects two forwarders to forward/rebroadcast the Interest along the highway. The purpose of selecting two forwarders is to spread the Interest packet(s) in both forward and backward directions via best available intermediate vehicles. Thus, alleviating the need for hop-by-hop geo-location information and data retrieval rate sharing. For this purpose, the DIFS lets each vehicle to utilize multiple attributes of the neighboring vehicles and calculate the eligibility of being a forwarder. The proposed DIFS ensures that only those vehicles may forward Interest packets, that have maximum connectivity time and good link quality with the con-
sumer so that the Data retrieval process avoids any additional delays and also the number of retransmissions are controlled.

Following is the summary of the dissertation organization. Future Internet architectures and Vehicular networks are discussed in Chapter II. The working principle of the proposed DIFS is discussed in Chapter III. Simulation environment and results are critically analyzed in Chapter IV. Finally, Chapter V. summarizes the dissertation.
II. Background

In this chapter, a brief overview of VNs and future Internet architectures have been presented. Moreover, the challenges that come across when integrating the Future Internet into the existing VNs (aka FVNs) are also highlighted. Additionally, the detailed working principle of NDN is also discussed. Finally, the strengths and weaknesses of the existing Interest forwarding schemes for FVNs in the literature are presented in this chapter.

1. Future Vehicular Networks

The rapid development and growth in the ICT have brought researchers at the edge to achieve a milestone of connecting everything and provision of all quality services to the users everywhere and anywhere. Today, users prefer to use high bandwidth and expect a great Quality of Experience (QoE) in the communication technologies ranging from cellular, Wi-Fi, WiMAX, Bluetooth to the Internet of Things (IoT) [18]. In a similar fashion, the past two decades have brought tremendous advancements in transportation and automation industries, where the assurance of all
quality information access services along with the safety and security of passengers became the baseline of what is being perceived today. For example, future autonomous vehicles must commute passengers safely and make available safety/non-safety application information to other vehicles on the road as well as the passengers and/or pedestrians [19]. As per the previous discussion, the key applications for the vehicular networks are but not limited to, traffic conditions, accident warnings, pedestrian collision warning system, smart parking, auto-braking system, live video streaming, and live gaming, etc. Hence, it is necessary for the future vehicular networks to adopt new communication technologies to meet those demands and satisfy the information need of these applications. In addition to that, a vehicular network must have to capability to establish a spontaneous network in case of network partition or disconnectivity. Following is the brief overview of the vehicular networks and the widely used future Internet architecture (NDN) and how this future Internet architecture is applied to the vehicular networks.
**Brief overview of Vehicular Networks:**

At present, vehicles are capable of sharing useful critical information including their current location, direction, passengers or goods they are carrying, speed, and so on, with their neighboring vehicles on the road through vehicle to vehicle (V2V) communication, and also pedestrians in their proximity via vehicle-to-pedestrians (V2P) communication, to avoid any possible hazards and collisions. In addition, this information can also be retrieved by nearby traffic or government center(s) through vehicle-to-infrastructure (V2I) communication to get a city-wide or regional mobility view. Furthermore, this information is also made available to individuals to plan trips, companies to track their goods, and the government to regulate traffic in the city. In short, smart transportation is a key strength of all the services expected in smart cities. Those services are, but are not limited to, a centralized fleet management system, real-time traveler information, a smart mass transportation system (SMT), a citywide transportation system, variable speed limit, smart parking, and smart electric vehicle charging. Nevertheless, to enable the aforementioned services, the ICT empowers the electronic devices with connectivity capabilities.
On the whole, ITS requires a plethora of information shared by every connected device(s) to provide all the preceding services to the consumers. However, the consumers are interested in small chunks of information, regardless of the location and identity of the provider(s). Notably, most of the communications take place on the move, where consumers are maneuvering while retrieving the required data. Unfortunately, the current ITS relies on the current IP-based Internet architecture for communication support among all devices, which fails to efficiently disseminate contents in the mobile environment. Additionally, it poses other issues such as inefficient IP assignment to mobile devices, intermittent connectivity, IP-dependent data, inappropriate interface selection, scalability of services, incompetent routing in disruptive networks, and so on.

Fig. 2-1 shows a typical VN scenario consisting RSUs and vehicles and the connectivity or communication patterns e.g., V2V, V2I, and V2P. In V2V communication scenario, vehicles communicate with other vehicles without relying on the infrastructure network elements i.e., RSUs, back-end servers, etc. This communication scenario is more suitable in a situation where a vehicle needs to disseminate emergency or critical
warning messages to other vehicles on the road. As connectivity to the infrastructure results in more delay information dissemination, the vehicles in the vicinity need quick critical information to act upon and avoid hazardous situations.

In V2I communication scenario, information is exchanged between vehicles or vehicles and back-end servers through RSUs. Mostly, non-safety applications use this communication scenario to share or access information related to traffic conditions, parking availability, live video streaming, Internet access, live gaming, etc. Another VN communication scenario that involves information exchanged between vehicles and the pedestrians is V2P (e.g., pedestrian collision warning messages). Vehicles share their heading, location, and other information with the pedestrians in the close proximity to avoid accidents especially at the locations with blind spots, road crossings, etc. In a similar manner, the pedestrians also share similar information with the vehicles to inform drivers about their presence. The future vehicular system can use this information to generate alarms or in a critical situation may activate the auto-breaking system to avoid accidents.

Future vehicular networks cannot be realized without information ex-
change and the main purpose of connecting vehicles is to share the content to fulfill the applications’ requirements. These services and information exchange in future vehicular networks are very challenging to realize because VNs have high volatility and dynamicity due to fast vehicles’ mobility. Even though the special protocol suite (DSRC and WAVE) has been designed and applied in the VNs, it is hard to ensure the low latency, high quality, and secured content or data\textsuperscript{1} retrieval in a robust manner. Despite the fact that these standards tend to support mobility and fast content delivery in VNs, still, the applications require destination address to communicate the content. Hence, the communication is contingent to

\textsuperscript{1}In the context of this dissertation, the terms \textit{data} and \textit{content} are interchangeable.
the vehicle’s identity (IP and/or MAC address) because the DSRC and WAVE protocols use the principles of conventional TCP/IP that were originally designed for a single conversation between two end-to-end entities widely known as “Client” and “Host”.

Content delivery to the farthest vehicles in the networks also require identities of intermediate nodes to establish the path. Path establishment, maintenance, and identity assignment in dynamic topology-based VNs are challenging and generate much overhead [20]. From the applications’ point of view, it requires content irrespective of the identity and location of the actual provider or producer of that content. Additionally, the vehicles require content regardless of the underlying communication technologies and the guaranteed and secure connectivity, which is challenging in the network that has intermittent connectivity.

A detailed discussion about the future Internet architecture, more specifically the NDN, and its working principle is presented in the following section.
**Future Internet Architecture:**

The original design of the Internet was based on providing communication between end-to-end hosts. With the passage of time, penetration of emerging technologies such as broadband and mobile devices changed the notion of the Internet into a people-connecting medium for content exchange. Users search for content over search engines such as Google, watch and upload videos on YouTube, and share data via P2P solutions such as BitTorrent [21]. As discussed before, content is increasing exponentially, and future Internet traffic consists mostly of video data.

Today, different technologies have been deployed for content dissemination and delivery to enable routing of data from a publisher to a consumer. Examples include content delivery services, content delivery networks (CDNs), and peer-to-peer (P2P) networks. These are used in conjunction with service providers such as Internet service providers (ISPs), CDN providers, and most importantly content providers [22]. The evolution of the end-to-end paradigm to content delivery has mainly been compelled by market needs and was not a preplanned decision. However, these technologies provide solutions for content delivery while forming an overlay on top of the existing Internet architecture, which is still end-to-
To mitigate the differences between the end-to-end architecture and the content delivery paradigm, the research community has turned its focus to ICN recently [12, 23]. Carofiglio et al. [21] have defined ICN as “a technique to create a network that can automatically interpret, process, and deliver content independently of its location.” ICN has different names such as data-oriented, content-centric, content-aware, named data, and information-based networking, but the goal is same, that is, disseminating and delivering content by name, not by location [24].

There have been and still are various ICN initiatives working on designing a mechanism that can oust the current host-based architecture. In this regard, both European Union and US agencies for the Internet have been actively involved in starting a number of promising projects. These projects include the data-oriented network architecture (DONA) project at Berkeley [23], the EU-funded publish-subscribe Internet technology (PURSUIT) project [25], the network of information (NetInf) [26], content-centric networking (CCN) by PARC [12], and the US-funded named data networking (NDN) project [10].

The core idea behind information-centric networking (ICN) archite-
tures is that who is communicating is less significant than what data is required. This paradigm shift has occurred due to end-users’ utilization of today’s Internet, which is more content-centric than location-centric, such as file sharing, social networking, or retrieval of aggregated data. The ICN concept was initially proposed in TRIAD [1], which proposed name based information communication. Since researchers have proposed then multiple architectures, please refer Fig. 2-2. In 2006, Data oriented network architecture (DONA) project [2] at UC Berkeley, proposed an ICN architecture, which improved the security, and architecture of TRIAD. The Publish Subscribe Internet Technology (PURSUIT) [3] project, a continuation of the Publish-Subscribe Internet Routing Paradigm (PSIRP) [4] project, both funded by the EU Framework 7 Program (FP7), have proposed a publish-subscribe protocol stack which replaces the IP protocol stack. Another approach, Network of Information (NetInf) project [5] was initially proposed by the European FP7 4WARD [6] project, and further development has been made by the Scalable and Adaptive Internet Solutions (SAIL) [7] project. Similarly, Van Jacobson, a Research Fellow at PARC, proposed Content-Centric Networking (CCN) project [8] in 2007. Currently, work is being carried out to enhance the CCN
architecture called Named Data Networks (NDN) [9].

