LAPEL: hop Limit based Adaptive PIT Entry Lifetime for Vehicular Named Data Networks

Safdar Hussain Bouk, Syed Hassan Ahmed, Dongkyun Kim, Kyung-Joon Park, Yongsun Eun, and Jaime Lloret

Abstract—Named Data Networking (NDN) is one of the widely investigated future Internet architectures for vehicular networks. NDN prioritizes the contents rather than the connection between the content requesting and providing network entities. Content name is used to locate and forward the content within the network. A content requesting node sends an Interest message for specific content and waits for the Data message containing the actual content. Interest message also includes the Time to Live (TTL) field to control the Interest broadcast storm. To keep track of the Interest’s state including the interface from where it was received, Interest identifier, etc., are stored in the data structure, known as Pending Interest Table (PIT). PIT holds the records of all pending Interests for a specific duration, called PIT entry lifetime (PEL). PIT entry is deleted when a node receives the Data message, or the node does not receive any Data message, and PEL expires. Interest and/or Data message loss in highly dynamic topology vehicular network is very high, which results in a significant PIT size depending upon the PEL. Hence, in this paper, we propose a hop limit based adaptive PEL (LAPEL) scheme, which adaptively estimates the PEL at each vehicle that forwards the Interest. 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 less PEL, controls the PIT size and achieves the similar Interest satisfaction ratio.

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., the 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 the content [5], [6]. The current communication architectures used by VANETs requires vehicle identification, i.e., IP or MAC address, to establish the connection between content requesting and providing vehicles [7]. Connection establishment prior to 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 difficult to support. Vehicle identification and connectivity based communication in VANETs inherit the similar challenges that are faced by the legacy wireless ad hoc networks [8]–[10].

Recently, a new set of communication architectures has been widely researched that satisfy the content demand of the applications irrespective of their content location, called Information Centric Networking (ICN) [11]. Named Data Networking (NDN) [12], is one of the most widely investigated ICN architectures that communicates and locates the content using the content name [13]. NDN is the enhanced implementation of CCN [14], and its feasibility is investigated in the vehicular networks [15]–[22].

If an application running on the On-Board Unit (OBU) of a vehicle (called consumer vehicle or node)1 in the NDN enabled VANET, requires any content, it sends a content request (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), Pendant...
ing Interest Table (PIT), and Content Store (CS). FIB is responsible to forward 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 with 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.

A node may receive millions of different Interest messages to acquire different contents, and the node performs PIT search for each Interest. Each 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 the 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. 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 can not 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 4s. In literature, there are few works that precisely focus on the PIT entry lifetime [24] [25]. In [24], 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 1s. The authors in [25] 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 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 802.11p 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 forwards? 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 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, the 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.
- 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.

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 PIT, FIB, and CS data structures to communicate contents in the network.

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 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 it 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 satisfied. Every PIT record contains Name, NONCE(s) and InFace(s) of the pending Interest. If a node receives multiple Interests requesting 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.

C. Previous Work

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

In [18], [19], authors control the Interest dissemination area by using the hop-limit or data dissemination limit in the Interest and Data packets. The authors in [21] use the providers’ geolocation to forward Interest-Data messages. Similarly, the Interest broadcast is minimized in [22] by selecting the Interest forwards 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., 4s) 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 [20]. 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 [24], 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 $\tau_C = 1s$. After receiving the first content chunk with response time $RTD_1$, $\tau_C = RTD_1$. For every next chunk $i$ of $C$, during the 60s interval, $\tau_C = RTD_i$ if $\tau_C < RTD_i$. After the 60s refreshing interval, the $\tau_C$ is refreshed as:

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

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 1s. The shortcomings of [24] are briefly addressed in [25]: 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 1s for the next Interest retry. Additionally, if the first
RTD$_i$ is less than all successive RTD$_j$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 [25] 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 $\tau_0$. The overall PEL at hop $i$, $\tau^{\text{eq}}_i$ is computed as:

$$\tau^{\text{eq}}_i = \tau_0 \times e^{-\lambda \times i \times (1 + \text{ISR})} \quad (2)$$

