

LAPEL: Hop Limit Based Adaptive PIT Entry Lifetime for Vehicular Named Data Networks

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Abstract—Named data networking (NDN) uses the content name instead of its location within the interest message to locate the content within the network. An interest is broadcasted by the content seeking node over the wireless channel with specific content name and waits for the data message containing the actual content. The broadcast region of an interest is restricted by using the time-to-live (TTL) field of the message. Record of every pending interest is stored in the pending interest table (PIT) for a specific duration, called PIT entry lifetime (PEL). The record is purged when a node either receives the data message or the PEL expires. The size of the PIT has a significant impact on the name prefix search during the interest or data message forwarding process. Additionally, the interest and/or data message loss in the vehicular network is very frequent, which results in a significant PIT size depending on the PEL. Vanilla NDN uses the fixed PEL of 4 s, and the very recent work considers the constant parameters to control the PEL, which fails to reduce the PIT size. Hence, in this paper, we propose a hop limit based adaptive PEL (LAPEL) scheme, which adaptively estimates the PEL at interest forwarding vehicle. LAPEL estimates PEL based on the lower layer parameters and has no constant factor that makes it more adaptive than the previously proposed schemes. Simulation results show that LAPEL has 52% less PEL, reduces 8.4% the PIT size, and achieves 4.5% more interest satisfaction ratio, for any simulated TTL and interest rates.

Index Terms—NDN, WSN, interest, holding time, broadcast storm.

I. INTRODUCTION

VEHICULAR Ad-hoc NETwork (VANET) has been envisioned as one of the promising technology for the

future transportation system. In VANET, vehicles act as routers with high mobility, large storage capacity, and high processing speed. Each vehicle is capable of communicating with other vehicles with and without the support of infrastructure, i.e., Road Side Units (RSUs) installed in the network to fulfill the content requirements of the applications [1]–[3]. Additionally, vehicles have the capability to store sufficient amount of contents that are either destined for other vehicles or to the vehicle itself. VANET uses Wireless Access in Vehicular Environment (WAVE) operation mode in IEEE 802.11p over Dedicated Short Range Communication (DSRC) band [4]. IEEE 802.11p is the key lower layer technology in VANETs that offers priority communication services related to the broad range of safety and non-safety applications.

The safety-related contents are assigned high priority and communicated with minimum delay compared to the background application traffic that has the lowest priority in VANETs. Safety and non-safety related applications require content to fulfill the applications' demands (e.g., security requirements, delay, etc.) and are not bound to the location of content [5]–[7]. The current communication architectures used by VANETs requires vehicle identification, i.e., IP or MAC address, to establish the connection between content requesting and content providing vehicles [8]. Connection establishment before the communication of the actual content is essential in the current communication architectures used by VANETs. However, the nature of the VANET architecture is highly dynamic, and the establishment of the end-to-end connection is relatively challenging to support. Vehicle identification and connectivity based communication in VANETs inherit the similar challenges that are faced by the legacy wireless ad-hoc networks [9]–[11].

Recently, a new set of communication architecture has been widely researched that satisfy the content demand of the applications irrespective of their content location, called Information Centric Networking (ICN) [12]. Named Data Networking (NDN) [13], is one of the most widely investigated ICN architectures that communicates and locates the content using the content *name* [14]. NDN is the enhanced implementation of CCN [15], and its feasibility is investigated in the vehicular networks [16]–[28]. In the context of this paper, the terms node, vehicle, and NDN enabled mobile network element are interchangeably used.

If an application running on the On-Board Unit (OBU) of a vehicle (called consumer vehicle or node) in the NDN enabled VANET, requires any content, it sends a content request

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(Interest) message containing the content name. In response, the vehicle(s) holding the requested content in their memory send content in the *Data* message. In addition to this simplified pull-based communication, NDN enables intrinsic security within the content itself, but not the channel. NDN also exploits the temporary caching to fulfill the future content demand in the network. These features of NDN communication are well suited for the highly dynamic and ad-hoc nature of the vehicular network.

Vanilla NDN architecture uses different data structures at every NDN enabled network element to achieve this simple pull-based content communication. These conventional data structures include Forwarding Information Base (FIB), Pending Interest Table (PIT), and Content Store (CS). FIB is responsible for forwarding Interest messages. It maintains the Name prefixes and the associated outgoing interface(s), *OutFace(s)*. When a node or a vehicle receives an Interest, it matches the name of that Interest with the name prefixes. In the case of matching prefix found in FIB, the Interest is forwarded to the associated interface of that prefix record. The next structure is the CS, which stores the contents (either full or partial) that are either generated or received by the vehicle. When a node receives an Interest, initially it performs the content search in the CS. If it finds any matching named content in the CS, the content is sent to the consumer in the *Data* message. Content fragmentation and re-assembly are also performed for the large size contents by the content providing node or the intermediate Data forwarding node(s).

Finally, the PIT data structure holds the record of the incoming Interests. Each entry in the PIT contains the content *Name*, large random number, called *NONCE*, and incoming Interface (interface from which the Interest has been received, simply denoted as *InFace*). The entry is purged if a node receives the corresponding *Data* message. If a node does not receive any *Data* message, then this entry removed after some predefined period. This whole PIT entry duration is termed as *PIT entry lifetime* or PEL. Interest message also has the Time to Live (TTL) field to limit the Interest broadcast scope in the wireless networks. Upstream nodes forward Interest until $TTL > 0$. If a node receives *Data* message for the specific Interest, then TTL is incremented, and it re-transmits the Interest again. Interest is retransmitted for a maximum of m times, and if a node does not receive any content during that maximum Interest retransmission limit or retry attempt, then the Interest is discarded. Selection of initial TTL value and its increment is application dependent.

Recently, NDN has been adapted in the vehicular networks to meet the data or content demand of the applications running over the VANET nodes [16]–[28]. These applications include, but not limited to traffic information, the Point of Interest (POI) details, road condition discovery, entertainment, and so forth, which use the pull-base data communication model. Fig. 1 shows the pull-based Interest-Data forwarding in the typical VANET scenario. An Interest is generated by the VANET application running over the consumer vehicle, *C*. Vehicles v_1 and v_2 receive Interest, and they search their CSs and PITs. If the requested content is not in CSs and PITs of the vehicles, then they further disseminate Interest in the network after adding name prefix in their

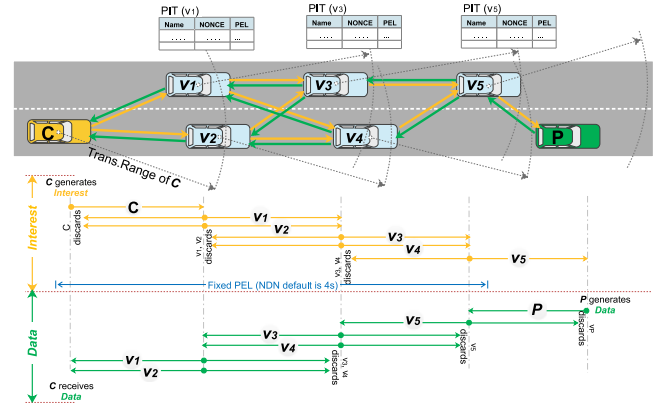


Fig. 1. Interest-Data forwarding in NDN-enabled VANETs.

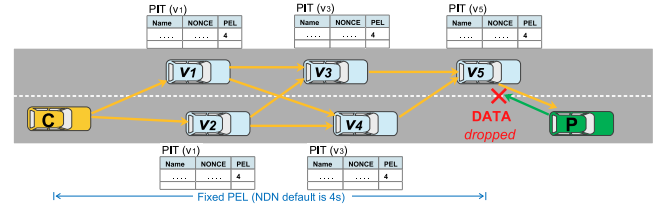


Fig. 2. Data message drop or failure scenario in NDN-enabled VANETs.

respective PITs. When vehicles (e.g., v_1 and v_2) forward the Interest, the vehicles (e.g., *C*) that have already valid PIT entry, receive the same Interest, they just discard the message because they have already forwarded the Interest. When vehicle *P*, with the requested content in its CS, receives the Interest, it replies with the *Data* message. The *Data* message is forwarded by all vehicles that have the valid PIT entry. After forwarding the *Data* message, the vehicle purges its respective PIT record. In case, the *Data* message is dropped, then all the vehicles hold the PIT record until its PEL duration, refer Fig. 2.