From all those ICN architectures, NDN is one of the widely used ICN architectures, which is the extended implementation of the CCN architecture. This is the reason that NDN has emerged into VNs (e.g., FVN) and many solutions have been proposed to validate the applicability of NDN into VNs. As stated earlier, NDN basically assigns \textit{name} to the content rather than the device (i.e., vehicles) and that name is used to retrieve the
required content. In NDN, a simplified pull-based communication model is considered, where content requesting vehicle (the Consumer) sends an Interest message and the infrastructure or vehicle with the required content (the Provider) sends back the Data message. Interest contains the required content name and unique NONCE value to identify the Interest message and avoid its duplicate transmission. On the other hand, the Data message contains the same content name and the embedded security information (e.g., digital signature) within it. Therefore, instead of securing the connection between the consumer-provider node pairs, the security is inherently augmented with the Data. Additionally, NDN supports multiple interfaces for a reliable and quick fetching of the required content.

Every NDN enabled vehicle maintains basic data structures, refer Fig. 2-3. The Content Store (CS) is a cache that holds received and forwarded Data temporarily. When receiving an Interest, it is first checked whether the requested Data message can be found in the CS. If this is the case, the Data message can be returned without further propagating the Interest. If Data cannot be found in the cache, the Pending Interest Table (PIT) is consulted. The Pending Interest Table (PIT) records from
which faces Interests have been received and to which faces they have been forwarded. A PIT entry is removed if matching Data comes back or if the Interest expires (based on the Interest lifetime defined in the Interest header). Existing PIT entries prevent forwarding of similar Interests (Interest aggregation). If there is no PIT entry, the Forwarding Information Base (FIB) defines over which faces Interests can be forwarded towards a content source. If there are no matching FIB entries, Interests are dropped. After receiving a Data message in return to an Interest, it is stored in the CS. The freshness Seconds field in the Data header determines how long a cached Data message remains valid until it expires. Based on recorded PIT information, Data messages can be forwarded on the reverse path towards requesters. To enable duplicate suppression, broadcast Data transmissions are scheduled with a broadcast delay. Then, if a node overhears the transmission of the same Data message from another node, it can cancel a scheduled Data transmission.

An Interest is uniquely identified by the NOCNE plus content Name. A node receiving Interest, first checks the NONCE list, to check either the Interest has been recently satisfied or not. If no entry is found in the NONCE list, then record of the received Interest is scanned in the PIT.
to verify that either Interest is still pending or not. Entry in PIT shows that the Interest has already been forwarded. Contrarily, the NONCE and Name are stored in the PIT along with the Interface from where Interest was received (called InFace). PIT entry is purged once the Interest is satisfied. If a node receives multiple copies of the pending Interest, the InFace(s) and other information are aggregated in the PIT record with the same Name. In a scenario where node receives a Data message, first
checks PIT record. Based on the PIT search result, the Data message is either forwarded if there exists an entry in the PIT or dropped otherwise. The satisfied Interest’s record is removed from the PIT and NONCE(s) information is stored in the NONCE list. Interest loop occurs when a node receives another copy of the satisfied Interest from the path with a large delay. Interest loop is avoided by checking the Interest’s record in NONCE list. This operational mechanism of Interest and Data messages is summarized in Fig. 2-4.
Naming:

The naming scheme used in NDN is human-friendly, hierarchical, and resembles URLs. An example is /ait.asia/home/index.html. It is not necessary for NDN names to be human-readable, and there to be DNS names or IP addresses in names. A name could simply be a hash of a string. In NDN, names of NCOs are matched on the basis of longest-prefix match; for example, /ait.asia/home/index.html can be matched and then further explored for any piece of information, for example /ait.asia/home/index.html/v1/s1, which might mean segment-1 from version-1 of that file. A subscriber could then ask for the next segment, e.g., /ait.asia/home/index.html/v1/s2, or could go to the next sibling under that hierarchy. Names should support exploration of prefixed name space and a longest-prefix match mechanism.

Another aspect of NDN naming is that subscribers can ask for content that has not yet been generated. A publisher can advertise a prefix for future content so that anyone interested can ask for it. This enables applications generating content dynamically where the complete set of content chunk names is not known in advance. An example would be a live video stream whose length is unknown a priori.
Mobility:

Handling subscriber mobility in NDN is quite similar to that in other ICN approaches in which the subscriber reissues interest messages from new locations while content against old interest messages is delivered to the old CR. Publisher mobility is difficult to handle because FIB entries have to be restarted when a publisher disconnect from one CR and connects to a new one. It is even more difficult to handle publisher mobility in very dynamic networks such as MANETs. For this purpose, NDN employs the “listen first, broadcast later” (LFBL) protocol [32]. In LFBL, subscribers flood interest messages to all publishers. Any publisher having content against interest checks whether any other publisher has already replied with the content or not, and if not, sends the content to the subscriber.

Benefits of applying NDN in VNs are discussed thoroughly in the recent works [28, 16, 13]. To be precise, the FVN separates the functions that assist in locating and supplying the required content from the underlying communication technologies used by the VNs. Each FVN node maintains the above set of data structures and follows the same Interest-Data forwarding mechanism as NDN, refer Fig. 2-5.
Fig. 2-5. FVN: all nodes maintain NDN data structures and have forwarding plane
1) Applications for Future Vehicular Networks

In this section, a brief overview of the application perspectives of Future Vehicular Networks is presented. Moreover, the following section also presents the candidate’s contribution to FVN.

Future Vehicular Networks in Smart Cities:

A smart city enhances the quality of its citizens’ lives by providing ease of access to ubiquitous services through integration using communication systems at the foundation. Additionally, ITS plays a major role in making a metropolitan area into a smart city. The current IP-based solutions for ITS have slanted the performance due to high demand for data on the move, especially when the consumers become the producers. Meanwhile, NDN has evolved as a promising future Internet architecture and is being
investigated extensively. In the recent work, an NDN architecture has been proposed for ITS in Smart Cities [29]. The idea is to discuss the core functionality of NDN followed by a new architecture proposed for ITS in smart cities. Also, the current and future research challenges are highlighted for NDN-enabled ITS in the context of smart cities.

**Smart Traffic Ticketing System:**

Recently, various applications for VNs have been proposed and smart traffic violation ticketing is one of them. On the other hand, the new Information-Centric Networking (ICN) architectures have been emerged and investigated into VNs, such as Vehicular Named Data Networking (VNDN) aka Future Vehicular Networks in the context of this dissertation. However, the existing applications in VNs are not suitable for VNDN paradigm due to the dependency on a “named content” instead of a current “host-centric” approach. Thus, a design is needed to emerge new architectures for FVN applications.

With such intentions, a smart Traffic Violation Ticketing (TVT) system for FVN is proposed and named as SmartCop [30], that enables a Cop Vehicle (CV) to issue tickets for a traffic violation(s) to the offender(s)
autonomously, once they are in the transmission range of that CV. The ticket issuing delay, messaging cost and percentage of violations detected for varying number of vehicles, violators, CVs, and vehicles speeds are estimated through simulations. In addition, a road map of future research directions is presented in the above-mentioned work for enabling safe driving experience in future cars aided with NDN technology.

**Software Defined Future Vehicular Networks:**

Named Data Networking (NDN) and Software Defined Networking (SDN) share the mutual courage of changing legacy networking architectures. In the case of NDN, the IP-based communication has been tackled down by naming the data or content itself, while SDN proposes to decouple the Control and Data planes to make various services in hands without physical interferences with switches and routers. Both NDN and SDN also support communication via heterogeneous interfaces and has been recently investigated for VNs. The naive VNs are based on the IP-based legacy that is prone to several issues due to the dynamic network topology, etc. In the recently accepted article [31], at first, a light has been put on both SDN and NDN enabled VNs through a Bird’s-Eye. In addition,
for the very first time, a novel architecture that combines SDN functionalities within VNs to retrieve the required content using NDN is also presented. Moreover, a discussion on a number of current research challenges and a precise roadmap that can be considered to jointly address such challenges by the research community has been made.

**Delay Tolerant Vehicular Named Data Networks**

One of the recent works described agent-based content retrieval (ACR) and showed that delay-tolerance in information-centric networks (ICN aka NDN) can be supported without modifications to ICN message processing [46]. This enables seamless operation in well-connected and disruptive networks. Furthermore, the authors have shown that mobile ICN communication does not require all messages to be transmitted via broadcast. Dynamic Unicast (DU) has resulted in faster content retrieval times than broadcast for slow and high node velocities (up to a certain path length). Symmetric Interest-Data forwarding paths have not been identified as limitation because Data messages are returned within milliseconds, i.e., the topology has not changed much.

The observations show that node mobility is not necessarily a dis-
advantage for wireless communication and ICN provides the means to exploit it. While multi-hop communication is faster with high node densities, ACR is superior in low and intermediate node densities where multi-hop communication does not work or results in frequent disruptions. Furthermore, ACR is beneficial for large file sizes and works well even under high mobility, where it can be combined with one-hop DU. Although, in the proposed scenarios, agents had to return to the requester to deliver content, agent delegation and content delivery can also be at different locations as long as both locations can communicate and coordinate with each other.

With the given approach, multi-hop DU and ACR can be combined. A requester could initially try to retrieve content via multi-hop communication and only delegate retrieval to agents if nothing has been found. Because all messages are stored in the same ICN message format, requesters could also retrieve (via multiple hops) content from agents, which were delegated by other requesters. However, concrete mechanisms to combine multi-hop DU with ACR under dynamic (time varying) network condition are still a subject for more investigations.
2. Research Challenges in Future Vehicular Networks

Although NDN provides a promising solution for VNs in the future, extending the model to support vehicular communications is not straightforward. Many open issues must be properly addressed. Therefore, in this section, a number of challenges in FVN/NDN domain are identified, which are new to grab attention from the research community.

