Multimodal Named Data Discovery With Interest Broadcast Suppression for Vehicular CPS

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Abstract—Cyber-physical system (CPS) provides a well-organized integration between *communication*, *computation*, and *control* (3C) technologies. CPS has been widely used in the vehicular networks and it requires to discover multimodal data from the physical system to make appropriate decisions and actions, for example, congestion warnings, applying brakes, adjusting speed limits, etc. Information discovery and availability at individual network elements is one of the fundamental foundations of CPS. In this paper, we proposed two multimodal network information discovery schemes for vehicular CPS using the Named Data Networking (NDN). One of the proposed schemes simply modifies the pull-based NDN communication mechanism to discover multimodal multi-hop data from the network and the other scheme uses the Interest broadcast suppression (IBS) mechanism. The proposed Interest broadcast suppression scheme adapts the holding time technique to defer the Interest forwarding and its computation involves the hop-count, distance, and other network parameters. Simulation results show that the proposed schemes discover about 172 and 162 percent more multimodal information from approximately 283 and 210 percent more network area by suppressing approximately 50 percent of the Interest broadcast storm in highway and the urban traffic scenarios, respectively.

Index Terms—NDN, VCPS, multimodal data, interest holding time, broadcast suppression

1 Introduction

Vehicular networks comprise fixed roadside infrastructure elements and mobile vehicles with communication capabilities to share information for the safe and ecstatic commute and better traffic management. It is one of the emerging and fast-growing networks due to rigorous research and rapid technological advancement. Due to its rapid growth, many safety and non-safety related applications have been realized to ensure safe and infotainment rich travel experience for the drivers and the passengers. The salient examples of those applications include forward collision warnings, emergency vehicle approaching, road and traffic conditions, parking, traffic congestion, the pedestrian crosswalk, and weather information, and so forth. These applications run over the onboard unit (OBU) mounted in the vehicle or the commuter's mobile device that can wirelessly communicate with other vehicles or the roadside equipment (RSE). The information communicated through these devices is made available to commuters through OBUs, mobile devices, the electronic road signs or boards, and dynamic speed limits installed over the highways and road sections.

Most of the vehicular network applications (ranging from delay-sensitive cruise control to delay-tolerant traffic management) require data from different sensors installed within the vehicles on the road, RSEs, and even the pedestrians' handheld or mobile devices. The data may be generated by sensors, cameras, GPS, range detectors (e.g., laser, Infrared, Ultrasonic, etc.), and other devices installed within the vehicles, the RSEs, and other network elements. Based on this data, electronic road signs dynamically generate directions for drivers, the speed limit is varied automatically, traffic light duration is regulated as per the traffic conditions, warnings are displayed over the OBUs or mobile devices, the vehicle's speed can be adjusted to prevent the hazardous situation, and so forth.

A typical instance of data in the vehicular application scenario, i.e., forward collision detection and avoidance (FCDA), includes; speed, angle of steering, throttle status, latitude-longitude, acceleration, distance, and so forth, of all the vehicles around the one that is running the FCDA. FCDA application continuously collects this real-time data from vehicular network elements through communication channels, computes the possibility of the collision based on the collected information, and takes the control actions by either applying brakes, reducing speed, generate warnings, and so forth, to avoid the collision. This close synergy of *computation*, *communication*, and *control* in the FCDA scenario is a typical example of the vehicular cyber-physical system (VCPS) [1], [2], [3], [4]. Other examples of the VCPS include, but not limited to, the dynamic cruise control, anti-braking system monitor, adaptive traffic light duration, and dynamic speed limits. It is worth mentioning here that in most of the VCPS control applications, the communication

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is envisioned as secure and with minimum or no packet loss. Before proceeding further, we clarify that the terms node and vehicle, and the data and content, are used interchangeably in the context of this paper.

In all the above VCPS applications, the data acquired through different sensors or instruments (installed within vehicles, RSEs, handheld devices, and so forth.) and collected from different sources, including vehicles, RSEs, and mobile devices, about the similar phenomenon (e.g., FCDA), is called the *multimodal* data. The term modality of the data is defined in [5] as; "*each acquisition of data about the same phenomenon generated by different types of sensors or detectors, at different conditions, in multiple subjects or experiments, among others*". The use of multimodal data in vehicular network applications is not new and a few proposals used multimodal data in the domain of intelligent transportation system (ITS) [6], [7]. Also, there are several examples of the CPS integration with the large heterogeneous multimodal (multisource) data sets in the literature [8], [9]. The authors used multimodal data to test different optimization models and event estimation schemes for the CPS. Most of the authors used the available multimodal data set. In reality, the collection of multimodal data in a highly dynamic environment is a challenging task [10], [11]. A typical vehicular network uses the dedicated short-range communication (DSRC) technology that offers the IEEE 802.11p standard [12], [13], [14] to offer wireless access in vehicular environment (WAVE). Other than DSRC/WAVE, there are several sets of access technologies used by vehicular networks to communicate data, which includes WiFi, long term evolution (LTE), and so forth [15].

Recently, a new communication architecture has been extensively investigated for vehicular networks that keep *data* at the center of communication than the nodes or vehicles, called named data networking (NDN) [16]. NDN is the detailed implementation of its predecessor architecture, named content-centric networking (CCN) [17], [18], [19]. It offers data security that is communicated along with the data itself and renders a detailed trust mechanism to identify the data and its producer. Data is named by NDN instead of its provider or producer, which unbinds content's dependence over its location. As a result, it offers great mobility support and proves to be the most suitable communication architecture for vehicular networks. NDN discovers content from the network in a pull-based manner. The consumer node or the content requesting node sends an Interest message with the desired content name. A node that has the matching content in its cache or can generate the requested content, replies with the Data message when it receives the Interest message. The content generating node and the node that caches the contents generated by other nodes are called, the producer and provider node, respectively. In addition to the content name, an Interest message also contains the NONCE, a large random number, to identify Interests from multiple consumers requesting the same content.

NDN uses the URI-like hierarchical naming scheme to recognize the content object. The Interest message contains the content name, NONCE, and the content and forwarding related information. The Data message contains the name of the content, content itself, content's signature, key locator, and so forth. NDN adapts the public key cryptography and the Key locator is the name of the digital certificate that authenticates the content. The Interest and Data messages are also used to communicate digital signatures. The trust is established through a chain of trust by verifying signatures through content to the trust anchor [20].

In literature, many authors have investigated the feasibility of NDN in vehicular networks and reported that NDN inherently deals with the mobility issue and efficiently retrieves the content from the network with or without the presence of the infrastructure nodes [21], [22], [23], [24], [25], [26], [27], [28], [29]. All of those schemes use NDN architecture to retrieve specific content that is either generated by or cached at a particular vehicle. The content requesting vehicle sends Interest and the vehicle that has the required content replies with the Data message. The intermediate Interest forwarding vehicles maintain an entry in the pending interest table (PIT) and that entry is purged once that node forwards or relays the requested Data message containing the required content. If an intermediate node receives a Data message that has no corresponding valid PIT entry, it considers that data as an unsolicited message and discards it.

In many VCPS application scenarios,[1] a vehicle or any ITS node requires multimodal data (the sensed data that is produced and/or provided by different vehicles or sensors) to take intelligent control actions, i.e., applying brakes, adjusting traffic signal duration, altering speed limits, etc. This multimodal data is discovered from different vehicles or nodes moving with the specific region, which is termed here as the information discovery region or interested region. Contingent upon the multiple producers or providers of the same content, the NDN only forwards the very first Data message towards the consumer and rest of the Data messages are discarded because the node has already purged its PIT entry or assume that the Interest is satisfied. The other solution to this multimodal data discovery problem is to send a separate Interest per content instance. This solution is infeasible because it will incur a very long content discovery delay because of multiple nodes and generates a very large Interest broadcast storm.

It is evident from the above discussion that all the vanilla NDN-based schemes in literature are not suitable for the multimodal data VCPS scenarios. This motivated us to propose a solution to discover or sense the NDN-based multimodal data from all the nodes within the information discovery region with minimum Interest broadcast storm. In this paper, we propose the multimodal named data discovery algorithm to collect multimodal data in reply to a single Interest message. Based on our knowledge, the proposed scheme is the first attempt to adopt NDN for discovering multimodal information in VCPS. To retrieve the multimodal Data, the Interest message includes a large resolution content name to collect information from all the vehicles within the interested region. Following are the key

1. The example VCPS application scenarios where the control decisions require multimodal data, include but not limited to; connected and dynamic eco-driving and routing, speed harmonization, traffic signal prioritization, traffic management, variable speed limits, pedestrian mobility management, and so forth.

contributions of the proposed multimodal Named Data discovery scheme for VCPS, (NDVCPS):

- We extended the Interest with "MultSource" option to retrieve multimodal data (one Interest and multiple Data) from different producers and/or providers.
- Explicit data retrieval from either producer of the content or any node in the network by introducing the "ProdOnly", producer-only, option.
- The Interest broadcast storm mitigation method is also proposed to reduce the Interest traffic.
- We introduced "Data-NONCE" option for each Data packet to distinguish each copy of the content instance produced or provided by the content producer or the provider, respectively.

The organization of the rest of the manuscript is as follows: NDN architecture and its working mechanism along with the literature review is discussed in Section 2. The Interest and Data packet forwarding schemes, including the Interest broadcast storm mitigation mechanism, are briefly elaborated in Section 3. Section 4 discusses the simulation environment and analyzes the simulation results. Finally, the conclusions are drawn in Section 5.

2 Communication in NDN and Related Work

In this section, we briefly discuss the working principle of NDN architecture and review the previous works published in the literature related to the domain of multimodal data discovery using NDN.