A node may receive millions of different Interest messages to acquire different contents, and the node needs to perform PIT search for every Interest. PIT search operation involves string prefix matching, which takes longer time (than the IP prefix search) due to a large and variable size of the content name. The large PIT size will worsen the search delay, which is not suitable for time-constrained content communication. In addition to that the size of the PIT may increase rapidly in the dynamic topology networks with fixed PEL because all Interests may not be satisfied due to packet drop, as shown in Fig. 2. Even the node has to wait for at least PEL amount of time to retry for the same content because an Interest for the same content name cannot be retransmitted by any node if it has the valid entry in its PIT. Therefore, the selection of PEL is vital in the NDN enabled VANET.

Vanilla NDN uses a fixed size PEL that is 4 s. In literature, there are few works that precisely focus on the PIT entry lifetime [30], [31]. In [30], authors used the Interest response time or Interest-Data round trip delay (RTD) to approximate the PIT entry life. However, the initial PEL for the first Interest is set to 1 s. The authors in [31] proposed the Dynamic PEL (DPEL) scheme. It uses the exponential decay model to reduce PEL at upstream nodes that forward the Interest dynamically. Initially,

a constant PEL value and the decay rate is set by the application, and at successive hops, the PEL is estimated using the node's Interest satisfaction rate and the provided constants.

In RTD based scheme, it is quite difficult to estimate the exact RTD in dynamic topology VANET that has a highly unpredictable link quality. Additionally, the Interest producer generates its first Interest with the fixed PEL, which is considered to be sufficient to receive the Data message. If there is no Data message within this fixed interval, then retransmission also uses the same PEL. The approximation of RTD at intermediate nodes is larger than the downstream nodes; then the Interest retransmissions can be suppressed. Similarly, each node has to estimate and maintain for each name prefix. The estimation of the fixed initial PEL and decay rate in DPEL is also challenging and impractical. To overcome these shortcomings, we proposed the hop limit based Adaptive PIT entry lifetime (LAPEL) for VANET.

LAPEL estimates 1-hop PEL based on the IEEE 802.11 p Medium Access Control parameters (e.g., Contention Window, backoff period, interframe space, etc.), propagation delay, and Physical layer parameters (e.g., the data rate to estimate Interest and Data message transmission delay.). This 1-hop delay is sufficient enough to receive Data message in response to the Interest message from the content provider at 1-hop distance. However, in multihop VANET, the content provider can be at any hop away from the content requesting node. Therefore, the question arises that what should be the maximum delay at the consumer node as well as at the intermediate Interest forwarders? Here, we used the concept of *TTL* that serves two purposes: 1) limit the broadcast scope of the Interest, and 2) estimate the PEL at consumer and all intermediate nodes between consumer and content provider nodes. The PEL decay rate between consumer and the last Interest broadcast node is adaptively determined using the modified well-know logistic model, which is briefly discussed in Section III-B. Interest may not be satisfied within its broadcast attempt and is retransmitted up to m number of retries. For the initial Interest broadcast, the retransmission count $Try = 1$ and for each successive attempt, Try is incremented until it reaches m . LAPEL only considers these two fundamental parameters (*TTL* and Try) to adaptively compute PEL at every node that participates in the Interest forwarding process.

List of contributions of the proposed LAPEL are as follows:

- The PEL is completely adaptive at each Interest forwarder in the vehicular network.
- The PEL decay rate is also adaptively computed.
- In the case of Interest loss, next Interest's PEL is adaptively adjusted using the maximum exponential backoff mechanism.
- No node identity is stored at any network component, which makes this scheme compatible to NDN.
- Adaptive PEL reduces the PIT size.
- Interest message does not include any additional information other than the *TTL*, retransmission count, and maximum hop count value.
- No further information is required to communicate Data messages other than the default NDN Data packet elements.

The organization of the manuscript as follows. Introduction to NDN and the recent work in the area of PEL estimation are discussed in Section II. The proposed LAPEL is discussed in Section III-B. Simulation results are discussed in Section IV. Finally, Section V concludes the paper.

II. BACKGROUND AND RELATED WORK

In this section, we briefly discuss the NDN basics and its working principle. In addition to that, we also present the detailed discussion about the previous work related to the PEL in NDN.

A. NDN Basics

As aforesaid, every NDN running network element primarily uses the PIT, FIB, and CS data structures to communicate the contents in the network.

The PIT maintains the state of Interests that are yet to be satisfied. Every PIT record contains Name, NONCE(s) and InFace(s) of the pending Interest. If a node receives multiple Interests requesting the same content (or same *Name*) and different *NONCE* and *InFace*, then the information is aggregated in the PIT. Along with the *Name*, *NONCE*, and *Inface*, a timer associated with that PIT record is also triggered, which is the PEL. This timer helps to limit the lifetime of a PIT entry. In summary, the PIT entry is only purged; when the Data message for that Interest is received, or the associated timer expires. PEL is directly proportional to the PIT size in the lossy networks and has a constant relation to the PIT search complexity.

FIB is responsible for forwarding Interests towards the upstream direction. It keeps the *Name Prefix*, *OutFace(s)*, and *Outface* metric to quantify the interest satisfaction quality of the *outFace*.

CS is the temporary cache to store contents or simply the Data messages. The decision of storing the content and how long the content should be kept in CS depends upon the caching and cache replacement policy in use.

B. NDN Working Principle

An application running on the NDN enabled node generates the content request in the form of Interest. When a node receives an Interest, it first checks its CS and replies with the Data message if the requested content is found in CS. In the case of failed CS search, the next step is to perform PIT search to find out whether the Interest has already been forwarded (still pending) or not. If there is no PIT entry with the same *Name* as in the Interest message, then PIT record is created, and then the Interest is forwarded depending upon the FIB name prefix search. The FIB name prefix search dictates the forwarding decision for the Interest. An Interest is sent to the *OutFace* that is associated with the *Name prefix* resulted by the successful FIB longest prefix search operation. Alternatively, the Interest is forwarded to all *OutFace(s)*, except the one from which the Interest was received. There may be the case that the network element, i.e., a vehicle or a node, has only one interface (e.g., WiFi, LTE (Long Term Evolution), or any other wireless interface.). In a single

wireless interface scenario, NDN forwarding strategy needs to alleviate the broadcast storm, which is a challenging task.

If no record found in the PIT, then the Interest is forwarded. However, if there a valid PIT entry with the same *Name* and *NONCE*, the Interest is just discarded. On the other hand, if there is a valid PIT record that has different *NONCE* but the same *Name*, then the *InFace* and *NONCE* are aggregated in the PIT. The PIT record is valid until the PIT entry timer is running. Once the timer expires and no Data message has been received, then the PIT record is purged. Hence, the size of PIT structure depends upon the duration of the timer and the Interest satisfaction ratio. In a wireless network scenario, the satisfaction of all Interests is not guaranteed due to packet drop and intermittent link conditions. Therefore, PIT has to keep all unsatisfied Interest records for the entire PEL duration. Precise estimation of the PEL is very critical to control PIT size and is a challenging issue. Adaptive estimation of PEL is the focal point of this work. In next section, we briefly summarize the work that has proposed the solutions for PEL estimation.

C. Previous Work

There have been a lot of research on the NDN based content dissemination in the vehicular networks. Following schemes merely focus on the Interest broadcast storm mitigation.

In [24], [25], authors control the Interest dissemination area by using the hop-limit or data dissemination limit in the Interest and Data packets. The authors in [27] use the providers' geolocation to forward Interest-Data messages. Similarly, the Interest broadcast is minimized in [28] by selecting the Interest forwarders based on the vehicles speed, interest satisfaction ratio, hop-count, and content satisfaction time. All of the above-discussed schemes reduce the Interest broadcast storm; however, they keep the PIT entry for the default and constant duration (e.g., 4 s) as implemented in the NDN.