1) Naming Schemes and Name Resolution

Content naming is the most important issue in FVN because all the basic NDN functionalities also depend on this feature [33]. There are different naming schemes that have been proposed for FVN that are categorized into different categories including flat, hierarchical, human-readable, hash-based, attribute-based, and hybrid-naming schemes. Which scheme is more suitable for FVN is still an open issue. Thus, in-depth and potential evaluation of each naming approach should be made.

Routing of the information can be achieved purely on the basis of the content name or it may require name resolution. Name resolution service is required for the overlay architecture i.e. NetInf, to resolve the
name into a locator that is used for information communication. The current Domain Name System is not suitable for name resolution system. Therefore, a new resolution technique is required for FVN.

**Channel Constraints and Dynamic Topologies:**

As discussed earlier, the Content retrieval starts with Interest broadcasting over the available network interfaces at the consumer node (e.g., the IEEE 802.11p interface in case of current vehicular devices) and the Interest forwarding is repeated by intermediate relays on the path to the content provider. However, due to the broadcast nature of wireless medium, two conclusions are made: firstly the broadcasting enables packets overhearing, thus helping to cache the content packets and to take decisions about packet forwarding; secondly, it can lead to the well-known broadcast storm problem [34], thus leading us to consequent scalability issues. A robust and bandwidth efficient transport solution is needed to enforce broadcast storm mitigation techniques and also cope with unreliable and maximum error-free wireless links.

Since a node in FVN communicates without the need to obtain the IP address, mobility can be natively supported in this domain. However,
because of connected links only for limited time and extremely fast connectivity dynamics, FVN represents a very unique and challenging environment for mobility management. More demanding approaches should be implemented in order to reduce disruption periods under intermittent connectivity.

2) Caching and Security:

One of the important concerns in FVN is content caching [35, 36, 37]. Currently, the storage is becoming cheaper and portable and many devices such as modern smart phones and tablets have significant storage capacity often reaching several gigabytes. Thus, caching space would not be a big matter, unless considering battery-constrained devices and sensors typically equipped with a few kilobytes memory. Several design options shall be considered to decide where what, and how long to cache data. For instance, in an environment with nodes equipped with heterogeneous capabilities, data storage could be distributed in a few nodes which are more powerful than the others. In a more general case, the popularity, the priority, and the type of contents could make the difference to decide what and how long to cache data.
The basic operation of FVN requires one Interest to be sent per packet, which may result in high signaling overhead [38]. Because of the broadcast shared medium, packets using the same route, or close routes, in opposite directions may severely affect each other: Interests on the forward path may contend with the related content on the reverse path and cause interference between interest and content packets. The storage time of contents inside the CS should be based on the information priority, usability, arrival time, size and many other factors. Each Request or Response message received or forwarded via any interface, must go through FIB and PIT structures of the FVN. There can be thousands of entries that are entered, removed or searched within the FIB and PIT structures. To provide timely communication in FVN, FIB and PIT management, maintenance and searching strategies should be fast and efficient.

Many issues related to security are completely open. It is worth mentioning that many wireless nodes are resource constrained devices and signature and authentication operations can be computationally expensive in terms of time and energy resources consumption.

This further complicates the management of the wireless security framework. Therefore, the use of public key cryptography claims for two
open tasks: (i) definition of an efficient key management methodology that works both with and without infrastructure environment, and (ii) development of computation and bandwidth efficient signature schemes.

3) Routing and Interest Broadcast Storm:

In FVN, multiple Interests asking for successive contents may be pipelined in the shape of sliding window flow control. By properly tuning the Interests transmission rate, traffic flow can be controlled according to the available network resources. However, as aforementioned, the high dynamics of FVN topologies coupled with the channel unreliable and congestion raises many challenges in the application of such a mechanism.

Similarly, the content routing is one of the actively researched parts of FVN [39, 40]. Request and Response forwarding between consumer and provider nodes is the responsibility of the routing scheme. The simplest routing scheme that has been used in the NDN is the breads-crumb technique. However, to achieve QoS in dynamic topologies such as VNs, there is a need for an efficient routing scheme to fulfill requests efficiently.
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3. Literature on Mitigating Interest Broadcast Storm

Like aforementioned, there are a few works mitigating the Interest flooding issue in FVN. These strategies are proposed based on the original NDN strategy [12] and the NDN forwarding strategy [10]. Table 2-1 summarizes the main aspects of these Interest forwarding mechanisms.

Data Location based Interest Forwarding:

Another approach to limit the interest flooding is proposed in [17], named Navigo. In this scheme, the content name in the interest packet is coupled with the geo-location of the data. To achieve these authors define a namespace and mapping algorithm for each geo-location. A namespace is defined using the Military Grid Reference System (MGRS), this namespace provides 100 meters precision in any geo-location. As the NDN architecture does not support the geolocation based mapping, Navigo introduces new outgoing interfaces/GeoFaces and a new rule in the FIB structure is added to bind the name prefix to a geo-location (GeoFace). Furthermore, a Link Adaptation Layer (LAL) is used which provides a mapping of the GeoFace to a geo-location, calculating the shortest path to the provider and also managing the wait time for each interest broad-
When a content is required by a vehicle, the vehicles NDN daemon sends an Interest packet to the corresponding GeoFace in FIB. This interest is passed to the LAL, where the corresponding geo area is determined through GeoFace to area mapping. Finally, the interest packet encoded with the geo-location information in its header is broadcast on the network. Upon receiving this interest, the vehicles LAL decodes and stores the geo-location. Next, the forwarding strategy in NDN daemon decides the fate of the interest packet. If the content is available then it is passed back to the consumer through the reverse path of the interest. In case the vehicle does not have the particular requested content, the NDN daemon sends the interest to the LAL layer, where it is encoded with the new geo-location and then broadcast over the network. In addition, if there is no geolocation in the interest, then the LAL adopts interest flooding using the suppression techniques [11]. Navigo implements a learning and directed flooding strategy to improve the data delivery.
Consumer Location based Interest Forwarding:

Another strategy, **NDN-geo** is presented in [27] which incorporates changes in the NDN architecture by including, (i) the consumer position and the next forwarder in the Interest packet and (ii) the provider position in the data packet. The authors use beacon message in order to acquire the vehicle id and its geo-location and use this information to direct the interest packet. Authors use the data naming design [42] to incorporate the geo-location of the provider in the contents name. In addition, multi-path forwarding [41] is used to target the vehicles at the intersection, thus, avoiding the obstacles in each direction.

Neighbor-Aware based Interest Forwarding:

In [16], the authors proposed **Robust Forwarder Selection (RUFS)**, in which any consumer/forwarder can select only one vehicle among the immediate neighboring vehicles for interest forwarding. Each vehicle maintains a local data structure which contains the list of satisfied interests information by that particular vehicle, termed Recent Satisfied List (RSL). The RSL is exchanged periodically using *beacon* messages with the neighboring vehicles. In addition, the FIB structure is replaced
with a Neighbors Satisfied List (NSL) structure, which is updated by each vehicle periodically on every beacon message received.

The NSL at each of the vehicles is used to aggregate the RSLs received from the neighboring vehicles. The consumer or forwarder applies a multi-criteria decision method to outrank the next ideal forwarder, using the multiple properties of each neighboring vehicle in the NSL as the selection criteria. The criteria used for a particular content are: time since the recent satisfaction of the content, content received hop-count, vehicle velocity. Furthermore, authors introduce a new criterion, the Interest Satisfaction Rate which is the ratio of total satisfied content to the total requested contents, by the vehicle. RUFS forwarder selection process limits the interest flooding in the dynamic VNs scenario. However, it may face issues when a single forwarder is selected by multiple vehicles, leading to collision, congestion, and delay. Also, the additional overhead in the network caused by the beacon messages should be optimized.
III. Distributed Interest Forwarding in Future Vehicular Networks

1. Motivations

Like aforementioned, some efforts have been made to mitigate the Interest flooding issue in NDN forwarding daemon when applied in the wireless network scenario. These strategies are proposed based on the original content centric strategy CCN and the NDN forwarding strategy [10].

These schemes minimize flooding of Interest packet (or minimize the number of copies of Interest propagated in the wireless network) by employing several techniques. As a recap, the Interest broadcast storm mitigation scheme in [14] divides the transmission range of a node into quadrants and selects Interest forwarder in each quadrant to minimize the broadcast storm. Other than the consumer node, every wireless node in the network just forwards three copies of the Interest message. The consumer node selects four farthest wireless nodes in each quadrant. Similarly, the Interest forwarder just skips the quadrant from where it received the copy of and Interest and selects three Interest forwarders in the remaining quadrants for Interest rebroadcasting.
Similarly, a forwarder is selected on the basis of its Data retrieval rate for a given content name and its distance to the consumer [15]. However, these selections fail in a dynamic scenario where the node(s) have unstable and short-term link or obsolete data retrieval rate information.

Another approach is to couple the geo-location of the data with the content name in the Interest packet[17]. However, as the NDN architecture does not support the geo-location based mapping, thus, additional algorithms for mapping the geo-locations and a namespace is defined to limit the Interest forwarding. A similar approach is used in [27], where the position of consumer, producer and next forwarder are used to forward the Interest and Data packets, respectively. However, the addition of location information of the content in the Interest and Data packet leads to the privacy issues and is also in negation to the main idea behind NDN/NDN.

In [16], only one vehicle among the immediate neighboring vehicles is selected on the basis of multiple criteria, i.e., a number of hops from where the content was received, current velocity, and the Interest Satisfaction Rate/data retrieval rate information. However, initially, the Interest is flooded in the network to update the Interest Satisfaction Rate. Further-
more, this scheme may face a scenario where a single forwarder may be selected in a direction opposite to the location of the actual provider, which may incur additional delays. Also, the scheme may forward Interest through the longer path between consumer and provider node pair, which results in less Interest satisfaction rate as well because of the highly dynamic nature of the network.