2.1 Working Principle of NDN

A node in the NDN enabled network manages pending interest table (PIT), forwarding information base (FIB), and content store (CS) or cache. These data structures are used to communicate Interest and Data messages. The format and functionality of the said data structures are as follows:

- *PIT*: stores information of the Interests that are yet to be satisfied in the structure as {*Name*, $I_{NONCE}(s)$, *in-Face(s), and out-Face(s)*}. Here, $I_{NONCE}(s)$ is the large random number that uniquely identifies the interest and *in-Face* is the interface from which the Interest was received. The Name prefix tree is maintained and each entry in this name prefix tree holds the $I_{NONCE}(s)$ of all the Interests that have been received by the node requesting content with similar name prefix. When a node receives an Interest {*Name*,I_{NONCE}, *Selectors*} from the *in-Face*, the *Name* of that Interest is first searched in the PIT. If a PIT entry with the similar *Name*, I_{NONCE}, and related record, is found, the Interest is simply discarded. Alternatively, if the *Name* search fails and the requested content is not available in the CS, the node creates a PIT entry and forwards the Interest. Moreover, if the *Name* is found in the PIT but with different I_{NONCE} or *in-Face*, then the entry is updated with I_{NONCE} or *in-Face* and the Interest is discarded.
- *FIB*: helps in forwarding the Interest towards the upstream direction and it keeps record of the *Name* prefixes in the format as {*Name*, *out-Face(s)*, *M*}. Each FIB entry is associated with the *Name* prefix tree that has at least one *out-Face*. Contingent upon the PIT and CS search failure, the content *Name* from the Interest message is then searched within the FIB. The output of the FIB search will return the associated *out-Face* through which the Interest is forwarded upstream in the network. Otherwise, the Interest is flooded to all the *out-Faces* or discarded, depending upon the forwarding strategy. Here, *M* represents the name prefix parameter(s) that helps to select a suitable *out-Face*.
- *CS*: is the cache, which stores content that is generated by the node itself or received from other nodes. Caching of the contents depend upon the caching policy.
- *Dead NONCE list* (DNL): holds all the NONCEs associated with the recently satisfied Interests or purged PIT entries.

The subsequent steps are followed by the NDN enabled node when it receives the Interest. A node first searches name within the name tree in the PIT. In case of a successful PIT search, the node discards the Interest because the Interest is already forwarded. Otherwise, the CS is searched for the named content and if the desired content is present in CS. If the content is present in the CS or the node can produce the content, it replies with the Data message. After satisfying Interest with the Data message, I_{NONCE} of the Interest is temporarily kept in the DNL to avoid multiple Data replies for the same Interest. The I_{NONCE} storage in DNL is necessary because a node may receive multiple copies of the Interest from its neighboring nodes within the short interval due to link delays (multipath arrival). Hence, the DNL is also searched to avoid loops and duplicate NOCNES. In case, the PIT and CS searches fail, the Interest is forwarded further in the network based on the FIB name prefix search output. Before, forwarding the Interest, the corresponding PIT entry is created and kept for the duration of *InterestLifeTime*, which is $4s$. If a node does not receive any Data during the *InterestLifeTime* duration, the PIT entry is purged. Conversely, if a Data message is received amid the *InterestLifeTime*, the node forwards the Data towards the downstream direction through the *in-Face* corresponding to the PIT entry. The PIT entry is deleted after transmission of the Data message.

In the above scenario, a node can satisfy the Interest if it is provider or producer of the named content. Otherwise, it assists in the communication of one Interest one Data communication. In the provider or producer case, a node replies with the Data message without maintaining the PIT record and does not assist in the further content discovery process because it assumes that the Interest is satisfied. Conversely, in the latter case, the node just purges the PIT entry when it forwards the Data message. If the node receives more Data message(s) in response to the purged Interest, it discards all Data message(s) due to unavailability of the PIT record. However, there may be the scenario where an application may require data from different nodes (i.e., traffic information from different vehicles, weather readings from multiple sensor nodes within the specific region, microscopic carbon emission data, and so forth.), which is termed as the multimodal data in the context of this paper. Vanilla NDN can not satisfy the multimodal data requirement of the application. There are very few works in the literature that have proposed solutions to this problem and are summarized in the following subsection.

2.2 Previous Work

In this section, we briefly summarize the previous work that deals with the NDN-based communication of the multimodal data produced by multiple nodes in response to an Interest message.

In [31] and [32], the authors modified the vanilla NDN to support data aggregation in the Internet of Things (IoT) based smart home scenario. All devices in the smart home, called producers, are connected to the home server, named as *collection point* (CP) [32], which interfaces smart home to the network. It is assumed that the producers in a smart home are in one-hop connectivity to the CP. If a remote user sends an Interest to request content from multiple smart home devices (such as the temperature of the room at first floor), this Interest must pass through CP in the smart home. The CP further disseminates the Interest towards all the producers. This Interest is called long live Interest (LLI) and it is not purged by the CP from its PIT until its PIT entry lifetime (PLT) expires. When smart home producers receive LLI from the CP, they reply with their respective content or sensed information. These producers do not forward the Interest further in the network because they use vanilla NDN and assume that the Interest is satisfied. The CP receives Data from producers and does not forward that Data towards the downstream remote consumer during the PLT duration. Once the PLT expires, the CP combines all the contents received from the producers in a single Data message and then it replies to the Interest message that it received from the remote consumer. Nonetheless, the communication between a remote user and the home server is carried out in a conventional pull-based vanilla NDN fashion where a single Interest is replied with the single Data. As packet loss is inevitable in the wireless networks, therefore, the CP may re-transmit the same Interest to receive information from the producers whose packets failed to reach the consumer in previous data exchange. The re-transmitted Interest contains the producers' information (within the exclude field of Interest message) that should not reply to that LLI. Authors in [31] and [32] restricted their schemes to one-hop data collection from multiple producers and the producers are not enabled to disseminate the Interest further in the network.

To efficiently collect the raw sensed data from the mobile IoT devices, authors in [33] extended the CCN architecture and call it MobCCN. MobCCN collects the node information using Interest-Data exchange between the mobile nodes and creates the information-centric gradient-based graphs. This information is stored along with the FIB entries, additional to the outgoing interfaces. Then, this information is provided to the utility functions to select the next Interest forwarder once the node receives the Interest. This scheme does not support multimodal data retrieval from the unknown number of data producers.

The authors in [34], used the network coding to retrieve content chunks, also called generations, from different providers or producers in the network. Here, the term generation represents the collection of different smaller content chunks and the larger contents are divided into different generations. The network coding is applied only to the chunks that belong to the same generation. If a node has enough coded segments that can easily decode the requested set of segments, then it will reply to the consumer with a Data message containing the coded segments. Otherwise, it forwards the message further in the network to find more innovative segments. In this work authors did not discuss, how individual segments / coded segments are handled in the PIT structure. Furthermore, the intermediate nodes must have the encoding vector available to decode the requested set of content segments. The scheme in this study considers the large content that is already available at different producers.

The multi-source data retrieval using network coding in the CCN enabled network has also been proposed in [35], called content-centric networking with built-in network coding (CCN-NC). In this work, a consumer sends an Interest to discover content and the providers reply with the content in the form of a coded message (CM). The CM provider or producer node may also forward the Interest to receive more coded messages from the network to receive the desired number of messages that are stated in the Interest or estimated by the provider. It is a priori that the Interest processing nodes must know the desired number of CM messages that must be received by the consumer to get the desired content. In CCN-NC, the interfaces in FIB are categorized as *coded*, *incoming*, and *uncertain*, depending upon the network events. When a new interface is added in the FIB entry, its status becomes uncertain. However, when the coded messages are received over the uncertain interface, it turns its status to the coded interface. The interface becomes incoming interface if it receives Interest through that interface. Nodes prefer to forward Interest through the coded interface because it has a large probability to receive CM through that interface.

In most of the previous schemes [31], [32], [33], the providers or producers do not forward the Interest further in the network to discover multimodal data. Similarly, in [34] and [35], a single producer can easily satisfy the content requested in the Interest, which is different from the case of multimodal data, where the content or data represented by the same name but generated by different producers with different raw data. Additionally, it is also assumed by these schemes that the content forwarder or the consumer must have some firsthand information to predict that what number of coded segments are required and based on that information the Interest is further forwarded in the network. Hence, these schemes are not valid in the scenario where multiple producers generate multimodal data and the number of producers is unknown, i.e., the information gathering in mobile IoT or dynamic vehicular network scenario. Therefore, in this paper, we propose the multimodal named data discovery scheme to gather information from multi-hop unknown number of mobile producers. Furthermore, we also proposed the Interest broadcast storm mitigation scheme to minimize the Interest overhead.

3 Proposed Multimodal Named Data Discovery Scheme

In this section, we briefly discuss the proposed Interest and Data message forwarding mechanisms to collect multimodal

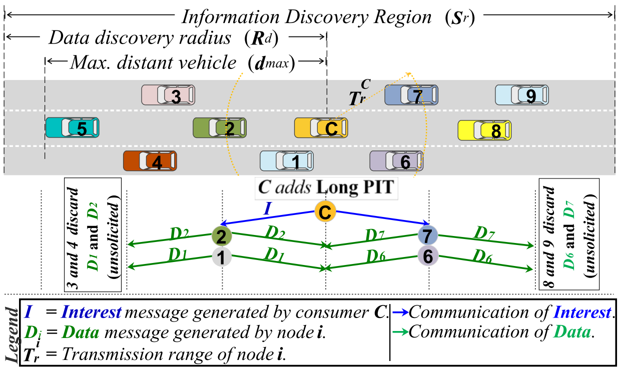


Fig. 1. Conventional NDVCPS scenario with interest and data forwarding.

named data to satisfy the data demand of the VCPS applications. We also discuss the proposed Interest broadcast storm mitigation scheme. Consider a vehicular network scenario where all network elements (e.g., vehicles, RSEs, sensors installed on the road, etc.) are running the NDN architecture. If an application on the consumer node requires traffic information (e.g., current location, heading direction, speed, temperature, etc.) from all the network elements of the specific road segment, the Interest and Data messages are exchanged between the consumer and all the vehicular network elements to collect information. Following subsection briefly discusses the information-gathering process of the proposed scheme, in contrast to the conventional state-of-the-art NDN-based scheme(s).

3.1 Introduction to Multimodal Named Data Discovery

NDN uses only the Interest and Data messages to communicate information in the network. As stated earlier, the consumer vehicle generates an Interest and the node with the requested content replies with the Data message. However, if the same content is available at or produced by multiple vehicles, only a single copy of that content is returned to the consumer. Consider a scenario where the consumer vehicle C requires traffic information of all the vehicles in the road segment covering the region called discovery region, S_r, as shown in Fig. 1. The distance between the center of S_r, which is the location of C, and its boundary is called the data discovery radius, R_d. In literature, there is only one scheme published in [31], [32], that collects content from multiple *one-hop producers*. The prime objective of that scheme is to collect multimodal data from C's one-hop neighbors or the vehicles within the transmission range of C, T_r^C, such as vehicles 1, 2, 6, and 7, refer Fig. 1. According to that scheme, the consumer C sends Interest to collect traffic information from all the nodes and C stores PIT entry for a longer time, called Long PIT entry. C does not purge the PIT entry even after receiving the first Data message. The Interest receiving nodes, i.e., the vehicles 1, 2, 6, and 7, do not forward the Interest further in the network, though the VCPS application running on C intends to collect data from all the nodes in S_r. Hence, the nodes 3, 4, 5, 8, and 9 will not generate any Data message and they also discard any Data message they receive from either 1, 2, 6, or 7 because they have no valid PIT entry. Thus, C receives partial or limited traffic information.