In literature, there are very few schemes that do not use the varying PIT entry life for vehicular networks. The Interest and Data messages are deferred based on the random timers in the NDN-based mobile ad-hoc networks [26]. However, this random defer duration is not efficient to control the Interest-Data message in the mobile ad-hoc networks because the location, hop distance, and/or round-trip time of Interest-Data is unpredictable.

In [30], authors used the Interest response time or Interest-Data round trip delay (RTD) to approximate the PIT entry life for lossy wired content centric networks. This adaptive PEL was then used to schedule the retransmission of Interests. Initially, Interest is sent for content *C* with a constant PEL that is $\tau_C = 1$ s. After receiving the first content chunk with response time RTD_1 , $\tau_C = RTD_1$. For every next chunk *i* of *C*, during the 60 s interval, $\tau_C = RTD_i$ if $\tau_C < RTD_i$. After the 60 s refreshing interval, the τ_C is refreshed as:

$$\tau_c = \frac{RTD_{\max} - RTD_{\min}}{2} + RTD_{\min} \quad (1)$$

The main objective of the RTD based scheme is to approximate the retransmission time of the next Interest. However, the entry of the first Interest is kept for the constant of 1 s. The

shortcomings of [30] are briefly addressed in [31]: delay of each chunk of the content can not be similar especially in the highly unpredictable nature of VANETs. In the case of no content chunk received after the first Interest, the PEL will be set to 1 s for the next Interest retry. Additionally, if the first RTD_1 is less than all successive RTD_i s, then it will fail to receive successive chunks because PEL will expire earlier and purged before the arrival of successive chunks.

Next, the authors in [31] proposed a dynamic PEL for vehicular named data networks, called DPEL. In DPEL, the PEL at each Interest forwarder hop decays with the constant rate of λ , Interest Satisfaction Rate (ISR), and the constant PIT entry lifetime τ_0 . The overall PEL at hop *i*, τ_i^c is computed as:

$$\tau_i^c = \tau_0 \times e^{-\lambda \times i \times (1 + ISR)} \quad (2)$$

The overall PEL depends on the constants τ_0 and λ that are decided by the consumer node. There is no discussion about how these values are estimated by the consumer node.

As stated earlier that PEL estimation in RTD based scheme solely depends upon the reception of the first Data message received by the consumer. Additionally, in VANETs, estimation of RTD is unpredictable and keeping the minimum RTD_i of content chunk *i* as PEL will fail to receive all the successive chunks RTD_j if their $RTD_i < RTD_j$ where $i < j$. Furthermore, the Interest producer generates its first Interest with the fixed PEL, which is considered to be sufficient to receive the Data message. If there is no Data message within this fixed interval, then retransmission also uses the same PEL. The approximation of RTD at intermediate nodes is larger than the downstream nodes, then the Interest retransmissions can be suppressed. Similarly, each node has to estimate and maintain for each name prefix. The estimation of the fixed initial PEL and decay rate in DPEL is also difficult and impractical.

III. PROPOSED LAPEL

In this section, we briefly discuss the proposed hop limit based adaptive PIT entry lifetime estimation scheme. First, we formulate the PEL duration for 1-hop and then extended it to the scenario when an Interest is forwarded to a maximum number of TTL hops in the network. In this paper, we estimate PEL duration by considering IEEE 802.11 p parameters that is the recommended standard for vehicular networks. However, the same solution can be extended to any other MAC standard where NDN is used as an overlay solution.

Let, the total time required to send a packet *P* (Interest, Data or optional Ack) of size *a* bytes to 1-hop neighboring vehicle(s), $T_{P_a}^1$ is:

$$T_{P_a}^1 = T_{\text{cont}} + T_{\text{trans}}^{P_a} + \alpha \quad (3)$$

where T_{cont} and $T_{\text{trans}}^{P_a}$ are the contention delay and transmission delay, respectively, and α is the propagation delay. T_{cont} is computed as:

$$T_{\text{cont}} = AIFS(i) + T_{\text{BOff}}^{\max} + T_{CN} \quad (4)$$

where $AIFS(i)$, $T_{\text{BOff}}^{\max}$, and T_{CN} are arbitration interframe space (AIFS) for content with access category *i*, backoff timer,

and channel negotiation time, respectively. The channel negotiation time is the message exchange duration between two vehicles to coordinate the particular channel for successful content communication. Channel negotiation or channel coordination function is adapted by vehicles when they communicate content over multiple channels. For example, high priority and management contents over CCH and general contents over SCH. However, a vehicle can operate in a continuous channel or access mode, i.e., continuous CCH or continuous SCH access [4]. In this case, the channel coordination is not required and T_{CN} time is zero.

As stated earlier, IEEE 802.11p standard offers different services or access categories (ACs) contingent upon the data priority. The safety-related contents are provided highest priority AC_0 and the application related background content traffic is assigned lowest priority AC_3 . For high priority content, the $AIFS(i)$ and $T_{BOff}^{\max}$ are very small to prioritize the medium access with minimum delay and vice versa. $AIFS(i)$ is the minimum duration through which a vehicle should monitor the medium before accessing it. If the medium is free and $AIFS(i)$ period expires, then the vehicle can transmit the data. In case, the medium is busy after $AIFS(i)$ expiration, then a vehicle should backoff the communication for a random duration of $T_{BOff}^{\max}$. The computation of $AIFS(i)$ and $T_{BOff}^{\max}$ are discussed below.

$AIFS$ for service category i is computed as:

$$AIFS(i) = AIFSN(i) \times aSlotDuration + SIFS \quad (5)$$

where $aSlotDuration$ is the time period of a single slot (13 μ s) and $SIFS$ is the short interframe space that is 32 μ s. In (5), the $AIFSN(i)$ is the number that is defined for each AC_i in the standard. For example, the lowest priority traffic (i.e., AC_3) has $AIFSN(3) = 9$ and for the highest priority data (i.e., AC_0) has $AIFSN(0) = 2$ in the standard. These values of $SIFS$ and $AIFSN$ for AC_0 and AC_3 clearly indicate that the highest priority communication has to wait for shorter time to access the medium.

Packet drop due to collision is not a new phenomenon in a scenario where all neighboring nodes contend for the channel over a broadcast nature wireless link. To avoid the collision probability of either Interest or Data message, a vehicle enters the backoff process and selects CW :

$$CW = \text{rand}[1, CW_j]. \quad (6)$$

where, j represents the retransmission count. After every Interest retry, CW_j is computed as:

$$CW_j = 2^j \times (CW_{\min} + 1) - 1. \quad (7)$$

where, $1 \leq j \leq m$ and m is the maximum number of retries. Maxim backoff time $T_{BOff}^{\max}$ for attempt j is computed as:

$$T_{BOff}^{\max} = CW_j \times aSlotDuration \quad (8)$$

If CW_j reaches $CW_{\max}$, then $CW_j = CW_{\max}$ is considered for the rest of the attempts until it reaches the maximum retry limit m or the packet is transmitted successfully.

The total transmission time for packet P (i.e., Interest, Data, or optional ACK) of size a bytes, $T_{trans}^{P_a}$, is computed as:

$$T_{trans}^{P_a} = \frac{a \times 8}{C_{DR} \times 10^6} \quad (9)$$

where C_{DR} is the maximum channel data rate in Mbps. If a consumer vehicle has to transmit Interest of size a in order to receive Data message of size b from 1-hop, then the maximum PEL is computed as:

$$\tau_{\max}^1 = T_{Interest_a}^1 + T_{Data_b}^1 \quad (10)$$

When the consumer sends an Interest to a maximum of n -hops (to limit the Interest broadcast storm, $TTL_{\max} = n$), then it has to wait or keep the PIT entry up to a maximum of $\tau_{\max}^n$ to receive Data message:

$$\tau_{\max}^n = \sum_{i=1}^n T_{Interest_a}^i + T_{Data_b}^i \quad (11)$$

Hence, if a consumer sends an Interest with $TTL = TTL_{\max} = n$, then it must keep the PIT entry for $\tau_{\max}^n$ period in its PIT and should wait for the Data message.