In short, the schemes available in the literature to mitigate the Interest broadcast storm fail to keep the philosophy of NDN/NDN intact while minimizing the Interest flooding. In this dissertation, therefore, a distributed Interest forwarder selection scheme aka DIFS is proposed, where two forwarders are selected in distributed manner to forward or relay the copy of the Interest packet along the highway. The purpose of selecting two forwarders is to spread the Interest packet(s) in both forward and backward directions of the vehicle via best available intermediate vehicles. Thus, alleviating the need for geo-location information and data retrieval rate, furthermore, this scheme is less susceptible to the dynamic nature of vehicular networks.

Following subsection briefly discusses a state of the artwork, which is used as the conventional scheme, to compare the performance with the
Preliminary Evaluations:

Consider a vehicular network scenario where the consumer vehicle requires content from an unknown provider that is multi-hop away from it, as shown in Fig. 3-3. The consumer generates the Interest packet and the intermediate vehicles forward that Interest until it is received by the provider vehicle. Provider replied with the Data packet containing the requested content. The consumer initiates or generates an Interest with the desired content name and random NONCE value. Instead of blindly forwarding the Interest packet, the proposed forwarder selection selects only one vehicle among the immediate neighboring vehicles in [16]. A vehicle with slow speed, large Interest satisfaction rate and less distance to the consumer in terms of hops is selected. Every vehicle in the network’s stores information about the recently satisfied Interests in a table (RSL-Recently Satisfied List). RSL is exchanged periodically among vehicles by using an extension header in a beacon message.

Information of the selected next-hop forwarder is added in the Interest message and sent over the wireless link. All vehicles will discard
the received Interest except the vehicle with matching information in the Interest packet. This node will perform the same operations and selects the next hop forwarder. For example, the consumer node in Fig. 3-1 selects node 1 as a potential forwarder among its 1-hop neighbors (i.e., 1, 2, 7, . . . , 11) at $t_0$. Likewise, at the next time interval $t_1$, node 1 computes the next hop forwarder, which is 2.

It is evident from the figure that vehicles 1, 2, 7, 9, 10, and 14 forward Interest from consumer to provider node. During the preliminary evaluations, it was observed that a number of satisfied interests by the RUFS is less than the conventional CCN, as shown in Fig. 3-2. The reason for this low-Interest satisfaction is that it unicast forwards Interest towards the provider over a multi-hop wireless and intermittent links.
2. Proposed Solution: Overview

Consider a vehicular network scenario where the consumer vehicle requires content from an unknown provider that is multi-hop away from it, as shown in Fig. 3-3. The consumer generates the Interest packet and the intermediate vehicles forward that Interest until it is received by the provider vehicle. Provider replied with the Data packet containing the requested content. The consumer initiates or generates an Interest with the desired content name and random NONCE value.

In the case of DIFS, the Interest generator or forwarder vehicle $s$ must
also include additional information in the Interest packet, which is its location \((x_s, y_s)\), velocity \(v_s\), and heading \(\theta_s\) in the Interest. All the neighboring vehicles within its transmission range \(T_{r(C)}\) (e.g., 1, 7, 8, 9, 10 and 11) receive the Interest packet, as shown in Fig. 3-3. Upon reception of the Interest packet, they perform all basic NDN operations i.e., CS and PIT search. If both the search operations return a null result, then the respective PIT entry is created and the forwarding decision is made. At this stage, different Interest forwarding strategies apply forwarding decision that either the vehicle should forward the Interest or not and at this stage the proposed DIFS scheme is applied.

Before discussing the Interest forwarding mechanism of DIFS scheme, the data structures are as mentioned below that are used in this process. DIFS maintains the neighbor list (NL) that contains the update information related to neighboring vehicles e.g., neighboring vehicle \(r\)’s current location \((x_r, y_r)\), velocity \(v_r\) and heading information \(\theta_r\), refer Fig. 3-4. The freshness of the information is ensured by the periodic or adaptive exchange of beacon messages, which is a priority.

In DIFS, not all the vehicles that receive a copy of the Interest forward it in the network and neither the Interest message contain any informa-
tion that shows that which vehicle is responsible for forwarding the Interest. When a neighboring vehicle receives an Interest, it first estimates the common neighbors between initiator or forwarder of the Interest and the vehicle itself. For example in Fig. 3-4, when vehicle 10 receives an Interest from $C$, it estimates the common neighbors (i.e., vehicle 9, 11, and $C$) by using the information from NL and Interest packet. Similarly, vehicle 1 approximates the common neighbors, which are 7, 8, and $C$.

Next, DIFS creates the decision list (DL) that hold the information about all the common neighbors, the Interest receiving vehicle itself and excluding the vehicle from which the Interest was received. DL contains the euclidean distance ($D$), relative velocity ($S$), and link duration ($L$) between Interest forwarder and the common neighbors. For example DL of vehicle 10 ($DL_{10}$) contains $D$, $S$, and $L$ of vehicles 9, 10, and 11. These parameters and their computation are discussed in much detail in
After creating the DL, the vehicle computes the final preference value or weight of all the forwarding candidate vehicles in the DL, refer Section 6. for more details. If vehicle’s own preference value is higher than all the neighbors in the DL, then it forwards the Interest. Otherwise, the vehicle discards the Interest. Before forwarding an Interest, a vehicle maintains the PIT entry and adds its heading, location, and velocity information in it. In a similar fashion, the successive vehicles perform the same set of steps to forward the Interest, refer Fig. 3-5. This procedure is followed by
all the vehicles until the producer receives the Interest and replies with the Data packet. At time instance $t_0$, consumer generates the Interest and vehicle 10 and 1 are the potential forwarders, as shown in Fig. 3-6.

At $t_1$, both the vehicles forward the Interest and node 14 and 2 next potential forwarders. In the next interval ($t_2$), 14 forwards the Interest, which is received by the provider ($P$). During this Interest forwarding course, all the forwarders maintain the PIT entries and rest discard the Interest. $P$ replies with the Data packet and all the nodes with PIT entries (e.g., vehicles 14 and 10 with PIT entries), propagate the Data packet
Fig. 3-6. DIFS Interest Forwarding Time-line

towards the $C$. In this manner, the Interest forwarders are selected in a distributed manner and the broadcast storm is mitigated by the proposed DIFS scheme.

In the following sections, a brief discussion on the assumption that is made in the DIFS is carried out in addition to the weight or preference calculation steps along with forwarder selection parameters.

3. Assumptions

Following is the list of assumptions that are made in the DIFS scheme:

1. *Location Information*: DIFS assumes that each vehicle is equipped with GPS module that continuously estimates its location information.
2. **Heading and velocity Information:** in addition to the location, every vehicle also continuously measures its velocity and heading direction information.

3. **Beacon Message:** each vehicle shares its information with the neighboring vehicles through beacons. This information includes the vehicle’s own location, velocity, and heading direction. DIFS assume that all vehicles share this information at regular intervals and each vehicle in the network maintains this updated information in its NL.

4. **Transmission Range:** The final assumption made by the DIFS is that all vehicles are homogenous in terms of the transmission range. For the fair comparison, we have limited the Transmission Range \( (T_r) \) of vehicles to 250m and 500m. In the recent book [45], the authors have performed experiments as shown in the Fig. Fig. 3-7. The results show that if we increase the \( T_r \) from 100m to 750m, the packet success ratio goes down to almost 40%. However, the experimental results proved that upto 500m, the packet success ratio was more than or equal to 70% and if we increase \( T_r \) more than that, it will be effecting the performance overall.
4. Distributed Interest Forwarder Selection Scheme

In following sections, the detailed description about the Interest forwarder selection parameters and procedure is presented.

5. Decision Metrics

As stated earlier that each vehicle keeps the updated $NL_s$ that has all 1-hop neighboring vehicle’s information. This information includes the neighboring vehicle $r$’s location $(x_r, y_r)$, velocity $v_r$, and heading $\theta_r$ information. However, when a vehicle receives Interest packet from $s$, it
forms DL that contains the metrics D, S and L of the common neighbors between s and the vehicle itself.

1) 1-hop Distance

1-hop distance $D(r, s)$ is the euclidean distance between vehicle $r$ and $s$ and is calculated as follows:

$$D(r, s) = \sqrt{(x_r - x_s)^2 - (y_r - y_s)^2} \quad (III.1)$$

The vehicle at the farthest distance is not preferable to be selected as the potential forwarder because there may be the chance of Interest drop due to link breakage.

2) Relative Velocity

Relative velocity $S(r, s)$ of vehicles $r$ and $s$ represents how slow or fast vehicle $s$ is moving with respect to vehicle $r$. The larger the $S(r, v)$, the faster the cars are moving with respect to each other. $S(r, v)$ is computed as:

$$S(r, s) = \sqrt{v_r^2 + v_s^2 - 2v_r v_s \cos \phi} \quad (III.2)$$
, where $\phi$ is the angle between $r$ and $s$ calculated as:

$$
\phi = \begin{cases} 
\tan^{-1}\frac{Y}{X} & X \geq 0, Y > 0 \\
\tan^{-1}\frac{Y}{X} + \pi & X < 0 \\
\tan^{-1}\frac{Y}{X} + 2\pi & X \geq 0, Y < 0 \\
\text{undefined} & X = 0, Y = 0
\end{cases}
$$

, where $X = (x_s - x_r)$ and $Y = (y_s - y_r)$. If the vehicles move at a constant velocity on the road, i.e. $v = v_r = v_s$, the relative velocity of the vehicles is computed as:

$$
S(r, s) = v \sqrt{2 (1 - \cos \phi)}
$$

(III.3)

3) Link Duration

Link duration $L(r, s)$ is the connectivity time between vehicle $r$ and its neighboring vehicle $s$ [43]. It shows time duration during which the link between $r$ and $s$ is intact or they are in transmission range of each other. To estimate the connectivity time between vehicle $r$ and its neighboring vehicle $s$, we compute the communication link duration using the method as [43],
\[
L(r, s) = \frac{\sqrt{(a^2 + c^2) - (ad - bc)^2} - (ab + cd)}{a^2 + c^2}
\]  
\\[\text{(III.4)}\]

, where \(a = v_r \cos \theta_r - v_s \cos \theta_s\), \(b = x_r - x_s\), \(c = v_r \sin \theta_r - v_s \sin \theta_s\),
\(d = y_r - y_s\).