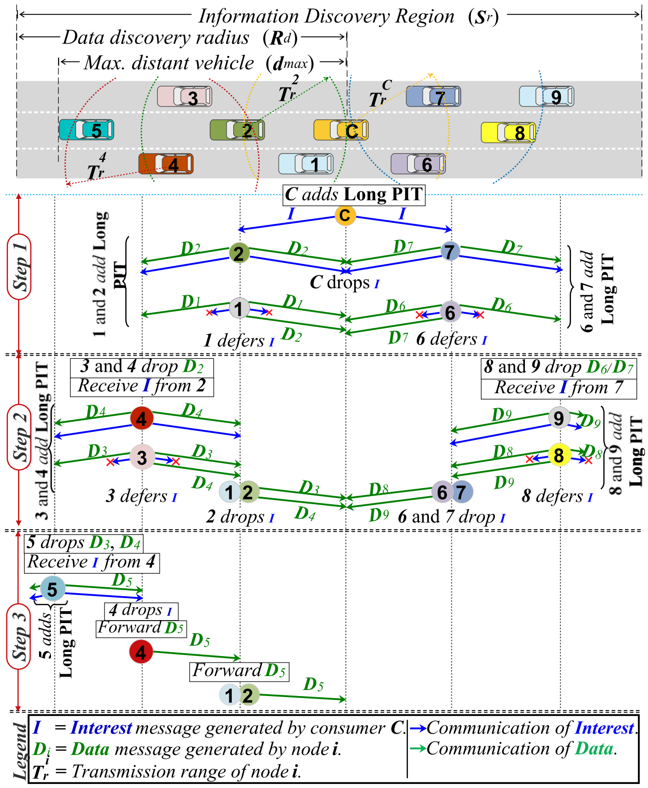


Fig. 2. NDVCPS scenario with interest and data forwarding.

On the contrary to the conventional multimodal data collection scheme, the proposed scheme collects content from all the vehicles within the S_r. The proposed multimodal data collection using NDN's multi-hop Interest-Data forwarding is depicted in Fig. 2 and discussed below.

Step. 1 The NDVCPS application running on C generates Interest, I, and stores the long PIT entry. Here, the term long PIT entry is the PIT record of the Interest that is kept for a specific duration and is not purged from the PIT even C receives the Data message, D, in response to that I. The maximum duration of the PIT entry is $4s$. All the neighboring nodes that receive I, first reply with D and then further forward I in the network.

In case of the example scenario shown in Fig. 2, the nodes 1, 2, 6, and 7 that are in T_r^C, respectively, reply with the Data message D_1, D_2, D_6, and D_7. After replying with the Data message, these nodes also create the long PIT entries and further forward I in the network. The node with valid PIT entry against I, defers the forwarding of I if it receives the additional copy(ies) of I. Let, vehicle 2 and 7 forward I, then their neighbors 1, C, and 6 defer I, because they already have a valid entry in their PIT. The consumer receives messages D_1, D_2, D_6, and D_7 because it is in the transmission range of all these Data message producers.

Step. 2 When, vehicles 3 and 4 receive D_2 and vehicles 8 and 9 receive D_6, D_7, they discard these Data messages because these messages are unsolicited (these vehicles didn't have valid PIT entries.). The instance when nodes 3 and 4 receive I from 2, they reply with

Data D_3 and D_4, respectively, and they maintain the long PIT entry. Let, vehicle 4 further forwards I, vehicle 3 defers I because it has already long PIT entry of that I. The D_3 and D_4 are further forwarded by 1 and/or 2 towards C. A similar set of actions is also performed by the vehicles 8 and 9 to process I and to forward D_8 and D_9 in the downstream direction towards C.

Step. 3 Vehicle 5 generates D_5 when it receives I and creates a long PIT entry. It further forwards I in the uplink direction to discover more multimodal data.

In order to enable multi-hop multimodal data discovery functionality in the NDN, we proposed the following modifications in vanilla NDN's forwarding daemon.

1) In NDN, the Interest message must contain *Name* and *NONCE*, and optional elements such as *Selectors* and so forth. *Interest{Name, NONCE, Selectors, ..}*. The discussion about the optional Interest elements is out of the scope of this paper. In our proposed scheme, the Interest message consists the additional elements; `MultSource` (Multiple Sources) element, when set to "1" indicates that the Interest is generated to collect data from different sources. Otherwise, the Interest is forwarded using the vanilla NDN procedure. Additionally, we introduced another field, called *producer only*, `ProdOnly`, which guarantees that only the data producers within the specified proximity will reply to the Interest message. The vehicles that did not produce the matching content and have cached or stale data in CS will not respond to the Interest message.
2) To differentiate between multiple Data messages that are generated by several producers in response to a single Interest, each producer adds a random two-byte NONCE (D_{NONCE}) in the Data message.
3) All Interest forwarding vehicles keep PIT entry for a longer duration, which is represented by PLT. The PIT entry is not purged before PLT expires even if the vehicle receives Data message(s) during the PLT duration.
4) A vehicle that receives Data message(s) in reply to the Interest, must also record the D_{NONCE} of the received Data message(s) in the relevant PIT entry.
5) Consumer node includes its location (x_C, y_C, z_C) and R_d information in the Interest message.
6) Interest message also includes the hop-count HC, which is incremented and updated by every Interest forwarding node.

Following subsections briefly discuss the Interest and Data message forwarding steps adapted by the proposed scheme.

3.2 Forwarding Interest Messages

In VCPS scenario, the consumer vehicle C generates an Interest to collect multimodal traffic information from different provider vehicles within the proximity of S_r. The proposed scheme requires some additional elements in the Interest message along with *Name* and random *NONCE* (I_{NONCE}). These additional Interest elements include *MultSource*, *ProdOnly*, HC, R_d, and the location information of C.

Algorithm 1. Interest Message Forwarding and Suppression

1: **procedure** INTEREST MESSAGE PROCESSING
2: Node n receives **Interest**
3: [Name, I_{NONCE}, *ProdOnly*, *MultSource*, R_d, HC, Loc., ..]
4: $i \leftarrow$ Interface from which n receives **Interest**
5: $PIT \leftarrow$ [Name, I_{NONCE}, LifeTime, in-Face(s), out-face(s),...]
6: $CS \leftarrow$ Content Store
7: $FIB \leftarrow$ [Name Prefix, out-face(s), ...]
8: $Loc. \leftarrow$ Location of C and Interest forwarder
9: $d_C \leftarrow$ Distance between C and Interest receiver
10: $d_R \leftarrow$ Distance between Interest sender and receiver
11: **if** ($d_C \leq R_d$) and (search(DNL, I_{NONCE})=Fail) **then**
12: **if** search(PIT, Name)=Fail **then**
13: **if** ProdOnly = 1 **then**
14: **if** Is Node Producer? = Yes **then**
15: Call SENDDATA(Content,i) (Algorithm 2)
16: **end if**
17: **if** *MultSource* = 1 **then**
18: Call FIBPROCESSING(Interest,i) (Line 36)
19: **end if**
20: **else**
21: **if** Search(CS, Name)=Success **then**
22: Call SENDDATA(Content, i) (Algorithm 2)
23: Check *MultSource* Flag (Line 17)
24: **else**
25: Add **PIT** [Name, I_{NONCE}, LifeTime, i,..]
26: Call FIBPROCESSING(Interest,i) (Line 36)
27: **end if**
28: **end if**
29: **else**
30: Discard Interest
31: **end if**
32: **else**
33: Discard Interest
34: **end if**
35: **end procedure**
36: **function** FIBPROCESSING(Interest,i)
37: **if** search(FIB, Name)=Success **then**
38: Compute T_I and Start **Timer(T_I)**
39: When **Timer**(T_I) *Expires* {
40: **if** (Copies **Interest**[Name, $I_{NONCE}, ..] \leq 2$) **then**
41: Increment and update HC in the **Interest**
42: Update Node Coordinates in **Interest**
43: Send **Interest** to Interface [search(FIB, Name)]
44: **else**
45: Defer **Interest** Transmission
46: **end if** }
47: **else**
48: Send **NACK** to Interface i
49: **end if**
50: **end function**

Any vehicle that receives the Interest message must follow the steps listed in the proposed Algorithm 1. The first step, when a vehicle receives the Interest, is to check whether the vehicle; has recently satisfied the Interest or not and is within the S_r. The former condition can be verified by searching I_{NONCE} of the received Interest within the *DNL* that temporarily holds NONCEs of all the Interests purged from the PIT. The latter condition is easy to verify through estimating the distance between C and the vehicle itself and comparing with the R_d. If any of those conditions is not satisfied, then no further processing on Interest is needed and it is simply discarded. After confirming that the node is within the information discovery proximity and received the fresh Interest, the vehicle applies the vanilla NDN's PIT search. The Interest is also discarded if it is found in the PIT that indicates that the node had already processed the same and is waiting for the Data message(s). Conversely, the Data message is sent by the node if the node is the content producer or holds the content in its CS, depending upon the value of *ProdOnly* field, refer lines 13 to 28 in Algorithm 1.

Furthermore, the Interest is forwarded in the network if the *MultSource* field is set, even the node is the content producer or provider. Before forwarding the message, the node performs the longest name prefix search in the FIB. The successful FIB search returns the outgoing interface(s) where the Interest should be forwarded. In case of the successful FIB search, the node creates a PIT entry, computes the Interest waiting time T_I, and starts the timer T_I. It is worth noting here that the PIT entry kept for the longer time (PLT duration) and these entries are not purged until the expiration of the PLT. When the timer T_I expires and during that waiting time if the node receives two or less than two copies of the Interest message, then it forwards the Interest. Otherwise, the Interest forwarding process is deferred and the Interest is discarded. The Interest receiving node increments the HC and updates its coordinates in the Interest message before forwarding it further in the network. In case of the unsuccessful FIB search, the node may send a negative acknowledgment (NACK) message towards the Interest sender through the incoming interface (in-Face). This T_I is used to minimize the Interest broadcast storm. In the literature, several message forwarding schemes have been used to minimize the broadcast overhead, such as [36]. Those schemes mostly rely on the node IDs and the physical and other network parameters. However, NDN only uses the content name, which is not bound to any node ID or location of the content. Hence, in the context of this paper, we do not consider any of broadcast storm mitigation schemes proposed for the legacy vehicular networks.