The overall PEL depends on the constants $\tau_0$ and $\lambda$ 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$_j <$ RTD$_i$ 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 802.11p 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), $T^1_{pa}$ is:

$$T^1_{pa} = T_{\text{cont}} + T^a_{\text{trans}} + \alpha \quad (3)$$

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

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

where $AIFS(i)$, $T^{\text{max}}_{BOff}$, 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 $T^{\text{max}}_{BOff}$ 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 $T^{\text{max}}_{BOff}$. The computation of $AIFS(i)$ and $T^{\text{max}}_{BOff}$ are discussed below: $AIFS$ for service category $i$ is computed as:

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

where $aSlotSN(i)$ is the time period of a single slot (13µs) and $SIFS$ is the short interframe space that is 32µs. In eq. (5), the $AIFS_N(i)$ is the number that is defined for each $AC_i$ in the standard. These values for $SIFS$ and $AIFS_N$ 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:

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

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

$$T^{\text{max}}_{BOff} = CW_j \times aSlotDuration \quad (8)$$

If $CW_j$ reaches $CW_{\text{max}}$, then $CW_j = CW_{\text{max}}$ is considered for 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, $T^a_{\text{trans}}$ is computed as:

$$T^a_{\text{trans}} = \frac{a \times 8}{C_{DR} \times 10^6} \quad (9)$$
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:

$$\tau_{max}^1 = T_{Interest}^1 + T_{Data}^1$$  \hspace{1cm} (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 maximum of $\tau_{max}^n$ to receive Data message:

$$\tau_{max}^n = \sum_{i=1}^{n} T_{Interest}^i + T_{Data}^i$$  \hspace{1cm} (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 the 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 4s at each node that forwards the Interest. However, in DPEL [25] 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:

$$\frac{dL}{dh} = -rL \left[ 1 - \frac{L}{K} \right]$$  \hspace{1cm} (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:

$$K = \tau_{max}^n + \rho$$  \hspace{1cm} (13)$$

where $\rho$ is the additional guard time, which is $CW_{min} \times aSlotDuration$. It can be observed in eq. (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 A for the detailed solution steps):

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

where,

$$A = \frac{K - L_0}{L_0}$$  \hspace{1cm} (15)$$

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

$$L_0 = \tau_{max}^0$$

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

$$r = \frac{\ln \left( \frac{K}{TTL_{max} - 1} \right)}{h}$$  \hspace{1cm} (16)$$

The value of TTL varies from $TTL_{max}$ or $n$ to 0 ($TTL_{max} \leq TTL \leq 0$), where as 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 eq.(10):

$$L(TTL_{max} - 1) = L(n - 1) = T_{Interest}^1 + T_{Data}^1$$  \hspace{1cm} (17)$$

If we know $K$, $A$, and value of $L$ at any hop (refer eq.(13), eq.(15), and eq.(17), respectively), then it is very easy to compute $r$ through eq.(16) and consequently $L(h)$ using eq.(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 eq.(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 the $L(TTL_{max} - TTL)$ (using eq.(14)) by first estimating $L(TTL_{max} - 1)$, $r$, $K$, and $A$ using eqs.(15)-(17). 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 eq.(17) and then forwards the Interest after decrementing the TTL. Finally, a vehicle that receives Interest with TTL = 0 does not forwards 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. 1. Next, we discuss the simulation analysis of the proposed LAPEL scheme.