The above metrics are kept in the DL and used by the proposed DIFS to distributively select the potential Interest forwarders in the VNDN. Further detailed description of the selection mechanism steps is presented in the following section.

6. Decision Model to select Interest Forwarder

Conventionally, a consumer vehicle generates the Interest packet containing the required Data name, NONCE value, and the security related information. The consumer first creates an entry of that Interest within its PIT\(^1\) and then forwards it to the outgoing face associate with the longest prefix matching record in the FIB table. Upon receiving any Interest, vehicle first performs the Data name search in the PIT and then CS. If the matching Data is found at the Interest receiving vehicle, then it replies with the Data message towards the consumer node through the

\(^1\)The incoming interface in the PIT entry at the consumer node will be the application interface.
incoming face. The Data message contains the same NONCE and other parameters from the Interest packet along with the requested Data. On the other hand, if CS search fails, the vehicle creates the PIT entry and forwards the Interest further in the network.

Likewise original NDN forwarding daemon, the consumer or any other vehicle $s$ generates or forwards an Interest packet containing the Data name, NONCE, security related header(s), and adds only the GPS header encompassing the $(x_s, y_s), \theta_s$, and $v_s$ information of the vehicle itself. Information in this header does not depend on any underlying communication layers and can independently be acquired and used in the Interest packet. When any vehicle ($r$) within the communication range of the $s$ receives that Interest, first searches the PIT. In case of no prior communication of the same Interest, vehicle $r$ computes the $DL_r$, based on the information available within its $NL_r$ and GPS header information in the Interest packet. The $DL_r$ holds the $D$, $S$ and $L$ of the all the vehicles, including $r$, that are commonly within the transmission range of $s$, $T_s$, and are in $NL_r$.

The road segment information can be obtained from the digital maps or GPS traces. Therefore, the horizontally or vertically oriented road
segment where consumer initiates the Interest. In this case, the Interest receiver \( r \) (e.g., node 2 and 13 in the illustration) vehicle forms the \( DL \) as follows:

\[
DL_r(i) = \{i \in NL_r | x_r > x_s \land x_i > x_s \land d(i, s) < T_s \} \quad (III.5)
\]

\[
DL_r(i) = \{i \in NL_r | x_r < x_s \land x_i < x_s \land d(i, s) < T_s \} \quad (III.6)
\]

The condition in eq. (III.5) and eq. (III.6), resemble the \( DL \) formation condition for Interest receiving vehicle \( r = 10 \) and \( r = 1 \), in Fig. 3-4. Similarly, the \( DL \) is created at every vehicle that receives the Interest. As stated earlier, every entry \( i \in NL_r \) represents the \((x_i, y_i), v_i, \) and \( \theta_i \) about neighboring vehicle \( i \) of node \( r \). Similarly, the \( NL_r \) information is used to compute \( D(i, s), S(i, s), \) and \( L(i, s) \) and respective entries are created in the \( DL_r \). The resulting \( DL_r \) with \( m \) number of common neighbors of \( s \) and \( r \) is shown in III.7. To simplify the notations, \( a_1 = D, a_2 = S, \) and \( a_3 = L \) is substituted in III.7.
\[
DL_r = \begin{bmatrix}
  a_1 & a_2 & a_3 \\
  v_1 & c_{1,1} & c_{1,2} & c_{1,3} \\
  v_2 & c_{2,1} & c_{2,2} & c_{2,3} \\
  \vdots & \vdots & \vdots & \vdots \\
  v_m & c_{m,1} & c_{m,2} & c_{m,3}
\end{bmatrix}
\]  

(III.7)

, where, \( i = 1 \ldots m, j = 1 \ldots 3 \) and \( c_{i,j} \) is the value of attribute \( a_j \) of a vehicle \( i \) that is common neighbor of \( r \) and \( c \). In case of vertical road segment, the \( DL_r \) can be formed using the following conditions:

\[
DL_r(i) = \{i \in NL_r | y_r > y_c \land y_i > y_c \land d(c, i) < T_c\} \quad \text{(III.8)}
\]

\[
DL_r(i) = \{i \in NL_r | y_r < y_c \land y_i < y_c \land d(c, i) < T_c\} \quad \text{(III.9)}
\]

The intersection scenario as well as the slanted road segments can use the combinations of the conditions from eq. (III.5)-eq. (III.6). The final \( DL_r \) may contain \( m \) number of common neighbors and is represented as follows:

When every Interest receiving vehicle completes the computation of \( DL_r \), it finds its relative importance (or weight) using the \( DL_r \) informa-
tion. In case a vehicle has highest relative weight among all the $DL_r$, then it creates the PIT entry and forwards the Interest packet, otherwise it discards the message.

A relative point to consider before weight computation is the parameters $(D, S, L)$ in the $DL_r$. The vehicle itself can be the suitable forward if it is at farther distance, with very less relative speed, and large link duration with respect to the Interest generating node and among all the members of $DL_r$. The prime objective of any Interest forwarding scheme is to quickly reach the provider with less copies of the Interest processed within the network. However, it is quite difficult to compute the weights in presence of the conflicting parameters with non-homogeneous scales (e.g. larger $D$, $L$ and smaller $S$ are preferred). Therefore, the multi-attribute decision making method is applied to find the weight for each entry in $DL_r$. Steps involved in the computation of the relative weights are as follows:

**Step 1.** As $a_1 \ldots a_3$ are the non-homogeneous and conflicting attributes, therefore, they should be normalized to the unit scale and represented in the homogeneous form as:
\[ u_{i,j} = \frac{c_{i,j}}{\sqrt{\sum_{l=1}^{m} c_{i,j}^2}} \text{ where, } i = 1 \ldots m, j = 1 \ldots 3 \quad (\text{III.10}) \]

\[ R_{i,j} = w_j * u_{i,j}, \text{ where } i = 1 \ldots m, j = 1 \ldots 3 \quad (\text{III.11}) \]

where, \( w_j \) is the weighting factor assigned to attribute \( a_j \) and must satisfy the condition: \( \sum_{j=1}^{3} w_j = 1 \). Higher the value of \( w_j \), the more priority to attribute \( a_j \) in the final ranking value of the vehicle. By setting \( w_j = 0 \) means the attribute \( a_i \) is omitted from the Interest forwarder selection process. For example, if \( w_1 = 0.8, w_2 = 0.2, \) and \( w_3 = 0 \), indicates that the 1-hop distance \( D(r, s) \) has higher priority, the \( S(r, s) \) has the lowest priority, and link duration \( L(r, s) \) has not been considered in the forwarder selection. This indicates that 1-hop distance dominates the other attributes in the Interest forwarder selection. The same can be the case with other attributes. Now the question is that which attribute should be prioritized and the answer to that question is the requirement of the application. The application that requires reliable connectivity may assign higher weight to \( L(r, s) \), and so on. Hence, the selection of the weighting factor value for each attribute is application dependent and out of the scope of this work. In the context of this work, every attribute
has the equal importance, therefore, \( w_j = 1/3 \).

**Step 2.** The positive ideal \((V^+)\) and non-ideal \((V^-)\) solutions for each attribute \(a_j\) are calculated as;

\[
V^+ = \{ R^+_1, R^+_2, R^+_3 \}, \quad (\text{III.12})
\]

\[
V^- = \{ R^-_1, R^-_2, R^-_3 \}. \quad (\text{III.13})
\]

For positive attributes\(^2\) i.e., \(a_1\) and \(a_3\), the \(R^+_j = \max \{ R_{i,j}, i = 1 \ldots m \}\) and \(R^-_j = \min \{ R_{i,j}, i = 1 \ldots m \}\) and for the negative attributes i.e., \(a_2\), \(R^+_j = \min \{ R_{i,j}, i = 1 \ldots m \}\) and \(R^-_j = \max \{ R_{i,j}, i = 1 \ldots m \}\).

**Step 3.** In this step, the positive \(\gamma^+\) and negative \(\gamma^-\) coefficient matrices are found, where each element represents the difference between the normalized attribute value of the \(m\) vehicles in the DL table eq. (III.7) with the positive \(V^+\) and negative \(V^-\) ideal solutions. Every element of the positive coefficient matrix, \(\gamma^+ = [\gamma^+_{i,j}]_{m \times 3}\) is computed as:

---

\(^2\)The attribute that has larger the value the better the alternative or the vehicle with large positive attribute is more preferable to forward the Interest.
\[ \gamma_{i,j}^+ = \gamma(u_{i,j}, R_j^+) = \frac{m^+ + \xi M^+}{\Delta_{i,j}^+ + \xi M^+}, \xi \epsilon(0,1) \]  

(III.14)

where, \( \Delta_{i,j}^+ = |u_{i,j} - R_j^+| \), \( m^+ = \min_i \min_j \Delta_{i,j}^+ \), \( M^+ = \max_i \max_j \Delta_{i,j}^+ \),

\( \xi \) is the distinguishing coefficient (\( \xi = 0.5 \)). Similarly, every element \( \gamma_{i,j}^- \) of the the negative coefficient matrix, \( \gamma^- = [\gamma_{i,j}^-]_{m \times 3} \), is computed as:

\[ \gamma_{i,j}^- = \gamma(u_{i,j}, R_j^-) = \frac{m^- + \xi M^-}{\Delta_{i,j}^- + \xi M^-}, \xi \epsilon(0,1) \]  

(III.15)

where, \( \Delta_{i,j}^- = |u_{i,j} - R_j^-| \), \( m^- = \min_i \min_j \Delta_{i,j}^- \), \( M^- = \max_i \max_j \Delta_{i,j}^- \).