The Interest holding time T_I used by the proposed Interest broadcast suppression (IBS) and forwarding algorithm discussed above, is computed as follows:

$$T_I = AIFS[i] + CD_I + \delta, \tag{1}$$

where, $AIFS[i]$ is the arbitration inter-frame spacing for access category i, $AC[i]$. There are different ACs that prioritize the messages as in IEEE 802.11p [13], [14]. The messages communicated through $AC[0]$ have the highest priority, whereas the $AC[3]$ is used for the background or low priority traffic. In the context of this paper, we assigned high priority to the Data messages assigned to $AC[0]$ and the Interest messages to the $AC[2]$. $AIFS[2]$ for the Interest message holding time in Eq. (1) is computed as

$$AIFS[2] = AIFSN[2] \times aSlotDuration + \rho, \tag{2}$$

where, AIFSN is the AIFS number, $AIFSN[2] = 6$ for $AC[2]$ and the slot duration $aSlotDuration$ is the backoff time unit of IEEE 802.11p that is $13\mu s$ with 10 MHz channel spacing. The last element in Eq. (2), ρ, is the short inter-frame space of $32\mu s$, which is considered to be an adequate time duration between the priority frames.

The next parameter in Eq. (1) is the random contention duration for Interest, CD_I, which is multiple of a random number of slots, the hop-count from which the Interest is received, and the slot duration

$$CD_I = (rand(1, CW_{min}[2]) \times HC) \times aSlotDuration, \tag{3}$$

where, the $CW_{min}[2]$ is the minimum contention window for the $AC[2]$ communication. The $CW_{min}[2]$ is estimated as $CW_{min}[2] = ((\frac{CW^{min}+1}{2}) - 1)$, refer [13]. The value of CW^{min} is considered in the computation of $CW_{min}[2]$ is 15. It is evident from the above expression that the nodes, which receive Interest from smaller hop-count (near the consumer), are given priority (forward Interest first) than the nodes with larger hop-count.

Finally, the term δ in Eq. (1) is the distance-based holding time priority factor to prefer the farthest distance nodes to be the potential Interest forwarders

$$\delta = rand(CW_{min}[2], (CW_{max}[2] \times \varepsilon)) \times aSlotDuration, \tag{4}$$

here, $CW_{max}[2]$ is the maximum contention window for $AC[2]$ that is $CW_{max}[2] = CW^{max} = 1023$, as in [13]. The element ε is distance ratio between nodes m and n in terms of the transmission range of m, T_R^m. Nodes near the boundary of the T_R^m have the smallest value of ε and are prioritized to forward the interest further in the network. The term ε is estimated as

$$\varepsilon = \frac{T_R^m - \sqrt{(x_m - x_n)^2 + (y_m - y_n)^2 + (z_m - z_n)^2}}{T_R^m}.$$

It is evident from the terms in Eqs. (3) and (4) that both CD_I and δ increase possibility for the nodes (within the same hop-count proximity) that are at the edge of the transmission range to become the Interest forwarders.

The Interest forwarding algorithm with no Interest broadcast suppression mechanism forwards all the received Interests. A node that is running the Interest forwarding algorithm with no IBS, only discards those Interests that are already received and recorded by the node (PIT has valid entries of those Interests). Next, we discuss the Data forwarding steps used by our proposed scheme.

3.3 Forwarding Data Messages

The content in a vehicular network can be the sensory data, coordinates, information and warning messages, video, audio, web, and so forth. All types of contents are communicated by NDN using the Data messages. Data messages produced by the nodes in response to the Interest message are termed as the *pull-based* communication. The messages are also received and forwarded by the nodes in the network. The contents may be produced by the vehicle itself or the vehicle may hold the contents in its CS that it received from or generated by other vehicles. The forwarding process of the Data message is modified by the proposed scheme to achieve maximum information coverage in the

NDN enabled VCPS. The proposed multimodal Data discovery scheme requires Data to carry D_{NONCE} in the Data message, which distinguishes the Data messages generated by different sources in the network. Additionally, the PIT also keeps the record of D_{NONCE} along with the $Name$, I_{NONCE}, and other Interest related parameters. Following is the detailed discussion of the Data message forwarding process that is well depicted in Algorithm 2.

Algorithm 2. Data Message Forwarding

procedure DATA MESSAGE PROCESSING ALGORITHM.
  Receives$\leftarrow$ **Data**[Name, D_{NONCE}, Content, Sign.,..]
  $i \leftarrow$ Interface from which n receives **Interest**
  $j \leftarrow$ Interface from which n receives **Data**
  $PIT \leftarrow$ [name, NONCE, Lifetime, in-Face(s), out-Face(s),...]
  $CS \leftarrow$ Content Store
  $FIB \leftarrow$ [Name Prefix, out-face(s), ...]
  if (Data Msg. *received* from Interface j) **then**
    if search(PIT, Name)=Success **then**
      Interface $i \leftarrow$ *search*(PIT, Name)
      if search(PIT, Name, D_{NONCE})=Fail **then**
        Compute T_D and Start **Timer**(T_D)
        When **Timer**(T_D) *Expires* {
          Form **Data**[Name, D_{NONCE}, Content,..]
          Send **Data** to Interface i
          Add(PIT, D_{NONCE})
        }
      else
        if Cache is Enabled **then**
          Add/Replace `Data` in CS
        end if
        Drop/Discard `Data`
      end if
    else
      Cache Unsolicited Data as Caching Policy
    end if
  end if
  if (Data Msg. *generated* in Reply to Interest) **then**
    Compute D_{NONCE}
    Compute T_D and Start **Timer**(T_D)
    When **Timer**(T_D) *Expires* {
      Add(PIT, Name, I_{NONCE}, D_{NONCE}, LifeTime, i)
      Form **Data**[Name, D_{NONCE}, Content,..]
      Send **Data** to Interface i
    }
  end if
end procedure

As stated earlier, a node either forwards the Data message that it receives from other nodes or it generates in response to the Interest. In the earlier case, when a node receives the Data message, the first step is to search the PIT to confirm that either the Data message is solicited (in reply to Interest with valid PIT entry) or unsolicited (no valid entry in the PIT). If PIT search for the Data message is successful, then D_{NONCE} is also matched with the D_{NONCE}s stored in the PIT record. The presence of D_{NONCE} in PIT indicates that the Data message had already been forwarded, hence, the message is dropped instantly. Alternatively, the absence of D_{NONCE} in the PIT signifies that the Data message is not forwarded earlier. Therefore, before forwarding the Data message further in the network, D_{NONCE} is added in the PIT and the vehicle computes a random defer time T_D to avoid collision between Data messages forwarded by different vehicles. The computation of T_D is discussed later in this section. Here, it is worth noting that the PIT entry is not purged even after forwarding the Data message and it persists until its PLT expires. This long PLT ensures that; a) The consumer must receive multiple instances of the Data provided or generated by different producers in the network. b) The intermediate nodes must assist in forwarding the multimodal data towards the consumer. Contingent upon the caching and replacement policies, the Data messages are cached at intermediate nodes between consumer and producer(s) accordingly.

In the other case, where the Data message is generated in response to the Interest, the vehicle has already verified that it received a new Interest and the vehicle is either producer of the content or has the content in its CS, refer Algorithm 1. The first step, in this case, is to compute random D_{NONCE} and then calculate and initiate the timer T_D. Once the timer T_D expires, the vehicle adds the PIT entry and sends the Data message through the interface from which it received the Interest.

Discovery of multimodal data using NDN results in a large Data traffic because many nodes generate and forward the Data messages. Hence, we introduced the random defer duration for Data message T_D to avoid Data packets' collision. The node first computes T_D and waits for the T_D duration before forwarding the Data. Once the T_D expires, a vehicle sends the Data message to the *in-face*. The T_D is estimated as follows:

$$T_D = AIFS[i] + CD_D + \delta_D, \tag{5}$$

where, $AIFS$ is computed as in Eq. (2), however, it considers the highest priority for Data messages, $AC[0]$. $AIFS[0]$ for the Data message is estimated as

$$AIFS[0] = AIFSN[0] \times aSlotDuration + \rho, \tag{6}$$

here, $AIFSN[0]$ for $AC[0]$ is 2 and CD_D is computed as

$$CD_D = (rand(0, CW_{min}[0]) \times HC) \times aSlotDuration, \tag{7}$$

where, HC is the hop-count from which the Interest was received, and when it is combined with $AC[0]$, they serve two purposes; a) the Data messages within the proximity of consumer are prioritized to reach consumer earlier than the messages from the vehicles at farther distances. b) It avoids the collision between Data messages and the Interest messages because forwarding of the Interests is delayed by using the lower priority $AC[2]$. Next, we estimate the δ_D as

$$\delta_D = rand(CW_{min}[0], CW_{max}[0]) \times aSlotDuration. \tag{8}$$

In the above expressions, $CW_{min}[0] = \left(\left(\frac{CW^{min}+1}{4}\right) - 1\right)$ and $CW_{max}[0] = ((\frac{CW^{min}+1}{2}) - 1)$, as in [13].

Performance of our proposed multimodal named data discovery scheme with IBS for VCPS is measured through simulations and discussed in the next section. The effectiveness of the proposed scheme is contrasted with its close counterparts in the literature and without the IBS to analyze how much Interest broadcast overhead is minimized by the proposed scheme.

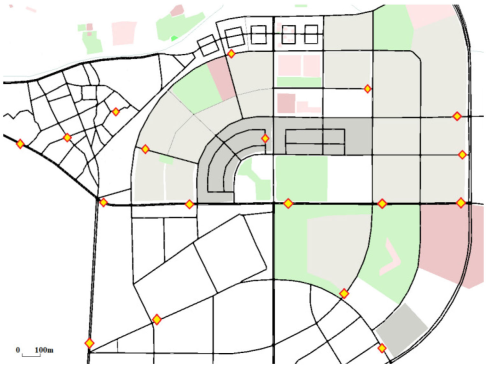


Fig. 3. Urban Scenario with road segment edge markers. Location: Sang-ri, Yuga-myeon, Dalseong-gun, Daegu, Korea.