After successfully computing PEL at consumer node, $\tau_{\max}^n$, now the question arises that what should be the PEL at each successive hop that is traversed by the Interest in upstream direction? Vanilla NDN uses a constant PEL of 4 s at each node that forwards the Interest. However, in DPEL [31], the consumer keeps PIT entry for a constant initial duration, which decays or decreases at a fixed rate over each successive node that forwards the Interest. This phenomenon of the fixed initial PEL and constant decay rate of PEL is not suitable for the dynamic topology VANETs. Therefore, we propose a hop limit based adaptive PEL estimation scheme for NDN enabled vehicular networks with Interest retransmission and hop-limit-based adaptive PEL.

A. Adaptive PEL Computation

Without loss of generality, assume that $L = \tau_{\max}^n$ at consumer node, then L decreases with rate r at each hop h ($0 \leq h \leq n$), is represented as:

$$\frac{dL}{dh} = -rL \left[1 - \frac{L}{K} \right] \quad (12)$$

The above expression is the logistic model with rate $-r$ and maximum delay limit of K . The maximum limit K of the Interest-Data packets delays at consumer vehicle for the set hop limit $TTL_{\max} = n$ is:

$$K = \tau_{\max}^n + \rho. \quad (13)$$

where ρ is the additional guard time, which is $CW_{\min} \times aSlotDuration$. It can be observed in (12) that if $L(h)$ is smaller than K , then $L(h)$ decreases $\frac{dL}{dh} < 0$ and vice versa, which is opposite to the phenomenon that had been presented by the logistic model.

The solution of the differential equation (12) is as follows (refer Appendix V for the detailed solution steps):

$$L(h) = \frac{K}{1 + Ae^{rh}} \quad (14)$$

where,

$$A = \frac{K - L_0}{L_0} \quad (15)$$

and L_0 is the initial PIT entry lifetime at hop zero (or consumer node) that is:

$$L_0 = \tau_{\max}^n \quad (16)$$

Now, it is easy to calculate the value of r as:

$$r = \frac{\ln\left(\frac{\left(\frac{K}{L(h)} - 1\right)}{A}\right)}{h} \quad (17)$$

The value of TTL varies from $TTL_{\max}$ or n to 0 ($TTL_{\max} \leq TTL \leq 0$), whereas the hop count h varies from 0 to n . Here, $TTL_{\max}$ or $h = 0$ represents the consumer vehicle. The vehicle that receives an Interest with $TTL = 0$ does not forward the Interest and consequently does not require to keep the PIT entry. Hence, the last vehicle that forwards the Interest and keeps the PIT entry, is the one that receives an Interest with $TTL = 1$. The minimum time that a pending Interest entry is held in the PIT of the last hop (when $TTL = 1$ or hop count $h = TTL_{\max} - 1$) is computed as follows, also refer (10):

$$L(TTL_{\max} - 1) = L(n - 1) = T_{\text{Interest}_a}^1 + T_{\text{Data}_b}^1 \quad (18)$$

If we know K , A , and the value of L at any hop (refer (13), (15), and (18), respectively.), then it is very easy to compute r through (17) and consequently $L(h)$ using (14).

B. Proposed Interest-Data forwarding

The application running over NDN forwarding daemon (NFD) generates Interest at the consumer vehicle with the parameters: content *Name*, *NONCE*, $TTL_{\max} = n$, $TTL = n$, $Try = 1$, and the content priority. When NFD at consumer receives Interest from the application, it first computes $L(TTL_{\max} - TTL)$ or $L(0)$. Before forwarding the Interest, it computes the random CW using (6) and backoff the Interest forwarding for the period of $CW \times aSlotDuration$ to avoid the Interest collision. When the backoff timer expires, the consumer vehicle, first decrements the TTL and then forwards the Interest.

Any vehicle that receives an Interest from the consumer, it first searches the CS for the named content. If there is a matching content in CS, then it replies with the Data message after a random backoff, otherwise, it will check the PIT. In case of no PIT record for the requested name is found, then it computes $L(TTL_{\max} - TTL)$ (using (14)) by first estimating $L(TTL_{\max} - 1)$, r , K , and A using (15)–(18). PIT record is created, and the timer is set for the duration of $L(TTL_{\max} - TTL)$. Next, it decrements the TTL and forwards the Interest.

The Interest is forwarded by all the vehicles when CS and PIT search fails. Similarly, the PEL is calculated, and PIT record is kept for the duration as stated earlier. The last Interest forwarder vehicle, which receives Interest with $TTL = 1$, it computes PEL as in (18) and then forwards the Interest after decrementing the

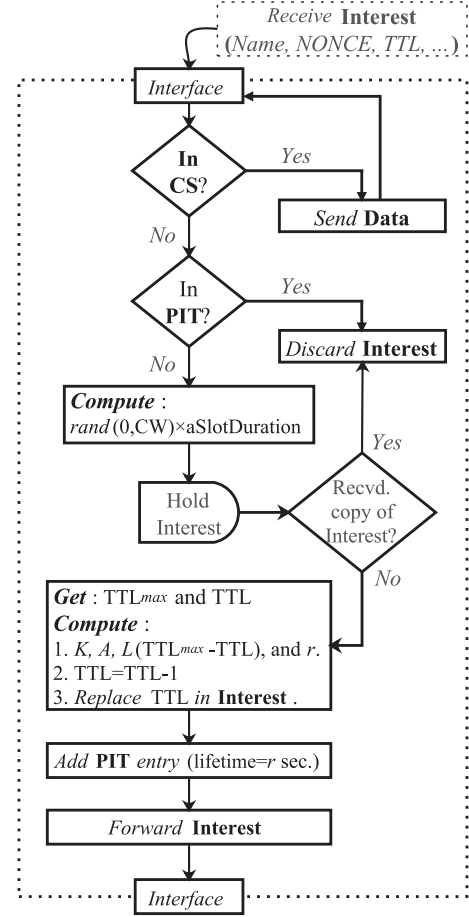


Fig. 3. LAPEL's detailed Interest processing flow diagram.

TTL . Finally, a vehicle that receives Interest with $TTL = 0$ does not forward the Interest further. This last hop vehicle may reply with Data message or just discards the Interest message conditional to the CS search result. Consumer vehicle will retry for generating another Interest with the incremented retry count, Try . This process continues until the retry count reaches its maximum number m or the consumer receives the content. The detailed flow diagram for Interest processing is shown in Fig. 3. Next, we discuss the simulation analysis of the proposed LAPEL scheme.

IV. SIMULATION ANALYSIS

In this section, the simulation performance of LAPEL is discussed in detail in contrast to the very recent PEL estimation scheme named DPEL [31], which is termed as a conventional scheme. NDN data structures and forwarding daemon over IEEE 802.11 p has been simulated in NS2.35. The four lane highway scenario of 10 km long with 70 randomly deployed vehicles, has been considered in the simulations [32]. The maximum transmission range of a vehicle is 500 m and the signal propagation follows the Two-Ray ground model. Each vehicle travels at an average speed of 55, 65, ..., 95 km/h. A vehicle randomly selects its speed between the average speed and ± 5 km/h. The standard wireless frequency band of 5.9 GHz with 10 Mhz

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Frequency Band (GHz)	5.9
Data Rate (Mbps)	6
Antenna	Omni Directional
Propagation Model	TwoRayGround
Retry limit or m	4
$CW_{\min}$ (slots)	64
$CW_{\max}$ (slots)	1024
AC	3
AIFS _N [3]	9
SIFS(μ s)	32
$aSlotDuration$ (μ s)	13
Symbol Duration (μ s)	8
Header Duration (μ s)	40
$TTL_{\max}$ (hops)	7, 9, and 11
Number of Vehicles	70
Average Speed (km/h)	55, 65, ..., 95
Interests/vehicle.sec	2
Transmission Range (m)	500

channels for IEEE 802.11 p with 6 Mbps bandwidth has been used in the simulation setup. The Interests are assigned to the AC = 3 with $CW_{\min} = 64$ and $CW_{\max} = 1024$. Additionally, the simulation environment considers the header, symbol, and the slot duration ($aSlotDuration$) of 40 μ s, 8 μ s, and 13 μ s, respectively.