**Step 4.** After computing the positive and negative coefficient matrices, now the overall dependence of each alternative (vehicle in the \( DL_r \)) on all attributes is evaluated. To simply state, this step evaluates the average value of relational coefficients at different attributes. For \( i^{th} \) vehicle in the \( DL_r \), the overall dependence on the positive ideal solution and negative ideal solutions is calculated as in eq. (III.16) and eq. (III.17):

\[ G_i^+ = \frac{1}{n} \sum_{j=1}^{n} \gamma_{ij}^+ \]  

(III.16)

\[ G_i^- = \frac{1}{n} \sum_{j=1}^{n} \gamma_{ij}^- \]  

(III.17)
Step 5. The overall weight of each member of the $DL_r$ is calculated as:

$$C_i = \frac{G_i^+}{G_i^+ + G_i^-}$$ \hspace{1cm} (III.18)

Step 6. Every vehicle that receives the Interest, calculates the $C$ from its $DL_r$. The node $f$ can only forward the Interest, if its own rank is higher than all the common neighbors of $r$ and $s$:

$$C_f = \max \{C_i\}, \text{ where } i = 1 \ldots m$$ \hspace{1cm} (III.19)

This whole process helps to select the suitable forwarder in a distributive manner. The forwarder selection is performed by the 1-hop neighbors of the $s$ and the same can be applied by vehicles that receive Interest from intermediate forwarder, $f$. However, the $DL_f$ must contain all the members that common to $f$ and $r$ but not the members that are the neighbors of the $s$, as shown in Fig. 3-5.
IV. Performance Evaluations

In this chapter, the performance evaluations of the proposed DIFS protocol against state of the art Interest Broadcast storm Mitigating schemes (i.e. NAIF [14] and RUFS [16]) is presented.

1. Simulation Environment

The vehicular NDN forwarding daemon is implemented in the Network Simulator (NS-2). Furthermore, NL and DL as an additional data structure were used with the conventional NDN structures (e.g., CS, PIT, and FIB). For a fair comparison, an identical mobility model as in RUFS is used along with a network of 20 to 50 vehicles with the transmission ranges of 250m and 500m, traveling at the varying speed is considered. To take into account the effect of mobility direction, DIFS used the relative velocity as one of the forwarder selection metric in DIFS. Also, the contents are randomly allocated to the vehicles in each simulation, which indicates that the provider, its mobility, and its direction, all are random. This scenario is more realistic and correlated with the NDN philosophy which does not focus on the proximity information of the provider but
the content itself. Additionally, to test the feasibility of DIFS, we used
the realistic highway scenario with bi-directional traffic flow. However,
it is a very interesting scenario to simulate the DIFS specific directional
mobility model and in future, DIFS may consider this scenario. The rest
of the simulation parameters are same as in Table 4-1.

Moreover, total 10,000 Data contents are equally distributed in the
network and the every vehicle randomly generates two Interests (becomes
consumer) during the simulation duration. Every vehicle shares its posi-
tion information with its neighbors through beacons with the rate of 5
beacons/s. Content caching at each forwarder is disabled, however, when
a consumer node receives the requested Data, it caches it in its CS. The
results were averaged from 30 runs and the confidence interval of the
evaluation is 90%.

<table>
<thead>
<tr>
<th>Table 4-1: Simulation Parameters</th>
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</thead>
<tbody>
<tr>
<td><strong>Parameter</strong></td>
</tr>
<tr>
<td>Network Size</td>
</tr>
<tr>
<td>Data Contents</td>
</tr>
<tr>
<td>Vehicle Speed</td>
</tr>
<tr>
<td>$T_x$ Power</td>
</tr>
<tr>
<td>$T_r$, Transmission Range</td>
</tr>
<tr>
<td>Frequency Band</td>
</tr>
<tr>
<td>Additional Data Structures</td>
</tr>
</tbody>
</table>
2. Quality Metrics

For comparisons, the following quality metrics are introduced:

1) Forwarded Interest Packets (FIP)

Forwarded Interest packets metrics shows the total copies of Interest packets forwarded in the network. It is fact that VANETs are broadcast in nature, have dynamic topology, intermittent link connectivity, and unpredictable link quality due to fast mobility. Under these conditions, the Interest broadcast storm must be minimized to avoid link congestion and unnecessary bandwidth consumption. Basically, NDN solves the challenges that are caused by the node mobility by relinquishing the content communication dependency on the node identities and end-to-end connection establishment. However, NDN ensures the content communication by leaving the bread crumbs (PIT entries) in the network. The larger the spread of the bread crumbs (many nodes broadcast Interest in the network), more the chances to successfully receive the content. In result, it increases the chance that one of the potential providers will receive the copy of Interest message to successfully fetch the content at the cost of link congestion and excessive bandwidth utilization. Therefore,
the scheme must reduce the Interest broadcast storm without compromising the content delivery ratio.

2) Satisfied Interest Packet (SIP)

Satisfied Interest packet metric shows the number of Data packets received in response to the Interest packet generated by the consumer vehicle. In NDN, the main objective of Interest message generation is sent to locate and communicate the content. Generally, the size of a content is larger than the size of the Data message because a Data message cannot exceed the limit of the Maximum Transmission Unit (MTU). Hence, a consumer vehicle needs to generate multiple Interests to receive a complete content if its size is larger than the MTU. An Interest is considered satisfied if the consumer receives Data message in its response. Therefore, any scheme proposed for NDN enabled network must ensure that SIP should be high because NDN’s core ideology is to successfully retrieve the content. Therefore, the SIP metric shows efficiency and effectiveness of any scheme proposed for the NDN enabled networks. In the context of this dissertation, the SIP depicted in the performance graphs is the average of multiple simulation runs.
3) **Interest Satisfaction Delay (ISD)**

Interest satisfaction delay is the time duration between the Interest generation and Data reception by the consumer vehicle. When consumer generates an Interest, it has to wait for the Data message and once it receives the Data message it computes the ISD. Data message for each Interest may not be generated by the single producer. Hence, the ISD is computed for the very first Data message received from one of the producers in the network. Long ISD may be the result of the dynamic network topology, producer, and consumer mobility, link quality, link congestion caused by the Interest broadcast storm, large hop distance between the consumer-producer node pairs, and so on. This performance metric is important and can be used by the delay sensitive applications running over the NDN enabled VANET nodes.

4) **Hop Count Number (HCN)**

The hop count number is the number of hops that an Interest has been propagated to successfully find the provider node. At every hop traversed by an Interest, the hop count value is incremented by each Interest forwarder. When this Interest is received by the producer vehicle, it replies
with the Data message containing the total number of hops from the Interest message. It is also a fact that the producer vehicle may not receive that Interest from the shortest path. Therefore, HCN of the satisfied Interest may be different from the smallest number of hops between consumer and provider node pair.

5) Hop Limits Threshold

NDN has its own mechanism to overcome the Interest Loop by enforcing the PIT Entry Lifetime (4 seconds). That means that whenever the Interest is broadcasted, the timer starts and after 4 seconds, if nothing arrives back, the PIT entry is discarded and the new Interest for same Data should be generated.

When we run simulations, the same procedure goes by each hop and the Interest keep traversing to the end of the road as every node has PIT and PIT management strategy makes each node to keep generating the Interest packet. Given that the mobile and dynamic environment of the VANETs is not friendly to such additional Interest generation process.

To overcome this scenario, we limit the Interest generation authorities to only 05 hops. Based on our previous works named as “CODIE” [13]
and “DPEL” [28], we have performed studies that mostly the successful Data is being retrieved within 05 hops. If the hop count increases more than that, the connection time is not enough to retrieve any chunk of the Data.

3. Results and Discussions

First, the performance of the proposed DIFS in terms of the average number of satisfied Interest packets is discussed. SIP of DIFS is analyzed for $Tr = 250m$ with varying network size and different speeds of the
vehicles in the networks, refer Fig. 4-1 and Fig. 4-2, respectively. Since NAIF forwards Interests into each quadrant and selects the forwarder with larger distance in each quadrant, chances of link breakage are high very high due to fast mobility direction. In result, it regenerates Interests and thus higher Interest traffic causes congestion, that forces the Data packet drop. Another important property of NAIF can be observed from the results that increase in the network size improves the average number of Interest satisfaction packets because there may be a large possibility to select suitable Interest forwarders in all four coordinates. The Fig. 4-2 shows that speed has not much impact on the SIR performance of NAIF.

In contrast to NAIF, the RUFS selects single forwarder that has high satisfaction rate, small satisfaction delay, minimum hop count, etc. This information ensures to select forwarder that has recently satisfied the same Interest or is closer to the provider. However, the Interest forwarding through dedicated vehicles may result in high Data packet loss resulted by the unstable path and the obvious reason is the highly dynamic nature of the network because of high mobility.

On the contrary, DIFS selects Interest forwarders in the forward and backward direction of the consumer that have stable links, large distance,
and less relative speed. This ensures that the path will be stable for sufficient enough time to retrieve the required Data packet. It is evident from the Fig. 4-1 and Fig. 4-2 that DIFS satisfies more number of Interests than NAIF [14] as well as the RUFS [16].