4 Simulation Analysis

The simulation analysis of the proposed multimodal named data discovery scheme is briefly discussed in this section. The effectiveness of our proposed scheme is compared with the only multi-source name data discovery scheme in the literature published in [31] and [32]. Both the schemes use a similar set of steps to collect data from multiple sources, henceforth, we collectively refer to those as the conventional scheme. Consumer nodes in the conventional scheme generate Interests to collect contents from its one-hop neighbors only because it does not provide any mechanism to forward Interests further in the network. The Interest is kept in the consumer's PIT for a longer duration and not purged until it receives data from multiple neighbors. When a node receives an Interest, it replies with the Data message similar to the vanilla NDN and does not keep the PIT record. Therefore, the nodes in the network do not further take any part in the Data and the Interest forwarding process.

All vehicles in the network use proposed named data forwarding scheme over IEEE 802.11p to communicate with other vehicles. A vehicle or any network element in a VCPS scenario (traffic light, smart speed sign, etc.) collects traffic information from its surrounding vehicles or vehicles in the specific proximity to make intelligent decisions. Hence, the efficiency of the scheme is measured in terms of how much information is discovered, how much area is covered, what is the discovery overhead, and so forth.

In order to properly evaluate the effectiveness of the proposed scheme, we simulated the network over the highway and the urban mobility scenarios. In both the scenarios, the common simulation parameters are considered as follows: The IEEE 802.11p offers a maximum transmission range of $1km$ and varying data rates [37], [38]. Therefore, the transmission range of vehicles is varied from 300 to $900m$ in highway scenario and 100 to $900m$ in Urban scenarios to evaluate effectiveness of the proposed scheme. Furthermore, we also performed simulations for varying network sizes to investigate scalability of the proposed scheme. The network sizes considered in the simulation scenarios extend from 50 to 100 vehicles and all the vehicles remain in the network throughout the simulation duration. Besides that, we considered the diversified number of consumers in the simulations, $C = 1$, 2, and 3. Each consumer discovers multimodal information from the data discovery radius of $1Km$ ($R_d = 1km$). Individual C generates Interests at varying rates (Interest rate-IR) that vary from 1, 3, and 5 Interest per second. The information discovery period of each C is $2s$.

TABLE 1
Simulation Parameters

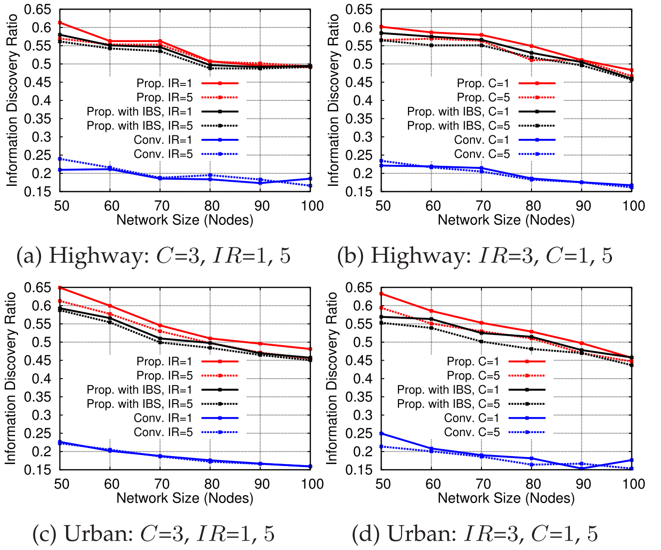
Simulation Parameter	Value
Common Simulation Parameters	
Communication Interface	IEEE 802.11p
Data Message Size	100 bytes
Interest Message Size	50 bytes
Network Size (N)	50, 60, ..., 100 Nodes
Transmission Range (T_r)	$300, 400, 500, \dots, 900m$
Max. PIT Entry Lifetime	$4s$
Interest Rate (IR)	1, 3, and 5
C	1, 3, and 5
Information Discovery Radius, D_r	$1Km$
Information Discovery Duration	$2s$
Simulation Duration	500s
Highway Scenario	
Highway Length	$10Km$
Lanes	4
Average Speed	50-80km/h
Urban Scenario	
Vehicle Acceleration	1.5 to $2.5m/s$
Vehicle Deceleration	2.5 to $4.8m/s$
Min. Inter-vehicle Distance	$4m$

In a highway mobility scenario, the road segment of $10Km$ long with four two-way lanes has been considered. All vehicles are randomly placed over the highway and they move towards the edge of the highway. Each vehicle randomly selects the speed between $50 - 80$ km/h that is the common speed of the urban highways in Korea. Once a vehicle reaches the edge of the highway, it starts traveling to the opposite edge of the highway. The urban mobility scenario used in the simulations considers the road network of Sang-ri city in Yuga-myeon, Dalseong-gun, Daegu, Korea, as shown in Fig. 3. All vehicles randomly select trips between the shown road segment edge markers on the map. The acceleration and deceleration of vehicles in this scenario range between 1.5 to 2.5 and 2.8 to 4.8, respectively. The minimum distance between two vehicles at the traffic light and on the move is $4m$. The unaltered traffic lights sequence and duration over the intersections have been used in the simulations. The vehicles reroute between the selected road edge markers throughout the simulation duration. It ensures that none of the vehicle exits from the network until the simulation ends.

The NDN forwarding daemon is implemented in Network Simulator (NS-2) and all the mobility traces are generated using Simulation of Urban Mobility (SUMO) [39]. Table 1 summarizes the rest of the simulation parameters.

The performance metrics that are monitored during simulation and contrasted with the conventional scheme, are as follows:

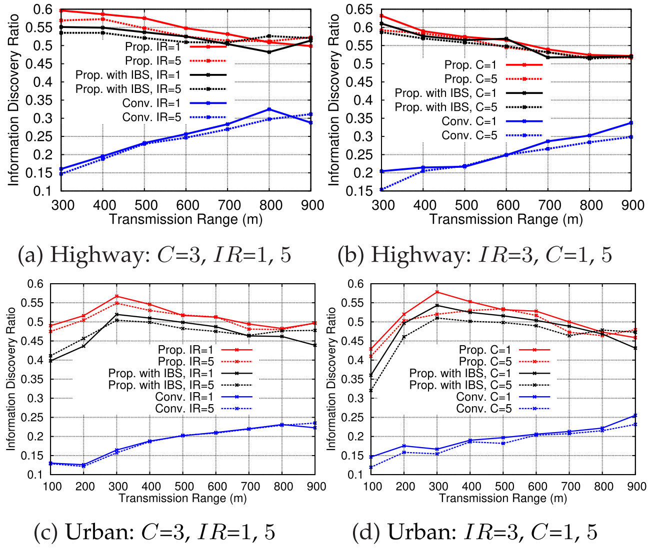
- *IDR-Information Discovery Ratio:* is the ratio of the total number of unique Data messages received from vehicles within the Information discovery region, S_r in response to the Interest generated by C, to the total number of vehicles in the S_r. IDR increases if C



(a) Highway: C=3, IR=1, 5 (b) Highway: IR=3, C=1, 5

(c) Urban: C=3, IR=1, 5 (d) Urban: IR=3, C=1, 5

Fig. 4. Information discovery ratio for varying N and T_r=400m in Highway (4a), (4b) and Urban (4c), (4d) scenarios.



(a) Highway: C=3, IR=1, 5 (b) Highway: IR=3, C=1, 5

(c) Urban: C=3, IR=1, 5 (d) Urban: IR=3, C=1, 5

Fig. 5. Information discovery ratio for varying T_r and N=70 in Highway (5a), (5b) and Urban (5c), (5d) scenarios.

successfully receives Data message from more number of vehicles in the S_r. To increase the IDR, nodes must efficiently forward the Interest throughout the S_r with minimum collision and overhead. Additionally, the nodes must also communicate the Data messages generated by the providers in the region towards C by alleviating the Data message collision

$$IDR = \frac{\text{Data msgs. received from vehicles in } S_r}{\text{No. of vehicles in } S_r}. \tag{9}$$

- *IDDR- Information Discovery Distance Ratio:* it is proportion of the farthest distant vehicle within S_r from which C has successfully received the Data message d_{max} over R_d

$$IDDR = \frac{d_{max}}{D_r}. \tag{10}$$

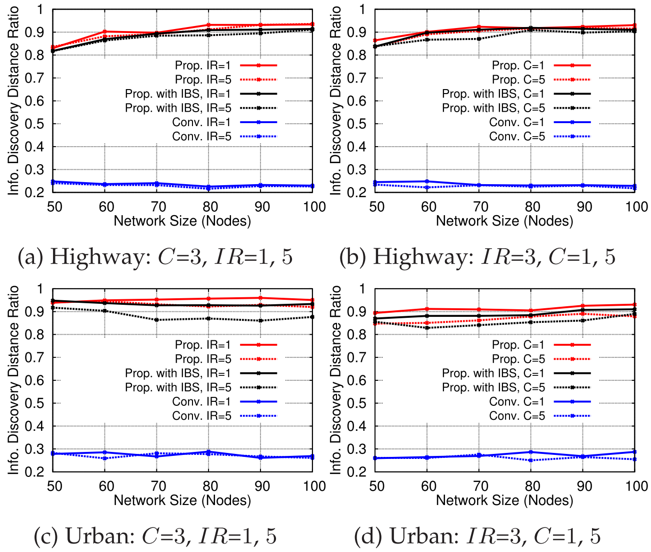
- *Total Forwarded Interest Messages:* is the total copies of the Interest messages processed with the network.
- *Total Forwarded Data Messages:* is the total copies of the Data messages forwarded by the vehicles in the network.
- *Average Delay / hop:* is the total end-to-end delay experienced by the Interest-Data exchange versus the total number of hops between C and the Data responding vehicle or the producer.

Following is the brief discussion of the simulated performance metrics simulated over the highway and the urban scenarios.