![LAPEL's detailed Interest processing flow diagram](image)

**Fig. 1:** LAPEL’s detailed Interest processing flow diagram.

**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 [25], which is termed as a conventional scheme. NDN data structures and forwarding daemon over IEEE 802.11p has been simulated in NS2.35. The highway scenario of 10km long with 70 vehicles has been considered in the simulations. Each vehicle randomly selects its speed between 55 to 95km/h. Each vehicle generates Interests at the rate of 2 Interest per second within the random duration of 5s. Contents are equally and uniquely distributed over the CSs of all vehicles on the road. For the conventional scheme, the initial PEL $T_0$ and decay rate $\lambda$ 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 [25], 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 with each simulation duration of 500s.

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.

**TABLE I: Simulation Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retry limit $m$</td>
<td>4</td>
</tr>
<tr>
<td>$CW_{min}$</td>
<td>64</td>
</tr>
<tr>
<td>$CW_{max}$</td>
<td>1024</td>
</tr>
<tr>
<td>$AC$</td>
<td>3</td>
</tr>
<tr>
<td>$AIFS$</td>
<td>9</td>
</tr>
<tr>
<td>$SIFS$</td>
<td>32\mu s</td>
</tr>
<tr>
<td>$aSlotDuration$</td>
<td>13\mu s</td>
</tr>
<tr>
<td>$TTL_{max}$</td>
<td>7, 9, 11</td>
</tr>
<tr>
<td>Number of Vehicles</td>
<td>70</td>
</tr>
<tr>
<td>Vehicle Speed (km/h)</td>
<td>55-95</td>
</tr>
<tr>
<td>Interests/vehicle.sec</td>
<td>2</td>
</tr>
<tr>
<td>Transmission Range (m)</td>
<td>500</td>
</tr>
</tbody>
</table>

![Theoretical and Simulated PEL of LAPEL for $TTL_{max} = 7, 9, 11$.](image)

**Fig. 2:** Theoretical and Simulated PEL of LAPEL for $TTL_{max} = 7, 9, 11$.

Initially, we investigate the theoretical and simulated PEL of LAPEL and DPEL and impact of $TTL_{max}$ on the PEL, which are shown in Fig. 2 and 3, 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 $1 \times 10^6$ samples. However, the simulated PEL of LAPEL is the average of all simulations runs. It is observed that the last hop Interest forwarder has almost similar PEL for any $TTL_{max}$ value, which is equal...
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. 2. On the other hand, PEL in DPEL has constant initial PEL $\tau_0$ and decay rate $\lambda$ and is not adaptive to $TTL_{max}$ scenario (refer Fig. 3). Next, the DPEL scheme has constant PEL at consumer for the fixed $\tau_0$ and any value of $\lambda$. 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 unadaptive for the wireless environment. Lastly, the estimation of initial PEL $\tau$ (PEL at consumer) and its decay rate $\lambda$ 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 Fig. 4 and 5. Figure 4 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 $\tau_0$ (i.e., 0.1, 0.3, and 0.5) and decay rates $\lambda$ (i.e., 0.1, 0.3, and 0.5) of DPEL have been investigated in the simulations. It shows that the constant $\lambda$ 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 PEL at the consumer and all the vehicles between consumer and the provider vehicles. The results show that that adaptively calculated PEL of LAPEL is smaller than the constant $\tau_0$ of DPEL. DPEL could use very small $\tau_0$, which could minimize the PEL at each node. However, DPEL does not provide any $\tau_0$ estimation mechanism and the smaller $\tau_0$ may reduce the Interest satisfaction ratio. The rationale behind this phenomenon is that small $\tau_0$ 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 large hop distance. It is apparent from the figure that LAPEL has very less and adaptive PEL compared to any DPEL’s $\tau_0$ and $\lambda$. 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.

Figure 5 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 $TTL = TTL_{\max}$. Figure 6 illustrates the PEL for different hop limits as well as the impact of node speed on the PEL at consumer vehicle. As per the 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 consumer slightly increases for larger $TTL_{\max}$, which is a natural phenomenon. Furthermore, the speed of vehicle results in more Interest or Data packet drop due to intermittent link, refer lower sub-figure of Fig. 6. 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.