Each vehicle generates Interests at the rate of 2 Interest per second within the random duration of 5 s. Contents are equally and uniquely distributed over the CSs of all vehicles on the road. For the conventional scheme, the initial PEL τ_0 and decay rate λ ranges between 0.1 to 0.5 and 0.01 to 0.05, respectively. If a vehicle does not receive content or Data message for an Interest, then it retries until the maximum number of retries m . Hence, the retry count Try has the value $1 \leq Try \leq m$. As in [31], no caching policy has been used in the simulations. Rest of the simulation parameters are summarized in Table I. Simulation results are the average of 20 independent simulations for each scenario parameter.

Following are the performance metrics of LAPEL that have been analyzed and compared with the conventional scheme:

- **PIT Entry Lifetime (s):** is the average time duration that an unsatisfied Interest's record is kept in the PIT.
- **Maximum No. of PIT Entries per Vehicle:** is the maximum number of PIT entries that have been observed at each vehicle during the simulation. This is the average of all vehicles in a simulation and for all the simulation runs.
- **Interest Satisfaction Ratio:** is the ratio of the satisfied interests over the total number of generated interests during the simulation run. Results show the average of all simulation runs.

Initially, we investigate the theoretical and simulated PEL of LAPEL and DPEL and impact of $TTL_{\max}$ on the PEL, which are shown in Figs. 4 and 5, respectively. Theoretical PEL is estimated from the random Try ($1 \leq Try \leq m$) and maximum contention time ($CW_{\min} \leq CW \leq CW_{\max}$) using the Monte Carlo method for 1×10^6 samples. However, the

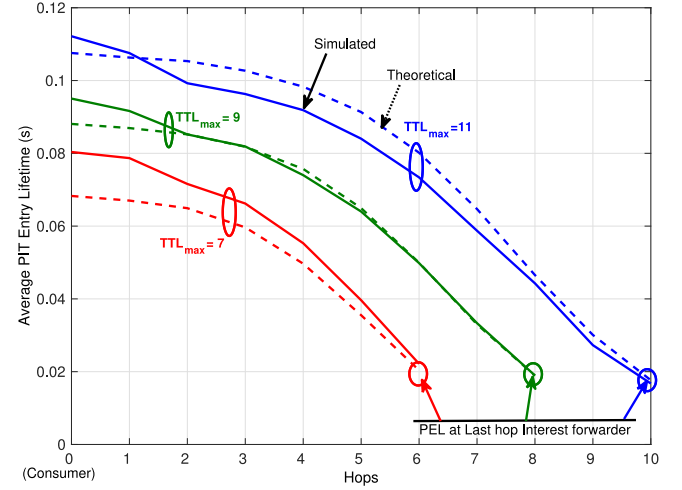


Fig. 4. Theoretical and Simulated PEL of LAPEL for $TTL_{\max} = 7, 9$, and 11.

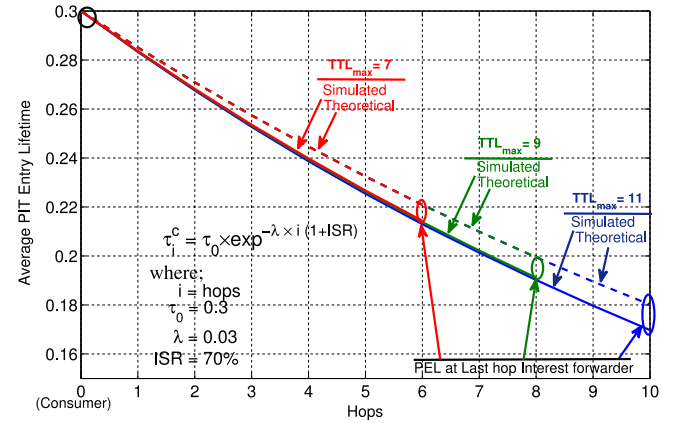


Fig. 5. Theoretical and Simulated PEL of DPEL for $\tau_0 = 0.3$, $\lambda = 0.03$, and $ISR = 70\%$ and $TTL_{\max} = 7, 9$, and 11.

simulated PEL of LAPEL is the average of all simulation runs. It is observed that the last hop Interest forwarder has almost similar PEL for any $TTL_{\max}$ value, which is equal to the maximum 1-hop Interest-Data delay. Conversely, the PEL at Consumer vehicle directly depends upon the maximum number of hops that an Interest is to be broadcasted. If a consumer broadcasts an Interest to larger hop distance or larger $TTL_{\max}$, then logically it has to hold PIT entry for a relatively longer duration than the PEL for smaller $TTL_{\max}$, which is obvious and can be visualized in Fig. 4. On the other hand, PEL in DPEL has constant initial PEL τ_0 and decay rate λ and is not adaptive to $TTL_{\max}$ scenario (refer Fig. 5). Next, the DPEL scheme has constant PEL at consumer for the fixed τ_0 and any value of λ . It is also evident from the figure that for any number of Interest re-transmissions, there will be no change in the PEL at any vehicle between the consumer and provider, which makes it infeasible to apply in a highly dynamic topology networks. Additionally, the $TTL_{\max}$ has no impact on the PEL at the consumer, last hop Interest forwarder and the PEL decay rate, which makes it

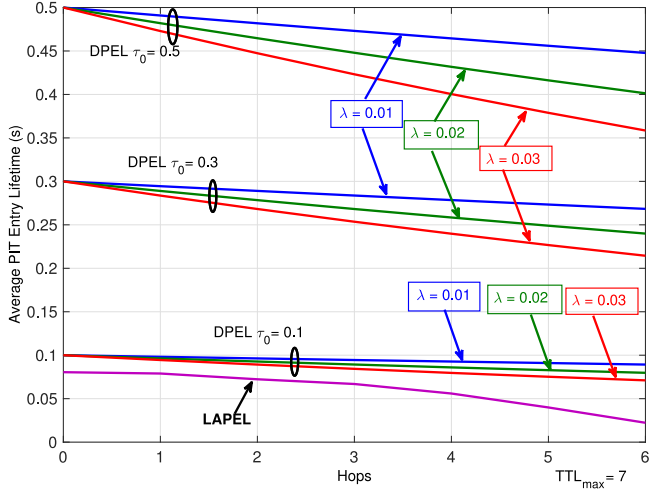


Fig. 6. Average PIT entry lifetime at each successive hop in the vehicular network for $TTL_{max} = 7$ and DPEL with $\tau_0 = 0.1, 0.3$, and 0.5 .

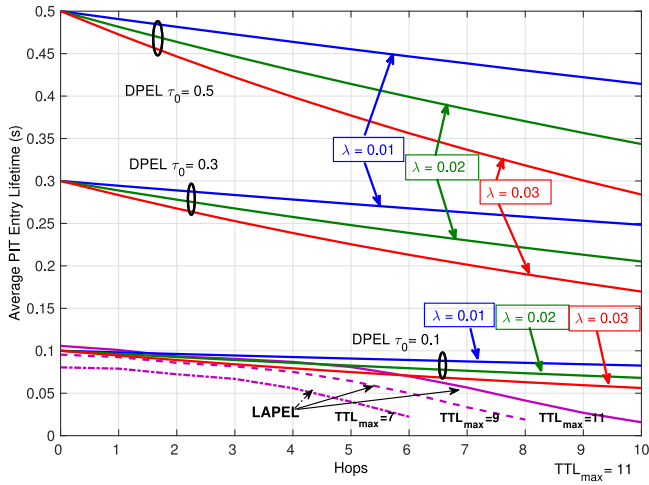


Fig. 7. Average PIT entry lifetime at each successive hop in the vehicular network for $TTL_{max} = 7, 9$, and 11 and DPEL with $\tau_0 = 0.1, 0.3$, and 0.5 .

unadaptive for the wireless environment. Lastly, the estimation of initial PEL τ (PEL at consumer) and its decay rate λ is quite difficult in DPEL, and their computation is not provided by the DPEL scheme. Nonetheless, the LAPEL adaptively computes the PEL at every vehicle from the consumer to the last hop of broadcast limit and the decay rate of PEL, once the TTL_{max} and Interest retry count Try are provided in an Interest. The usage of TTL_{max} in a wireless broadcast environment is coherent as well as fundamental to limit the broadcast storm.