4.1 Simulation Results

Initially, we analyzed the IDR of a network scenario with a fixed transmission range of $400m$ versus the varying network sizes and the network scenario with constant network size of 70 nodes versus the varying transmission ranges, as shown in Figs. 4 and 5, respectively. The IDR observed in the highway usescase is depicted in Figs. 4a, 4b, 5a, and 5b. Similarly, Figs. 4c, 4d, 5c, and 5d show the IDR estimated in the urban scenario. There are few points that can easily be observed from these graphs, such as:

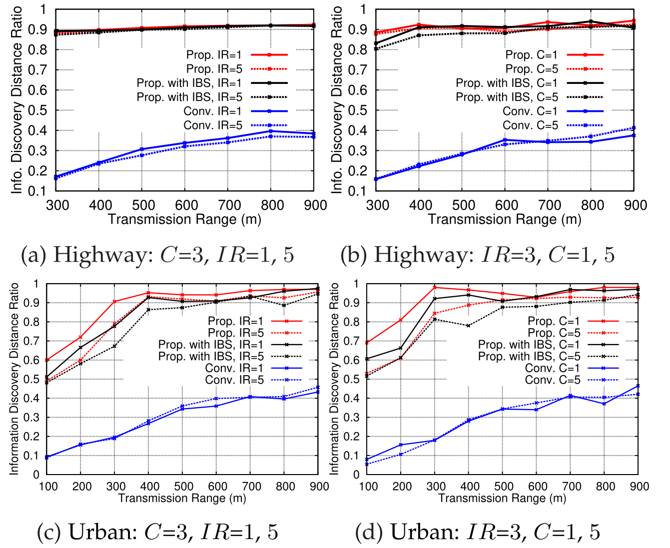
- Proposed scheme discovers more multimodal information than the conventional scheme which is obvious because the conventional scheme restricts the multimodal information discovery to one-hop.
- IDR of both the schemes reduces as the network size increases, which is mainly due to the collisions resulted by the Interest-Data broadcast.
- IDR of the conventional scheme slightly increases with the increase in the transmission range of the network. On the contrary, the IDR of the proposed scheme moderately lessens when the large transmission range is used by the vehicles. The principal cause behind this trend is that the conventional scheme restricts the communication of the Interest-Data at one-hop, which avoids collisions in the network. Also, the larger transmission range propagates Interest message to farther nodes in the network to collect more multimodal data. However, it is worth noting here that even though the transmission range is almost similar to R_d, the conventional scheme only discovers information from a maximum of 30 to 35 percent nodes in the discovery region in highway scenario and maximum of 25 percent in the urban scenario respectively shown in Figs. 5a and 5b, and Figs. 5c and 5d. The reasons for this low IDR includes packet drop due to collision and network partitioning. The packet drop due to collision occurs at C because all vehicles generate and forward information in Data packets directly to C and because of no coordination, the chances of Data collision become higher. The other reason for this low IDR is the network partitioning due to high mobility. In this scenario, different isolated clusters are formed within the S_r (the information discovery region) with no connectivity to the C. In result, all nodes within the large S_r fail to receive Interest packet, and successfully reply and forward the Data packets to C.



(a) Highway: C=3, IR=1, 5 (b) Highway: IR=3, C=1, 5

(c) Urban: C=3, IR=1, 5 (d) Urban: IR=3, C=1, 5

Fig. 6. Maximum information discovery distance ratio for varying N and T_r=$400m$ in Highway (6a), (6b) and Urban (6c), (6d) scenarios.



(a) Highway: C=3, IR=1, 5 (b) Highway: IR=3, C=1, 5

(c) Urban: C=3, IR=1, 5 (d) Urban: IR=3, C=1, 5

Fig. 7. Maximum information discovery distance ratio for varying T_r and N=70 in Highway (7a), (7b) and Urban (7c), (7d) scenarios.

- In the sparse network scenario (less number of nodes or small transmission range) it is also observed that the proposed scheme without IBS has marginally more IDR than the proposed scheme with IBS. However, in a dense network scenario, the proposed scheme with and without IBS has almost identical IDR. The fundamental cause of this phenomenon is that the proposed scheme tries to minimize the IBS and during that process, the Interest could not reach all nodes within the discovery region. Additionally, the IDR decreases with the decrease in the T_r, which is obvious because the unsuccessful Interest and Data messages dissemination in the network due to intermittent links.

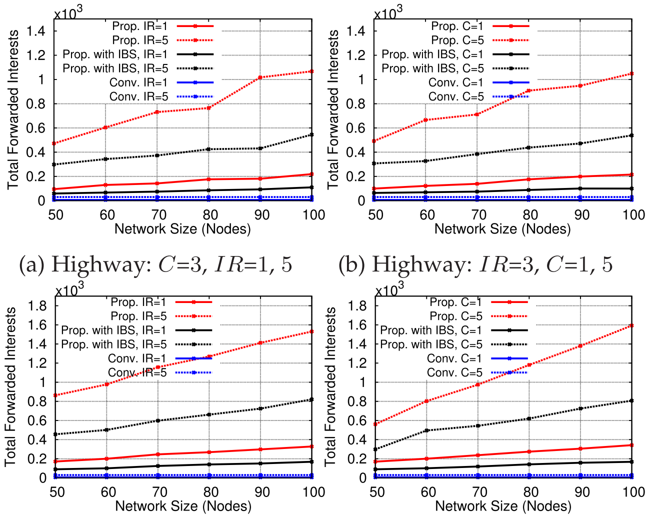
The simulations results observed for the highway scenario in Fig. 4a show that respectively the proposed scheme without and with IBS discover about 193 and 176 percent more information than the conventional scheme for $IR = 1$ and, 182 and 173.5 percent more IDR for $IR = 5$ Interests per second. It is also important to observe that IDR of the proposed scheme without IBS has about 5 percent more IDR than the proposed scheme with IBS. In the same scenario, Fig. 4b, the proposed scheme has an almost similar improvement over the conventional scheme for $C = 1$ and $C = 5$ network scenario. On average, the proposed scheme achieves about 180 percent more IDR than the conventional scheme in Figs. 4a and 4b. The obvious IDR improvement achieved by the proposed scheme in the urban scenario can also be visualized in the same figure, refer Fig. 4c and 4d.

In addition, the overall improvements achieved by the proposed scheme in contrast to the conventional scheme for varying T_r in the highway use case, are about 142 and 148 percent, as shown in Figs. 5a and 5b, respectively. Correspondingly, the performance of the proposed scheme in the urban scenario is identical to the highway scenario that can easily be observed from Figs. 4 and 5.

The next parameter we investigated through simulations is the IDDR in highway and urban traffic conditions for varying network sizes and the transmission ranges, as shown in Figs. 6 and 7, respectively. This performance metric measures the distance of the farthest node to the consumer from which C has successfully received the multimodal content. It is evident from the results that the proposed scheme has successfully received multimodal content from the farthest nodes in the network than the conventional scheme. Fig. 6 shows that the proposed scheme discovers information from approximately three times more distant nodes than the conventional scheme for any network parameters and traffic scenarios. The graphs in Fig. 6 also reveal that the proposed schemes collected multimodal data from more than 90 percent of the S_r in both highway and the urban traffic conditions. It is also clear from the figures (in Fig. 6) that as the network size increases, a significant increase in the IDDR also witnessed for the proposed scheme. The reason behind this trend is that the proposed scheme forwards Interest-Data through intermediate nodes to the farthest nodes in the S_r. On the contrary, no impact of the high network density has been witnessed for the conventional scheme in Fig. 6. It is worth noting here that the IDDR performance of both the proposed schemes (Proposed scheme without IBS and with IBS) is almost identical in the graphs.

Furthermore, the IDDR for varying transmission range in Fig. 7 depicts that the proposed schemes achieve an identical performance of discovering multimodal data from more than 90 percent of the S_r area in both highway and urban traffic conditions. Nonetheless, a large increase in the IDDR has also been observed for the conventional scheme because the larger transmission range helps the conventional scheme to collect information from the distant nodes. On the other hand, the conventional scheme could hardly discover information from 40 percent of the area even if the transmission range is increased to 90 percent of the R_d. That is due to large Data message traffic at C that results in the high Data packet drop.

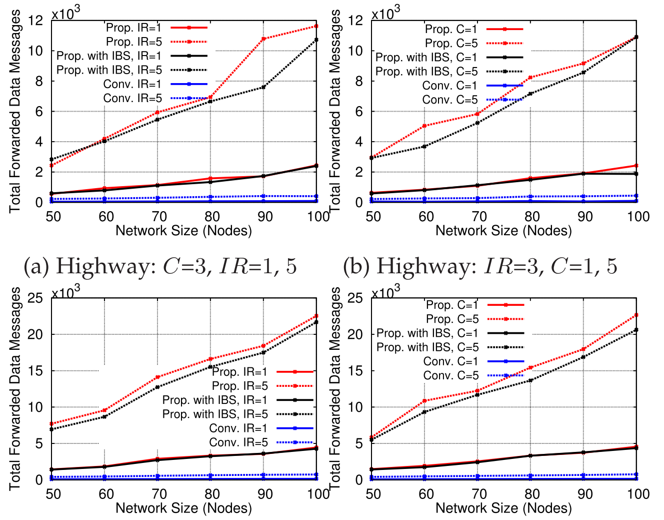
From the above discussion, we observed that the proposed schemes have almost identical performance in terms of IDR and IDDR. The main difference between the proposed scheme without and with IBS is obvious that the later one minimizes the Interest broadcast storm by employing



(a) Highway: C=3, IR=1, 5 (b) Highway: IR=3, C=1, 5

(c) Urban: C=3, IR=1, 5 (d) Urban: IR=3, C=1, 5

Fig. 8. Forwarded Interest messages for varying N and T_r=$400m$ in Highway (8a), (8b) and Urban (8c), (8d) scenarios.