To be precise, the average ration of the SIP achieved by DIFS compared to NAIF is 48.38% and 64.02% for different network sizes and vehicles’ speed, respectively. Similarly, 7.19% and 17.36% more Interests are satisfied by DIFS than RUFS, which is evident from those graphs.

Another scenario in which the SIP of the proposed DIFS scheme has
Fig. 4.3. Satisfied Interest Packets ($T_r=500$)

Table 4-2: Average number of SIP improved by DIFS compared to NAIF and RUFS

<table>
<thead>
<tr>
<th>Different</th>
<th>NAIF</th>
<th>RUFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_r$</td>
<td>Nodes</td>
<td>Speed</td>
</tr>
<tr>
<td>250m</td>
<td>48.38%</td>
<td>64.02%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>17.36%</td>
</tr>
<tr>
<td></td>
<td>132.93%</td>
<td>20.64%</td>
</tr>
<tr>
<td>500m</td>
<td>166.97%</td>
<td>19.42%</td>
</tr>
</tbody>
</table>

been analyzed through simulations is the large transmission range, $T_r = 500m$, refer Fig. 4-3 and Fig. 4-4. Similar trends have been observed in SIP for the large transmission range as well. Figures show that the DIFS achieves twice the better SIP performance than the conventional scheme because it selects more stable forwarders in a distributed manner. Average SIP performance improvements gained by DIFS are summarized

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The next performance metric that is compared through simulations is the average hop count from which the Interest has been satisfied. The Fig. 4-5 and Fig. 4-6 show the average Interest satisfaction hop count for different network sizes and speeds, respectively. It is obvious from the graphs that RUFS forwards Interests in a unicast manner, which fails to satisfy Interests from consumers that are at a distant location in the network. Hence, it only satisfies the Interests of the consumers that are only a few hops away. This is the reason that RUFS has the less Interest...
Fig. 4-5. Interest forwarding Hops ($T_r=250$)

Fig. 4-6. Interest forwarding Hops ($T_r=250$)
Fig. 4-7. Interest forwarding Hops ($T_r=500$)

satisfaction hop count. On the other hand, the average hop count for NAIF is relatively larger than RUFS and DIFS because it may satisfy some Interest from the distant consumers. However, the cost of Interest satisfaction is very large in terms of more number of copies of the Interest than RUFS and DIFS that is discussed later in the section.

Unlikely, DIFS avoids the Interest congestion and distributively forwards the Interests through more stable paths. The Interests are satisfied from the providers that are either in the close proximity of the provider as well as the providers that are at the distant location. This is the rea-
son that average hop count of DIFS is in between the NAIF and RUFS with moderate Interest packet overhead in the network. DIFS satisfies Interests from the consumers that are about at slightly larger distance (in terms of hops) compared to RUFS, refer Fig. 4-5 and Fig. 4-6. However, DIFS only satisfies Interests from the consumers that are 33.16% hops away compared to the NAIF.

Another hop count analysis scenario is the large transmission range, $T_r = 500m$, as shown in Fig. 4-7 and Fig. 4-8. For larger transmission ranges, DIFS’s Interest satisfaction hop count is almost twice the hop
count of RUFS and very near to the NAIF. The Interest satisfaction hop count performance is summarized in 4-3, where a negative value indicates that DIFS satisfies Interest from less number of hops in contrast to the NAIF.

Table 4-3: Average Interest satisfaction hop count performance gained by the DIFS

<table>
<thead>
<tr>
<th>Different</th>
<th>NAIF</th>
<th>RUFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tr 250m</td>
<td>Nodes</td>
<td>- 33.16 %</td>
</tr>
<tr>
<td>Speed</td>
<td></td>
<td>- 44.27 %</td>
</tr>
<tr>
<td>Tr 500m</td>
<td>Nodes</td>
<td>- 19.39 %</td>
</tr>
<tr>
<td>Speed</td>
<td></td>
<td>- 34.6 %</td>
</tr>
</tbody>
</table>

The Fig. 4-9 and Fig. 4-10 show the number of Interest packets forwarded in the network for different network sizes and average vehicle
speed on the road, respectively. NAIF has a large number of forwarded Interests because every time when a node receives an Interest, it selects multiple forwarders. Furthermore, the RUFS has less number of forwarded Interests because most of the Interest are lost due to improper selection of the forwarding nodes. Like aforementioned, the DIFS has moderate average hop count due to distributive forwarder selection, therefore, has a moderate number of forwarded Interests.

Performance analysis of DIFS in terms of an average number of forwarded Interest packets for larger transmission range has the similar
Fig. 4-11. Forwarded Interest Packets ($T_r=500$)

Fig. 4-12. Forwarded Interest Packets ($T_r=500$)
Table 4-4: Performance gain of DIFS in terms of average number of forwarded Interests in the network.

<table>
<thead>
<tr>
<th></th>
<th>Different</th>
<th>NAIF</th>
<th>RUFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tr 250m Nodes</td>
<td>- 45.51 %</td>
<td>25.14 %</td>
<td></td>
</tr>
<tr>
<td>Tr 250m Speed</td>
<td>- 67.85 %</td>
<td>23.50 %</td>
<td></td>
</tr>
<tr>
<td>Tr 500m Nodes</td>
<td>- 34.51 %</td>
<td>117.19 %</td>
<td>155.06 %</td>
</tr>
<tr>
<td>Tr 500m Speed</td>
<td>- 26.52 %</td>
<td>155.06 %</td>
<td></td>
</tr>
</tbody>
</table>

As it was obvious from the hop count graphs that DIFS count not satisfy Interests from distant consumers for short transmission ranges. This is the reason that an average number of forwarded Interest packets by the DIFS is comparable to the RUFS. On the other hand, DIFS forwards almost twice the number of Interests than RUFS by gaining more Interest satisfaction ratio as discussed previously.

4-4 shows the overall forwarded Interest packets performance comparison of the DIFS. On the whole, DIFS forwards 45.51% and 67.85% fewer copies of Interests and 21.14% and 23.5% more copies of Interest than NAIF and RUFS in the scenario with $T_r = 250m$, respectively. However, for large transmission range scenario, DIFS forwards more copies of Interests than RUFS because it satisfies more Interests from the distant consumers.

In last, the performance in terms of Interest satisfaction delay of the
Fig. 4-13. Interest Satisfaction Delay ($T_r=250$)

Fig. 4-14. Interest Satisfaction Delay ($T_r=250$)
schemes is compared and shown in Fig. 4-13 and Fig. 4-16. It is obvious from the previous discussion that DIFS satisfies Interest from distant forwarder nodes by forwarding large number Interests in the network. This is the reason that Interest satisfaction delay of DIFS is smaller than both the schemes for small transmission range because it generates moderate Interest overhead. However, for large transmission range scenario, the Interest satisfaction delay increases due to high-Interest overhead in the network. The reason behind this phenomenon is the distributive selection of forwarders. In larger transmission range use-case, there may be selected multiple forwarders near Interest relaying or consumer node because of the large forwarder selection area. From the summary of the Interest satisfaction delay in 4-5, it is clear that in all cases DIFS has less delay compared to both the schemes except RUFS in the large transmission range scenario. DIFS has 51.20% and 112.34% more delay as compared to RUFS in $T_r = 500m$ scenario.

Moreover, it is worth noting that DIFS satisfies number of Interests, which is the main objective of any application running on the on board unit inside the vehicle.

On the whole, DIFS satisfies a large number of Interest packets than
Fig. 4.15. Interest Satisfaction Delay ($T_r=500$)

Fig. 4.16. Interest Satisfaction Delay ($T_r=500$)
Table 4-5: Interest satisfaction delay gained by DIFS

<table>
<thead>
<tr>
<th>Different</th>
<th>NAIF</th>
<th>RUFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tr 250m</td>
<td>Nodes: -39.15%</td>
<td>-14.66%</td>
</tr>
<tr>
<td></td>
<td>Speed: -51.17%</td>
<td>-10.58%</td>
</tr>
<tr>
<td>Tr 500m</td>
<td>Nodes: -21.58%</td>
<td>51.2026%</td>
</tr>
<tr>
<td></td>
<td>Speed: -11.02%</td>
<td>112.34%</td>
</tr>
</tbody>
</table>

NAIF plus RUFS and less Interest overhead and Interest satisfaction delay than NAIF. However, it has slightly larger Interest overhead and delays as compared to RUFS that is justified because RUFS fails to satisfy the Interests in the FVN.

4. Qualitative Comparison with Recent Literature

This section provides a qualitative analysis of the proposed DIFS against very recent and state of the art scheme been proposed in the literature.

1) DIFS vs Navigo

The authors in [17] developed a self-learning scheme (Navigo) to enable effective data delivery in highly dynamic vehicular environments (WoW-MoM 2015). The Navigo strategy is to learn where the Content resides and then steer Interest towards such area. In contrast with IP-based georouting, which attempts to deliver packets to a specific end node, Navigo forwards Interests towards the area content resides in, enabling fetch-
ing from any available data carriers within the region, either producers, mules, or RSUs. The Navigo automatically learns content’s geographical location and requires no location service or oracle which are typically required by traditional Geo-routing. Furthermore, while IP-based geo-routing is connectivity-dependent and uses a one-hop hello protocol to maintain the local topology, all Navigo traffic is related to Interest–Data transactions, i.e. if there is no request for content, there would be no packet in the network.

In contrast, the proposed DIFS is not depending on the location information of any potential provider, i.e. the consumer or intermediate vehicles are not aware of provider direction or \(x, y\) coordinates. One of the reason is that DIFS is proposed for vehicular networks and no RSUs or Data mules are considered. Hence, the dependency on the location of a mobile vehicle is too ambitious. Hence, the proposed DIFS is taking more realistic parameters to make DL and take adequate decisions.