A detailed PEL analysis of LAPEL and DPEL for different values of TTL_{max} is shown in Figs. 6 and 7. Fig. 6 illustrates the comparison of PEL between proposed and conventional DPEL at each successive hop in the vehicular network for $TTL_{max} = 7$. To fairly contrast the performance of both the schemes, different values of τ_0 (i.e., $0.1, 0.3$, and 0.5) and decay rates λ (i.e., $0.1, 0.3$, and 0.5) of DPEL have been investigated in the simulations. It shows that the constant λ of DPEL has no impact on PEL at the consumer (the vehicle at 0-hop) and the PEL at each successive Interest forwarding vehicle decays at the constant rate. On the other hand, LAPEL adaptively computes the

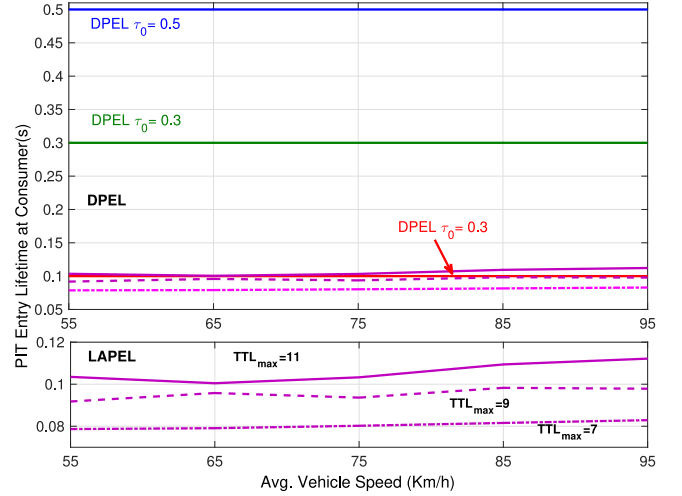


Fig. 8. Average PIT entry lifetime at *Consumer* vehicle for $TTL_{max} = 11$ versus average speed of vehicles.

PEL at the consumer and all the vehicles between the consumer and the provider vehicles. The results show that that adaptively calculated PEL of LAPEL is smaller than the constant τ_0 of DPEL. DPEL could use very small τ_0 , which could minimize the PEL at each node. However, DPEL does not provide any τ_0 estimation mechanism and the smaller τ_0 may reduce the Interest satisfaction ratio. The rationale behind this phenomenon is that small τ_0 causes downlink Interest forwarders to delete their PIT entries earlier due to short PEL and fail to participate in the Data forwarding process when the provider is at a large hop distance. It is apparent from the figure that LAPEL has very less and adaptive PEL compared to any DPEL's τ_0 and λ . On average, LAPEL holds PIT entries for approximately 33.59%, 77.90%, and 86.76% less duration than the DPEL with $\tau_0 = 0.1, 0.3$, and 0.5 , respectively.

Fig. 7 shows the PEL for $TTL_{max} = 7, 9$, and 11 hops. It depicts that different values of TTL_{max} have no impact on DPEL's PEL. However, the consumer vehicle's PEL and its decay rate depend upon the TTL_{max} in LAPEL. The only scenario where LAPEL has large PEL than DPEL (with $\tau_0 = 0.1$) is $TTL_{max} = 11$. In this case, LAPEL has less PEL at all the nodes that are 6 or more than 6-hops away from the consumer. DPEL's short PEL for large TTL_{max} has an adverse impact on the Interest satisfaction ratio because it fails to satisfy Interests from the farthest hop distance, which is discussed later in this section. The detailed comparison of overall PEL improved by LAPEL in contrast to the DPEL is shown in Table II.

After PEL analysis at each node that takes part in the Interest forwarding process, we analyze the PEL at each consumer vehicle. PEL at a consumer denotes the maximum duration of an entry in the PIT table of a vehicle with $TTL = TTL_{max}$. Fig. 8 illustrates the PEL for different hop limits as well as the impact of node speed on the PEL at consumer vehicle. As per previous discussion, DPEL has constant PEL at the consumer and has no effect of decay rate as well as the hop limit and even the node speed, which leads to the Interest or Data message drop. However, the PEL at the consumer slightly increases for larger TTL_{max} , which is a natural phenomenon. Furthermore,

TABLE II
SUMMARY OF PEL IMPROVED BY LAPEL COMPARED TO DPEL.

τ_0	λ	$TTL_{max} = 7$				$TTL_{max} = 9$				$TTL_{max} = 11$			
		Avg. PEL (s)		% less PEL	Overall % less PEL	Avg. PEL (s)		% less PEL	Overall % less PEL	Avg. PEL (s)		% less PEL	Overall % less PEL
		DPEL	LAPEL			DPEL	LAPEL			DPEL	LAPEL		
0.1	0.01	0.09448		36.98%	23.14%	0.09274		28.39%	23.14%	0.09103		23.19%	16.21%
	0.02	0.08939		33.41%		0.0862		22.97%		0.08316		15.91%	
	0.03	0.08464		29.66%		0.08025		17.26%		0.07617		8.20%	
0.3	0.01	0.28366	0.0595	79.01%	77.85%	0.27847	0.0664	76.16%	74.42%	0.27343	0.0699	74.43%	72.13%
	0.02	0.26839		77.82%		0.25889		74.35%		0.24985		72.01%	
	0.03	0.25439		76.59%		0.24138		72.49%		0.22926		69.50%	
0.5	0.01	0.4729		87.41%	86.73%	0.4643		85.70%	84.67%	0.4559		84.66%	83.30%
	0.02	0.4479		86.71%		0.4322		84.64%		0.4173		83.24%	
	0.03	0.4248		85.98%		0.4032		83.53%		0.3830		81.74%	

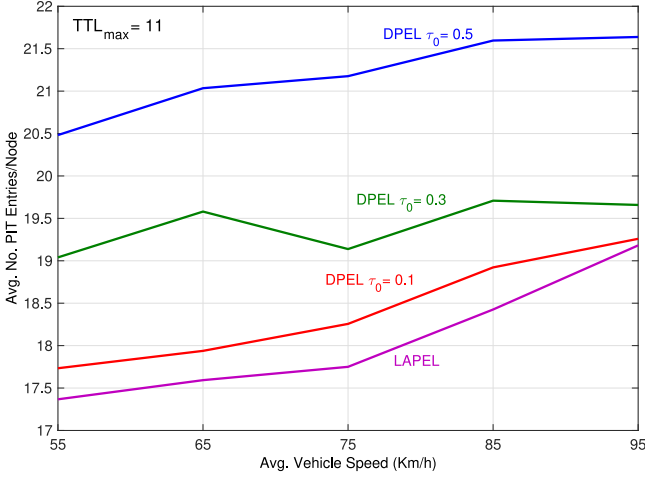


Fig. 9. Maximum number of PIT entries per Vehicle for $TTL_{max} = 11$ versus average speed of vehicles.

the speed of vehicle results in more Interest or Data packet drop due to intermittent link, refer lower sub-figure of Fig. 8. In this case, LAPEL recalculates the PEL with every next retry attempt. To simply state that LAPEL also adapts the PEL with every Interest retransmission or retry count. LAPEL approximately has 19.53%, 73.17%, and 83.90% for $TTL_{max} = 7$ and 4.53%, 68.18%, and 80.91% for $TTL_{max} = 9$ compared to DPEL's $\tau_0 = 0.1, 0.3$, and 0.5 , respectively. Similarly, 64.75% and 78.85% less PEL at consumer is experience by LAPEL compared to the $\tau_0 = 0.3$ and 0.5 when $TTL_{max} = 11$. However, in a similar scenario, the LAPEL has 5.4% more PEL when DPEL's initial PEL is 0.1, which is reasonable because the consumer has to keep PIT entry for a longer time when it generates Interest for larger hop-limit.