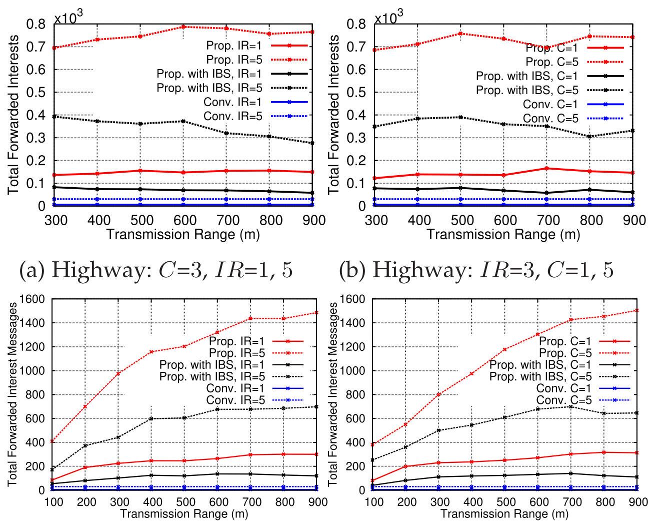


(a) Highway: C=3, IR=1, 5 (b) Highway: IR=3, C=1, 5

(c) Urban: C=3, IR=1, 5 (d) Urban: IR=3, C=1, 5

Fig. 10. Forwarded Data messages for varying network size and T_r=$400m$ in Highway (10a), (10b) and Urban (10c), (10d) scenarios.

the distance and hop-count information. During simulations, we also counted the total number of forwarded or processed Interest messages throughout the simulation duration for varying network sizes and transmission ranges in the highway and urban traffic scenarios as shown in Figs. 8 and 9, respectively. There are few points worth noting from those graphs that; a) The proposed scheme with IBS suppresses approximately 55 percent Interests than the proposed scheme without IBS in highway as well as the urban traffic scenarios. b) The conventional scheme generates only one Interest for every multimodal Information discovery instance depending upon the IR and discovers only a fractional amount of the multimodal data. Hence, the number of forwarded Interests by the conventional scheme is less and besides the point to be considered in the comparison. However, we plotted the number of Interests processed by the conventional scheme in the results. c) The total



(a) Highway: C=3, IR=1, 5 (b) Highway: IR=3, C=1, 5

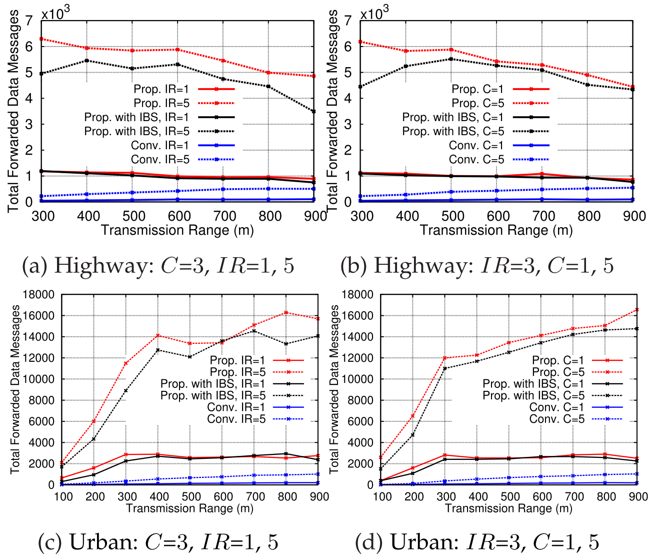
(c) Urban: C=3, IR=1, 5 (d) Urban: IR=3, C=1, 5

Fig. 9. Forwarded Interest messages for varying T_r and N=70 in Highway (9a), (9b) and Urban (9c), (9d) scenarios.

number of forwarded Interests decreases with the increase in the transmission range for the proposed scheme with IBS, which is not the case for the proposed scheme without IBS in highway traffic conditions, refer to Figs. 9a and 9b. However, in the urban scenario where many vehicles are on the move around all quadrants of the Interest forwarder, the forwarded number of Interests is very high compared to the highway scenario. In result, the proposed scheme without IBS forward more Interests packets in the urban scenario compared to the one in the highway use case. Nonetheless, the proposed scheme with IBS reduces Interest traffic up to 50 percent in the urban scenario compared to the proposed scheme without IBS, refer Figs. 9c and 9d. d) The total number of Interests processed in the network are directly proportional to the IR and the number of consumers, which can easily be observed from the results, in Figs. 8 and 9. Nevertheless, the modified proposed scheme with IBS support clearly reduces the Interest broadcast storm significantly in any traffic scenario.

Aside from analyzing the number of forwarded copies of the Interest, we also recorded the total number of Data messages processed in the network. In NDN, the Data messages are forwarded by all the nodes that have a valid entry in the PIT. In contrast to the vanilla NDN, the nodes in the proposed schemes maintain long PIT entries and do not purge the entry even if they receive multiple copies of the Data message. Similarly, the nodes that receive a copy of the Interest requesting multimodal content, they generate Data messages. In the CPS-based vehicular scenario, each generated Data message contains a different instance of the important data and should be communicated to the consumer to make an appropriate decision. Therefore, the number of forwarded Data messages by the proposed schemes is larger than the conventional scheme. Simulation results in Fig. 10 shows the total forwarded Data messages in the network for varying network sizes in both the traffic scenarios.

The number of Data messages forwarded by the proposed schemes for IR=1 and C=1 in the highway (Figs. 10a and 10b) are almost identical. The urban scenario follows



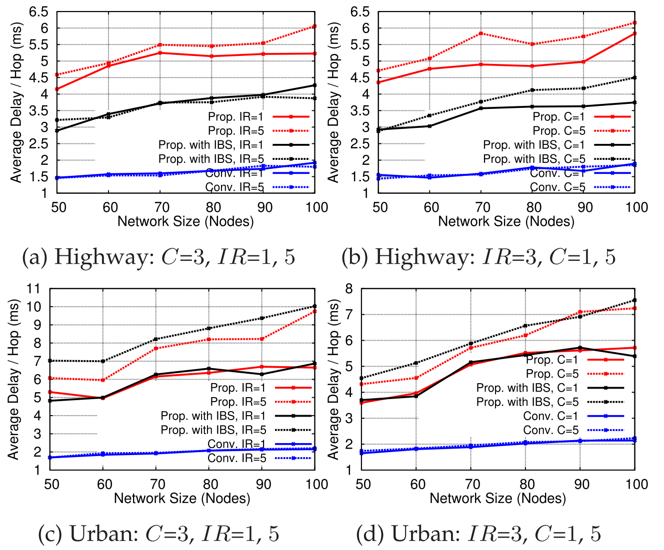
(a) Highway: C=3, IR=1, 5 (b) Highway: IR=3, C=1, 5

(c) Urban: C=3, IR=1, 5 (d) Urban: IR=3, C=1, 5

Fig. 11. Forwarded Data messages for varying T_r and N=70 in Highway (11a), (11b) and Urban (11c), (11d) scenarios.

the same trend if we compare the Figs. 10a and 10b. However, it is observed that the proposed scheme with IBS could not forward as much number of Data messages as the proposed scheme without IBS in the $IR = 5$ and $C = 5$ in all traffic scenarios in Fig. 10. This is because the proposed scheme with IBS selects the forwarders that are at the edge of the transmission range of the Interest sender. However, due to large contention window range CW_{min} and CW_{max}, as well as the distance factor, it could not properly propagate the Interest throughout the S_r. Thus, it discovers slightly less amount of multimodal data from the network that can be observed in Figs. 4, 5, 6, and 7. The similar trends can also be observed from the graphs in Fig. 11.

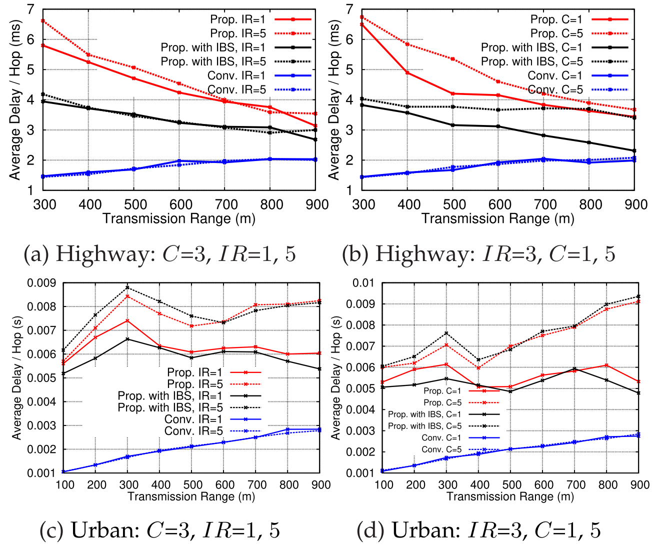
Finally, we discuss the average end-to-end delay per hop for the satisfied Interests. Average delay per hop for varying network sizes and the transmission ranges are shown in Figs. 12 and 13, respectively. It is observed from the graphs that the conventional scheme has less average delay per hop than both the proposed schemes. The basic reason behind this phenomenon is that vehicles in the one-hope of the consumer simply reply to the Interest without further waiting for any additional delay. Another trend of the conventional scheme that has been observed is that it's per-hop delay slightly increases when the network size and transmission range increase. It is obvious that the propagation delay is directly proportional to the distance between nodes and in case of more number of nodes, the large number of Data packets will increase the chances of packet collisions. Furthermore, the proposed schemes have large per-hop delay which is due to holding time for both Interest as well as the Data messages. The holding time is computed at every hop and it also depends upon the number of hops the Interest has traversed in the network. Fig. 12 depicts that the per-hop delay increases as the network size increases. This slow rise in the delay is owing to the successful Interest-Data delivery between C and the vehicles in S_r because there are many vehicles available to forward the Data messages. Conversely, the per-hop delay alleviates as the transmission range gets larger. The obvious reason for that decrease in the delay is because of the small number of holding timers at fewer hops.



(a) Highway: C=3, IR=1, 5 (b) Highway: IR=3, C=1, 5

(c) Urban: C=3, IR=1, 5 (d) Urban: IR=3, C=1, 5

Fig. 12. Average delay per hop for each satisfied Interest versus the varying N nd T_r=$400m$ in Highway (12a), (12b) and Urban (12c), (12d) scenarios.



(a) Highway: C=3, IR=1, 5 (b) Highway: IR=3, C=1, 5

(c) Urban: C=3, IR=1, 5 (d) Urban: IR=3, C=1, 5

Fig. 13. Average delay per hop for each satisfied Interest versus the varying T_r and N=70 in Highway (13a), (13b) and Urban (13c), (13d) scenarios.

Figures also show that the proposed scheme with IBS has a smaller delay than the proposed scheme without IBS. The proposed scheme prioritizes the nodes that are at the edge of the transmission range to forward the Interests, which ensures the quick interest forwarding within the S_r. Proposed scheme with IBS has about 29 and 30 percent less average per-hop delay compared to the proposed scheme without IBS for the highway scenario in Figs. 12a and 12b, respectively. On the other hand, the per-hop delay increases in the urban scenario and both the schemes experience almost same per hod delay, refer to Figs. 12c and 12d. This is due to the large Interest and Data message traffic handled by both the schemes in this scenario, as discussed above. The average delay per hop performance for varying T_r in Fig. 13 also shows the matching trend and performance improvement as in Fig. 12.

To summarize the above discussion, our proposed schemes discover *more* multimodal information (high *IDR*) from the farthest nodes in the S_r (large *MICDR*) by minimizing the Interest broadcast storm, compared to the conventional NDN-based multimodal Data discovery scheme. The proposed schemes also prove that they perform efficiently in highway and the urban traffic scenarios. Results also indicate that the conventional scheme has the lowest per-hop delay compared to the proposed schemes. The rationale behind this phenomenon is that the nodes in one-hop simply reply to the Interest message without any additional delay.