2) DIFS vs Priority Based Content Dissemination

Recently, a priority based NDN architecture has been proposed for vehicular named data networks [44] and published in IEEE PIMRC 2016.
The authors specifically proposed a mechanism, pNDN, for named-data vehicular networks that uses information codified in the name for the prioritization of contents. The work aims to promote the adoption of NDN in VANETs as a key networking solution for content distribution, and further improves its basic (and successful) forwarding fabric to meet the heterogeneous delivery demands of vehicular applications. The proposed solution has the virtue of simplicity, it is fully distributed and does not require any additional signaling. pNDN is highly flexible in that it can be easily integrated in different basic NDN forwarding strategies that do not provide prioritization, without altering their logic. Moreover, simulation results show that pNDN outperforms them. It reduces the latency of high priority packets, which is crucial in vehicular environments, where connectivity suffers from being short-lived and is further penalized from multi-hop communications.

On the other hand, DIFS has been uniformly treating the Data. The main difference between the pNDN and DIFS is that the former scheme deals with prioritized Data packets and reduces the latency of a selected group of Data in vehicular ndn, while the later DIFS is proposed for a generic type of Data.
3) DIFS vs Delay Tolerant Interest Forwarding

While scanning the recent literature, the paper entitled as “Density-Aware Delay-Tolerant Interest Forwarding in Vehicular Named Data Networking” is found [47] published in the year 2016. In this paper, the authors have proposed DADT: a Density-Aware Delay-Tolerant Interest forwarding strategy to retrieve traffic data in vehicular NDN with the purpose of improving packet delivery ratio. It considered rebroadcast and retransmission together, also specifically addressing data retrieval during network disruptions using DTN. Further, the authors have implemented DADT through simulation and demonstrated its performance by comparing against other DTN strategies. The results show that DADT achieves higher satisfaction ratio than other strategies without introducing much transmission overhead.

Unlikely, the proposed DIFS is not a case specific like aforementioned delay tolerant scheme. The DIFS is applicable to the vehicular NDN and can retrieve the results in more robust manner as compared to the DTN schemes.
5. Proposed DIFS as a Recommendation System

Based on my understanding and limited knowledge about the Recommendation Systems and Reinforcement Algorithms, my proposed DIFS scheme can be categorized as a recommendation system. The rationale behind such claim is that DIFS basically provides the Decision List (DL) to every node that helps in selecting itself as a next forwarder or not. The proposed DL is updated with the real time information of neighboring nodes.

On the other hand, the Reinforcement Learning (RL) is a method of learning while interacting with a fixed environment. In spite of explicit teaching, the RL agent continuously learns from the consequences of its action on the environment. Since RL is a trial and error learning method, the RL-agent selects its action based on both previously made actions and by making new choices. In the fixed environment under consideration, with every move RL-agent receives a numerical reward whose value varies depending if the choice of that move was right or wrong. While keeping the environment fixed, after repeating the procedure large number of times (depending upon the task and environment mainly repeating thousands of times) and keeping the record of every move (action) and ef-
fect (state), the algorithm comes up with an educated moves to maximize the required gains while keeping the cost factors as low as possible.

Based on the above discussion, it would be more ambitious that the DIFS is related with any reinforcement algorithm in its current form. Nevertheless, my future plans include to extend my proposed system, while keeping the RL architectures and support into the account.
V. Conclusion

In this dissertation, the Interest broadcast storm mitigation scheme for the future vehicular networks has been proposed. Interest broadcast storm consumes the network resources, especially the network bandwidth. There are several schemes in the literature that alleviate the Interest broadcast storm. However, all of those schemes are the sender or Interest forwarder initiated schemes, where the Interest forwarder or sender vehicle selects the next suitable forwarder node(s). The next hop Interest forwarder selection in those schemes also requires maintaining large data structures and complex computations to select the next Interest forwarder(s). In addition to that, the ID(s) of the selected forwarder(s) are also included in the Interest message, which may increase the Interest overhead. Once the Interest is received, the all neighboring nodes parse the Interest and relay Interest if their ID is present in the packet. Moreover, some of those schemes (especially RUFS) also periodically share the large neighborhood tables additional to the neighborhood vehicles’ information in Beacons.

To overcome the Interest broadcast storm in future vehicular net-
works, in this dissertation, a distributed Interest forwarder selection or DIFS scheme is proposed. In contrast to the sender-initiated schemes, the next hop forwarder selection decision in DIFS is taken by each vehicle independently and distributively when it receives the Interest packet. Each vehicle maintains only the neighboring vehicles’ speed, direction, and position information that is shared through basic safety messages (aka beacons). Based on this information, DIFS estimates distance, link duration, and relative speed of the vehicles with respect to the Interest relaying vehicle. Each node computes the weights based on those criteria for all the neighboring vehicles that are common to the Interest forwarder and receiver vehicles including the Interest receiving vehicle itself. If the Interest receiving vehicle has the highest weight among all of the common 1-hop neighbors, then it will forward the Interest, otherwise, it will discard.

The effectiveness of DIFS is compared with the state of the art schemes in the literature through simulations (e.g., RUFS and NAIF). The comparison parameters include a number of forwarded Interests, average Interest satisfaction rate, average Interest satisfaction delay, and the average number of hops from where the Interest is satisfied. Network param-
eters used for those simulations are varying vehicle speed, transmission range, and network size.

Simulation results show that DIFS forwards less number of copies of the Interest packets compared to NAIF and satisfies a number of Interest than the both the schemes. It is also observed that DIFS satisfies Interests from the providers that are located more hops away than the RUFS. In terms of Interest satisfaction delay, DIFS has far less delay than NAIF and RUFS as well, except the RUFS in the use-case when transmission range is very high. This is justifiable because DIFS satisfies more Interests that both the schemes, which is the main objective of the FVN applications.
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미래 차량 네트워크에서의 효율적인 정보 흐름

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(지도교수 김동균)

(초록)
차량 네트워크는 최근까지 다양한 응용을 제공해 왔으며 향후 몇 년 내에 완전자율주행차량이 우리 주위에서 흔할 것으로 전망된다. 이와 유사하게 네트워크에서는 정보 중심 네트워킹 (Information Centric Networking, ICN) 및 그 변형 형태의 네트워킹에서 제3의 혁명이 일어나고 있음을 우리는 확인하였다. 그 예로ICN의 한 종류인 NDN (Named Data Networking)은 미래 인터넷 아키텍처로 간주되며 차량 네트워크에 적용되어왔다. 이러한 네트워크를 우리는 미래 자량 네트워크 (FVNs)라 부른다.

최근 FVNs에서는 Interest플러딩 문제를 최소화 하고자 하는 노력이 있었다. 그 예로 무선 환경에서 여러 노드의 Interest 전송을 억제하거나 선택된 노드만이 Interest를 전달할 수 있도록 하여 Interest broadcast storm 을 최소화하는 것이다. 전송자 선택은 분산되어 수행되거나 Interest 메세지 안에 포함되어 전달된다.

Interest broadcast storm의 경감 기법 중 하나로 Interest 전송자 주변의 지역을 사분 면으로 나누고 이를 Interest전송 지역으로써 사용한다. 이 기법은 Interest를 전송할 전송자를 각 사분 면마다 하나씩 선정하여 Interest 를 전달하도록 하여 제공자에게 Interest가 도착할 때까지 각 사분 면의 모든 전송자는 같은 방식으로 전송한다. 또 다른 차량 네트워크 환경에서의 Interest 전송 경감 기법 중 하나로 가장 큰 데이터 회수율과 소비자까지의 거리를 고려하여 전송자를 선택하는
방법이 있다. 이런 방법들은 이웃차량 중 전송자가 되기 적합한 인자를 가진 차량 하나만을 선택한다. 이 파라미터들은 데이터를 수집한 곳으로부터의 홈 수, 현재 차량의 속도 그리고 Interest 만족도 등이 될 수 있다.

이 외에도 Interest 전송 경감 기법으로는 데이터의 지리적 위치와 Interest 패킷에 있는 이름을 연결하는 방법이 있다. 하지만 NDN 아키텍처는 지리적 기반의 매핑을 지원하지 않으므로 이를 지원하기 위해 지리적 위치와 이름 공간을 매핑하는 추가적인 알고리즘이 필요하다. 전송자 선정 방식과 무관하게 Interest broadcast storm 경감 기법의 주된 목표는 전송하는 Interest의 복사본 수를 줄이는 데 있다. 하지만 이런 기법들은 노드가 불안정하고 링크의 유지시간이 짧은 특성을 지닌 동적이고 분산된 차량 네트워크를 고려하여 여러 인자들을 기록하고 갱신한다. 이것은 오히려 차량 네트워크에서 응용의QoS(Quality of Service)와 같은 제한조건을 충족해야 하는 경우 작업을 거듭하게 만든다.

본 논문에서는 차량 네트워크에서 Interest broadcast storm을 경감시키기 위해 분산된 Interest 전송자 선택 기법(Distributed Interest Forwarder Selection, DIFS)을 제안한다. DIFS는 고속도로를 따라 Interest를 전달하거나 다시 broadcast하기 위해 두 개의 전송자를 선택한다. 두 개의 전송자를 선택함으로써 Interest 패킷은 Interest를 전달하기에 가장 적합한 이웃 차량을 통해 앞뒤로 분산된다.

이를 통해 홀간의 지리적 위치 정보와 데이터 회수율의 급상승을 완화한다. 다시 말해 DIFS는 각 차량이 다수의 이웃 차량의 속성을 활용할 수 있게 하여 어떤 차량이 전송자로서 적합한지 계산할 수 있도록 한다. 본 논문에서 제안한 DIFS는 Interest패킷을 전달하기 위해 선택된 차량이 최대 연결 시간, 소비자와의 링크 품질을 보장하며 이러한 데이터 회수 과정은 추가적인 지연이나 재전송을 회피할 수 있게 한다.