Next, we evaluated the average number of PIT entries (called the average PIT size) at each vehicle in the network. Size of the PIT at each vehicle in the network depends on two factors: PEL and the Interest satisfaction ratio. If all the Interests are satisfied, then there will be no Interest pending in the PIT data structure irrespective of the maximum PEL. Conversely, if there is low Interest satisfaction ratio, then the entries will be accumulated in the PIT and will increase its size.

Fig. 9 shows the average number of PIT entries per vehicle for different τ_0 and $TTL_{max} = 11$ versus the varying speed of vehicles. It depicts that LAPEL has less number of PIT entries compared to DPEL and it increases with the increase in the vehicles' average speed. This is true because vehicles' fast

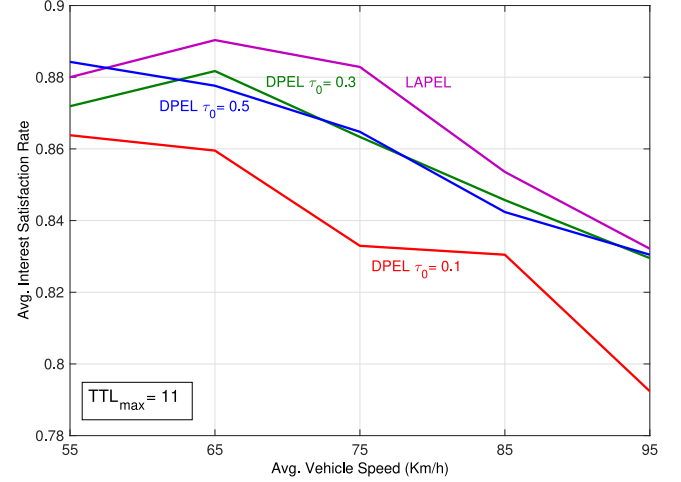


Fig. 10. Average Interest satisfaction ratio for varying speed and $TTL_{max} = 11$.

mobility leads to more Interest or Data message drop that leads to large PIT size. Similarly, the larger the initial PEL of DPEL, the higher the PIT size, which is evident from the figure. The closest DPEL scenario with a slightly larger number of PIT entries is the one with $\tau_0 = 0.1$. In the previous discussion, it has been observed that LAPEL has 5.4% more PEL; however, DPEL fails to receive Data messages from the distant providers and results in more pending entries in the PIT.

In last, the average Interest satisfaction ratio of the network has been discussed. The average Interest satisfaction ratio for varying vehicle speed and τ_0 is shown in Fig. 10. The Interest satisfaction ratio decreases when network topology changes rapidly because of the high average vehicle speed, and the same trend can be observed from the figure. As discussed earlier, the smaller τ_0 of DPEL reduces the number of PIT entries. However, it fails to receive the contents from the distant providers in the large TTL_{max} scenario. As a result, DPEL with small initial PEL has less Interest satisfaction ratio. The average Interest satisfaction ratio of LAPEL is almost similar to DPEL for $\tau_0 = 0.3$ and 0.5 that is only 1% more than DPEL. However, LAPEL has approximately 4% more Interest satisfaction ratio than the DPEL when $\tau_0 = 0.1$. During the simulations, we considered the fixed Interest rate of 2 Interest/s. Since, it is obvious that the high Interest rate has an impact on the PIT size, due to the increased Interest and Data packet collision. In result, due to large PEL of the conventional scheme, its PIT will naturally be far larger than the proposed scheme.

To summarize the discussion, LAPEL reduces the PEL for any hop-limit based scenario in the vehicular ad-hoc network, which ultimately minimizes the PIT size at each vehicle. Furthermore, LAPEL achieves the similar Interest satisfaction ratio as compared to the DPEL, which is a state of the art PEL estimation scheme for NDN enabled VANETs.

V. CONCLUSION

This paper proposes the adaptive PIT entry lifetime estimation scheme for the vehicular networks that employ NDN communication architecture. It is a well-known fact that PIT size is directly proportional to the PEL duration. Additionally, the efficiency of the name prefix search can be improved if the PIT size is minimized without penalizing the Interest-Data communication. In literature, there are only a few schemes that either use the constant PEL or pre-defined parameters to compute the PEL. In this paper, we proposed the hop limit based adaptive PIT entry lifetime estimation scheme for vehicular named data networks.

A vehicle uses the standard IEEE 802.11 p parameters, in addition to the hop-limit value, to estimate the PEL and its decay rate and does not require any additional information other than the hop limit and Interest retransmission count. Hence, Interest lifetime between consumer and provider vehicles is entirely adaptive to the network dynamics that includes the number of Interest retransmissions due to highly dynamic network topology. In LAPEL, a content requesting vehicle generates an Interest with the broadcast limit plus retry count, and the scheme just decays the PEL at each successive Interest forwarders' PIT until it reaches the broadcast boundary. This behavior of LAPEL is entirely in line with the Interest-Data response time that varies with the change in the maximum hop limit. It is also verified through simulations that the proposed LAPEL scheme reduces 66%, 60%, and 57% PEL lifetime for $TTL_{\max} = 7, 9$, and 11 hops compared to DPEL's different τ_0 values. The simulation results also signify that LAPEL reduces the PIT size upto 7.8%, 9.2% and 8.2%, and achieves 1.5%, 5.2%, and 6.9% more Interest satisfaction rate than the DPEL for the hop-limit of 7, 9, and 11, respectively.

There are multiple factors that we intend to investigate in the future extension of this work, the most notable one are as follows: First, we plan to study the increment rate of the $TTL_{\max}$ that is the rate at which $TTL_{\max}$ should increase or decrease if there is any change in the Interest satisfaction ratio. Next, we plan to propose the Interest suppression mechanism depending upon the adaptive PEL to minimize the Interest broadcast storm in the vehicular network.

APPENDIX PROOF OF THE LOGISTIC MODEL

$$\frac{dL}{dh} = -rL \left[1 - \frac{L}{K} \right].$$

Separation of variables and taking integral gives:

$$\frac{dL}{L \left[\frac{L}{K} - 1 \right]} = r dh. \quad (19)$$

Left hand side of (19) can be written as:

$$\frac{1}{L \left[\frac{L}{K} - 1 \right]} = \frac{A}{L} + \frac{B}{\left[\frac{L}{K} - 1 \right]}. \quad (20)$$

Multiply both sides with $L \left[\frac{L}{K} - 1 \right]$, we get:

$$1 = A \left[\frac{L}{K} - 1 \right] + BL, \quad (21)$$

$$1 = \frac{AL}{K} - A + BL, \quad (22)$$

$$1 = -A + L \left[B + \frac{A}{K} \right]. \quad (23)$$

There is no term L at left hand side of the equation, therefore, it must hold for $L = 0$ and $L = K$.

$$A = -1 \text{ for } L = 0, \text{ and} \quad (24)$$

$$B = \frac{1}{K} \text{ for } L = K. \quad (25)$$

By substituting A and B in (20), we get:

$$\frac{1}{L \left[\frac{L}{K} - 1 \right]} = -\frac{1}{L} + \frac{\frac{1}{K}}{\left[\frac{L}{K} - 1 \right]}. \quad (26)$$