5 Conclusion

Information discovery and availability at individual vehicular network component in the vehicular cyber-physical systems is important to take the proper control decisions. Thus, we proposed the communication model involving future Internet architecture to discover multimodal contents in the NDVCPS. In order to discover multimodal data from a specific region of the network, the Interest message is disseminated to all nodes within that area. Consequently, the Interest broadcast storm is one of the issues that is resolved by the proposed using the IBS technique. Our proposed scheme discovers about 172 and 120 percent more traffic information from the network, and increase the information discovery area about 283 and 200 percent network area compared to the conventional scheme for varying network sizes and transmission ranges, respectively. Our proposed scheme with IBS respectively disseminates 50 percent less number of Interests and has 28.3 percent lower delay relative to the proposed scheme without IBS.

It is observed that the proposed schemes discover more multimodal information from the network that results in a large amount of Data message traffic. Hence, we intend to further investigate on reducing the Data overhead by adapting the holding time and packet deferring methods. Furthermore, we witnessed that the proposed schemes have a large per-hop delay and intend to improve the holding time computation methods to further alleviate the delay.

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References

[1] C. Chen, X. Liu, T. Qiu, and A. K. Sangaiah, "A short-term traffic prediction model in the vehicular cyber-physical systems," *Future Gener. Comput. Syst.*, vol. 105, pp. 894–903, 2020.

[2] D. B. Rawat and C. Bajracharya, "Adaptive connectivity for vehicular cyber-physical systems," in *Vehicular Cyber Physical Systems*. Berlin, Germany: Springer, 2017, pp. 15–24.

[3] D. Jia, K. Lu, J. Wang, X. Zhang, and X. Shen, "A survey on platoon-based vehicular cyber-physical systems," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 1, pp. 263–284, Firstquarter 2016.

[4] J. Wan, D. Zhang, S. Zhao, L. T. Yang, and J. Lloret, "Context-aware vehicular cyber-physical systems with cloud support: Architecture, challenges, and solutions," *IEEE Commun. Mag.*, vol. 52, no. 8, pp. 106–113, Aug. 2014.

[5] D. Lahat, T. Adali, and C. Jutten, "Multimodal data fusion: An overview of methods, challenges, and prospects," *Proc. IEEE*, vol. 103, no. 9, pp. 1449–1477, Sep. 2015.

[6] S. Lim and J. H. Yang, "Driver state estimation by convolutional neural network using multimodal sensor data," *Electron. Lett.*, vol. 52, no. 17, pp. 1495–1497, 2016.

[7] J. Zhang, F.-Y. Wang, K. Wang, W.-H. Lin, X. Xu, and C. Chen, "Data-driven intelligent transportation systems: A survey," *IEEE Trans. Intell. Transp. Syst.*, vol. 12, no. 4, pp. 1624–1639, Dec. 2011.

[8] A. Gal *et al.*, "REMI, reusable elements for multi-level information availability: Demo," in *Proc. ACM Int. Conf. Distrib. Event-Based Syst.*, 2017, pp. 323–326.

[9] B. Donovan and D. B. Work, "Empirically quantifying city-scale transportation system resilience to extreme events," *Transp. Res. Part C, Emerg. Technol.*, vol. 79, pp. 333–346, 2017.

[10] K. Golestan *et al.*, "Vehicular ad-hoc networks (VANETs): Capabilities, challenges in information gathering and data fusion," in *Proc. Int. Conf. Auton. Intell. Syst.*, 2012, pp. 34–41.

[11] F. Sattar, F. Karray, M. S. Kamel, L. Nassar, and K. Golestan, "Recent advances on context-awareness and data/information fusion in ITS," *Int. J. Intell. Transp. Syst. Res.*, vol. 14, no. 1, pp. 1–19, 2016.

[12] "IEEE draft standard for amendment to standard [for] information technology-Telecommunications and information exchange between systems-Local and metropolitan networks-Specific requirements-Part II: wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications-Amendment 6: Wireless access in vehicular environments," *IEEE Std P802.11p/D11.0 April 2010*, pp. 1–35, June 2010.

[13] "IEEE standard for information technology–Local and metropolitan area networks–Specific requirements–Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications amendment 6: Wireless access in vehicular environments," *IEEE Std 802.11p-2010 (Amendment to IEEE Std 802.11-2007 as amended by IEEE Std 802.11k-2008, IEEE Std 802.11r-2008, IEEE Std 802.11y-2008, IEEE Std 802.11n-2009, and IEEE Std 802.11w-2009)*.doi: 10.1109/IEEESTD.2010.5514475.

[14] C. Han, M. Dianati, R. Tafazolli, R. Kernchen, and X. Shen, "Analytical study of the IEEE 802.11p MAC sublayer in vehicular networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 2, pp. 873–886, Jun. 2012.

[15] M. Gerla, C. Wu, G. Pau, and X. Zhu, "Content distribution in VANETs" *Veh. Commun.*, vol. 1, no. 1, pp. 3–12, 2014.

[16] L. Zhang *et al.*, "Named data networking," *SIGCOMM Comput. Commun. Rev.*, vol. 44, no. 3, pp. 66–73, 2014.

[17] X. Wang and X. Wang, "Vehicular content-centric networking framework," *IEEE Syst. J.*, vol. 13, no. 1, pp. 519–529, Mar. 2019.

[18] S. H. Ahmed, S. H. Bouk, and D. Kim, "Content-centric networks: An overview," in *Applications and Research Challenges*. Berlin, Germany: Springer, 2016.

[19] V. Jacobson, D. K. Smetters, J. D. Thornton, M. F. Plass, N. H. Briggs, and R. L. Braynard, "Networking named content," in *Proc. 5th Int. Conf. Emerg. Netw. Experiments Technol.*, 2009, pp. 1–12.

[20] Z. Zhang *et al.*, "An overview of security support in named data networking," *IEEE Commun. Mag.*, vol. 56, no. 11, pp. 62–68, Nov. 2018.

[21] G. Grassi *et al.*, "ACM HotMobile 2013 poster: Vehicular inter-networking via named data," *ACM SIGMOBILE Mobile Comput. Commun. Rev.*, vol. 17, no. 3, pp. 23–24, 2013.

[22] G. Grassi, D. Pesavento, G. Pau, R. Vuyyuru, R. Wakikawa, and L. Zhang, "VANET via named data networking," in *Proc. IEEE Conf. Comput. Commun. Workshops*, 2014, pp. 410–415.

[23] G. Grassi, D. Pesavento, G. Pau, L. Zhang, and S. Fdida, "Navigo: Interest forwarding by geolocations in vehicular named data networking," in *Proc. IEEE 16th Int. Symp. World Wireless Mobile Multimedia Netw.*, 2015, pp. 1–10.

[24] S. H. Ahmed, S. H. Bouk, D. Kim, and H. Song, "Named-data-networking-based its for smart cities," *IEEE Commun. Mag.*, vol. 55, no. 1, pp. 105–111, Jan. 2017.

[25] S. H. Ahmed, S. H. Bouk, M. A. Yaqub, D. Kim, and H. Song, "DIFS: Distributed interest forwarder selection in vehicular named data networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 19, no. 9, pp. 3076–3080, Sep. 2018.

[26] S. H. Bouk, S. H. Ahmed, M. A. Yaqub, D. Kim, and M. Gerla, "DPEL: Dynamic PIT entry lifetime in vehicular named data networks," *IEEE Commun. Lett.*, vol. 20, no. 2, pp. 336–339, Feb. 2016.

[27] S. H. Ahmed, S. H. Bouk, M. A. Yaqub, D. Kim, H. Song, and J. Lloret, "CODIE: Controlled data and interest evaluation in vehicular named data networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 6, pp. 3954–3963, Jun. 2016.

[28] S. H. Ahmed, S. H. Bouk, and D. Kim, "RUFS: RobUst forwarder selection in vehicular content-centric networks," *IEEE Commun. Lett.*, vol. 19, no. 9, pp. 1616–1619, Sep. 2015.

[29] S. H. Bouk, S. H. Ahmed, and D. Kim, "Hierarchical and hash based naming with Compact Trie name management scheme for vehicular content centric networks," *Comput. Commun.*, vol. 71, pp. 73–83, 2015.

[30] B. Ahlgren, C. Dannewitz, C. Imbrenda, D. Kutscher, and B. Ohlman, "A survey of information-centric networking," *IEEE Commun. Mag.*, vol. 50, no. 7, pp. 26–36, Jul. 2012.

[31] M. Amadeo, C. Campolo, and A. Molinaro, "Information centric networking in IoT scenarios: The case of a smart home," in *Proc. IEEE Int. Conf. Commun.*, 2015, pp. 648–653.

[32] M. Amadeo, C. Campolo, and A. Molinaro, "Multi-source data retrieval in IoT via named data networking," in *Proc. 1st ACM Conf. Inf.-Centric Netw.*, 2014, pp. 67–76.

[33] E. Borgia, R. Bruno, and A. Passarella, "MobCCN: A CCN-compliant protocol for data collection with opportunistic contacts in IoT environments," in *Proc. 11th ACM Workshop Challenged Netw.*, 2016, pp. 63–68.

[34] J. Saltarin, E. Bourtsoulatze, N. Thomos, and T. Braun, "NetCodCCN: A network coding approach for content-centric networks," in *Proc. IEEE INFOCOM*, 2016, pp. 1–9.

[35] W.-X. Liu, S.-Z. Yu, and P.-Y. Zhu, "Multisource dissemination in content-centric networking," in *Proc. 4th Int. Conf. Netw. Future*, 2013, pp. 1–5.

[36] L. Zhang, B. Hassanabadi, and S. Valaee, "Cooperative positive orthogonal code-based forwarding for multi-hop vehicular networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 7, pp. 3914–3925, Jul. 2014.

[37] M. E. Renda, G. Resta, P. Santi, F. Martelli, and A. Franchini, "IEEE 802.11p VANets: Experimental evaluation of packet inter-reception time," *Comput. Commun.*, vol. 75, pp. 26–38, 2016.

[38] J. A. Fernandez, K. Borries, L. Cheng, B. V. K. Vijaya Kumar, D. D. Stancil, and F. Bai, "Performance of the 802.11p Physical layer in vehicle-to-vehicle environments," *IEEE Trans. Veh. Technol.*, vol. 61, no. 1, pp. 3–14, Jan. 2012.

[39] M. Behrisch, L. Bieker, J. Erdmann, and D. Krajzewicz, "Sumo-simulation of urban mobility," in *Proc. 3rd Int. Conf. Advances Syst. Simul.*, 2011, pp. 63–68.

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