Taking integral of (19) and substituting the simplified solution in (26), we get:

$$-\int \frac{1}{L} dL + \int \frac{\frac{1}{K}}{\left[\frac{L}{K} - 1 \right]} dL = \int r dh. \quad (27)$$

let, $u = \left[\frac{L}{K} - 1 \right]$, then $du = \frac{1}{K} dL$, and above expression is simplified as:

$$-\int \frac{1}{L} dL + \int \frac{1}{u} du = \int r dh, \quad (28)$$

$$-\ln(L) + c_1 + \ln(u) + c_2 = rh + c_3, \quad (29)$$

$$-\ln(L) + \ln(u) = rh + c, \quad (30)$$

where, $c = c_3 - c_2 - c_1$,

$$\ln \left(\frac{L}{u} \right) = -rh - c. \quad (31)$$

By putting the value of u , we get:

$$\ln \left(\frac{L}{\left[\frac{L}{K} - 1 \right]} \right) = -rh - c, \quad (32)$$

$$\frac{L}{\left[\frac{L}{K} - 1 \right]} = C e^{-rh}, \quad (33)$$

where, $C = e^{-c}$,

$$L = \frac{L C e^{-rh}}{K} - C e^{-rh}, \quad (34)$$

$$L = \frac{C e^{-rh}}{\frac{C e^{-rh}}{K} - 1}. \quad (35)$$

Multiply and divide numerator and denominator with Ke^{rh} :

$$L = \frac{CK}{C - Ke^{rh}}. \quad (36)$$

At $h = 0$:

$$L_0 = \frac{CK}{C - K}. \quad (37)$$

Solving for C , we get:

$$C = \frac{L_0K}{L_0 - K}. \quad (38)$$

By substituting the value of C in (36), we get:

$$L = \frac{\left(\frac{L_0K}{L_0 - K}\right)K}{\left(\frac{L_0K}{L_0 - K}\right) - Ke^{rh}}. \quad (39)$$

After multiplying and dividing (39) with $\frac{L_0 - K}{K}$ and simplifying, we get:

$$L = \frac{K}{1 + \left(\frac{K - L_0}{L_0}\right)e^{rh}}, \quad (40)$$

or

$$L(h) = \frac{K}{1 + Ae^{rh}}, \quad (41)$$

$$\text{where, } A = \left(\frac{K - L_0}{L_0}\right).$$

REFERENCES

- [1] W. I. Khedr, "Improved lightweight authentication scheme for IEEE 802.11 p vehicle-to-infrastructure communication," *Ad Hoc Sensor Wireless Netw.*, vol. 31, pp. 227–258, 2016.
- [2] F. J. Martinez, C. K. Toh, J. C. Cano, C. T. Calafate, and P. Manzoni, "Emergency services in future intelligent transportation systems based on vehicular communication networks," *IEEE Intell. Transp. Syst. Mag.*, vol. 2, no. 2, pp. 6–20, Summer 2010.
- [3] H. Yang, L. Huang, and H. Xu, "Distributed compressed sensing in vehicular ad-hoc network," *Ad hoc Sensor Wireless Netw.*, vol. 25, pp. 121–145, 2015.
- [4] *IEEE Standard for Wireless Access in Vehicular Environments (WAVE)–Multi-Channel Operation*, IEEE Std 1609.4-2010 (Revision of IEEE Std 1609.4-2006), Feb. 7, 2011.
- [5] K. Grover, A. Lim, S. Lee, and Q. Yang, "Privacy-enabled probabilistic verification in broadcast authentication for vehicular networks," *Ad Hoc Sensor Wireless Netw.*, vol. 32, no. 3/4, pp. 239–274, 2016.
- [6] D. B. Rawat, G. Yan, B. Bahadur Bista, and M. C. Weigle, "Trust on the security of wireless vehicular ad-hoc networking," *Ad Hoc Sensor Wireless Netw.*, vol. 24, no. 3/4, pp. 283–305, 2015.
- [7] K. Zrar Ghafoor, J. Lloret, A. Safa Sadiq, and M. Aziz Mohammed, "Improved geographical routing in vehicular ad hoc networks," *Wireless Personal Commun.*, vol. 80, no. 2, pp. 785–804, 2015.
- [8] J. Zhao, Y. Zhang, and G. Cao, "Data pouring and buffering on the road: A new data dissemination paradigm for vehicular ad hoc networks," *IEEE Trans. Veh. Technol.*, vol. 56, no. 6, pp. 3266–3277, Nov. 2007.
- [9] T. Yan and G. Wang, "Collecting vehicle trajectory through message dissemination," *Ad Hoc Sensor Wireless Netw.*, vol. 29, no. 1–4, pp. 153–176, 2015.
- [10] J. J. Blum, A. Eskandarian, and L. J. Hoffman, "Challenges of intervehicle ad hoc networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 5, no. 4, pp. 347–351, Dec. 2004.
- [11] F. Domingos da Cunha, A. Boukerche, L. Villas, A. Carneiro Viana, and A. A. F. Loureiro, "Data communication in VANETs: A survey, challenges and applications," INRIA Saclay, Palaiseau, France, Tech. Rep. RR-8498, 2014.
- [12] 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.
- [13] L. Zhang *et al.*, "Named data networking," *SIGCOMM Comput. Commun. Rev.*, vol. 44, no. 3, pp. 66–73, Jul. 2014.
- [14] S. Hussain Bouk, S. Hassan Ahmed, and D. Kim, "Hierarchical and hash based naming with Compact TRIE name management scheme for vehicular content centric networks," *Comput. Commun.*, vol. 71, no. 1, pp. 73–83, Nov. 2015.
- [15] 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. Emerging Netw. Exp. Technol.*, Dec. 2009, pp. 1–12.
- [16] L. Wang, A. Afanasyev, R. Kuntz, R. Vuyyuru, R. Wakikawa, and L. Zhang, "Rapid traffic information dissemination using named data," in *Proc. 1st ACM Workshop Emerging Name-Oriented Mobile Netw. Design-Archit., Algorithms, Appl.*, ACM, New York, NY, USA, 2012, pp. 7–12.
- [17] 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.
- [18] 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*, Toronto, ON, Canada, 2014, pp. 410–415.
- [19] M. Chowdhury, A. Gawande, and L. Wang, "Secure information sharing among autonomous vehicles in NDN," in *Proc. IEEE/ACM 2nd Int. Conf. Internet-of-Things Des. Implementation*, Pittsburgh, PA, USA, 2017, pp. 15–26.
- [20] M. Amadeo, C. Campolo, and A. Molinaro, "Named data networking for priority-based content dissemination in VANETs," in *Proc. IEEE 27th Annu. Int. Symp. Personal, Indoor, Mobile Radio Commun.*, Valencia, Spain, 2016, pp. 1–6.
- [21] S. Hussain Bouk, S. Hassan Ahmed, 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.
- [22] S. Hassan Ahmed, S. H. Bouk, D. Kim, D. B. Rawat, and H. Song, "Named data networking for software defined vehicular networks," *IEEE Commun. Mag.*, vol. 55, no. 8, pp. 60–66, Aug. 2017.
- [23] C. A. Kerrache, C. T. Calafate, J. C. Cano, N. Lagraa, and P. Manzoni, "Trust management for vehicular networks: An adversary-oriented overview," *IEEE Access*, vol. 4, pp. 9293–9307, 2016.
- [24] S. Hassan Ahmed, S. Hussain Bouk, M. Azfar 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.
- [25] S. Hassan Ahmed, S. Hussain Bouk, M. Azfar Yaqub, D. Kim, and M. Gerla, "CONET: Controlled data packets propagation in vehicular named data networks," in *Proc. 13th IEEE Annu. Consumer Commun. Netw. Conf.*, 2016, pp. 620–625.
- [26] R. A. Rehman, T. Dinh Hieu, H.-M. Bae, S.-H. Mah, B.-S. Kim, "Robust and efficient multipath interest forwarding for NDN-based MANETs," in *Proc. 9th IFIP Wireless Mobile Netw. Conf.*, 2016, pp. 187–192.
- [27] 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.*, Boston, MA, USA, 2015, pp. 1–10.
- [28] S. Hassan Ahmed, S. Hussain 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. Gao, H. Zhang, and B. Zhang, "Energy efficient interest forwarding in NDN-based wireless sensor networks," *Mobile Inform. Syst.*, vol. 2016, Art. no. 3127029.
- [30] A. James Abu, B. Bensaou, and J. Min Wang, "Interest packets retransmission in lossy CCN networks and its impact on network performance," in *Proc. 1st ACM Conf. Inf.-Centric Netw.*, New York, NY, USA, 2014, pp. 167–176.
- [31] 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.
- [32] M. Torrent-Moreno, J. Mittag, P. Santi, and H. Hartenstein, "Vehicle-to-vehicle communication: Fair transmit power control for safety-critical information," *IEEE Trans. Veh. Technol.*, vol. 58, no. 7, pp. 3684–3703, Sep. 2009.



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