![Fig. 6: Average PIT entry lifetime at Consumer vehicle for $TTL_{\max} = 11$ versus average speed of vehicles.](image)

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 the two factors: PEL and the Interest satisfaction ratio. If all the Interest 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.

Figure 7 shows the average number of PIT entries per vehicle for different $\tau_0$ 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 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.

![Fig. 7: Maximum number of PIT entries per Vehicle for $TTL_{\max} = 11$ versus average speed of vehicles.](image)

![Fig. 8: Average Interest satisfaction ratio for varying speed and $TTL_{\max} = 11$.](image)

In last, the average Interest satisfaction ratio of the network has been discussed. The average Interest satisfaction ratio for varying vehicle speed and $\tau_0$ is shown in Fig. 8. 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
TABLE II: Summary of PEL improved by LAPEL compared to DPEL.

<table>
<thead>
<tr>
<th>T</th>
<th>Avg. PEL (s)</th>
<th>% less PEL</th>
<th>Overall % less PEL</th>
<th>Avg. PEL (s)</th>
<th>% less PEL</th>
<th>Overall % less PEL</th>
<th>Avg. PEL (s)</th>
<th>% less PEL</th>
<th>Overall % less PEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.01</td>
<td>0.094414</td>
<td>36.98%</td>
<td>0.01</td>
<td>0.094744</td>
<td>36.98%</td>
<td>0.01</td>
<td>0.094744</td>
<td>36.98%</td>
</tr>
<tr>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td>0.03</td>
<td>0.061346</td>
<td>36.98%</td>
<td>0.03</td>
<td>0.061346</td>
<td>36.98%</td>
</tr>
<tr>
<td>0.3</td>
<td>0.01</td>
<td>0.28366</td>
<td>71.82%</td>
<td>0.02</td>
<td>0.28359</td>
<td>71.82%</td>
<td>0.02</td>
<td>0.28359</td>
<td>71.82%</td>
</tr>
<tr>
<td>0.5</td>
<td>0.02</td>
<td>0.4479</td>
<td>87.56%</td>
<td>0.03</td>
<td>0.4479</td>
<td>87.56%</td>
<td>0.03</td>
<td>0.4479</td>
<td>87.56%</td>
</tr>
</tbody>
</table>

earlier, the smaller $\tau_0$ of DPEL reduces the number of PIT entries. However, it fails to receive contents from the distant providers in the large $TTL_{max}$ scenario. As a result, DPEL with small initial PEL has less Interest satisfaction ratio. 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 $\tau_0 = 0.1$.

To summarize the discussion, LAPEL adaptive 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.

APPENDIX

Proof of the Logistic Model

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

Separation of variables and taking integral gives:

$$\frac{dL}{L \left[\frac{L}{K} - 1\right]} = rdh$$

Left hand side of eq.(18) can be written as:

$$\frac{1}{L \left[\frac{L}{K} - 1\right]} = A + \frac{B}{\left[\frac{L}{K} - 1\right]}$$

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

$$1 = A \left[\frac{L}{K} - 1\right] + BL$$

By substituting $A$ and $B$ in eq. (19), we get:

$$1 = -A + L \left[\frac{B + A}{K}\right]$$

Taking integral of eq.18 and substituting the simplified solution in eq. refsolstep2, we get:

$$- \int \frac{1}{L} dL + \int \frac{1}{K \left[\frac{L}{K} - 1\right]} dL = \int rdh$$

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

$$- \int \frac{1}{L} dL + \int \frac{1}{u} du = \int rdh$$

$$-ln(L) + c_1 + ln(u) + c_2 = rh + c_3$$

where $c = c_3 - c_2 - c_1$

$$ln\left(\frac{L}{u}\right) = -rh - c$$
By putting the value of $u$, we get:

$$\ln(\frac{L}{K^{1-c}}) = -rh - c \quad (31)$$

$$\frac{L}{K^{1-c}} = Ce^{-rh} \quad (32)$$

where $C = e^{-c}$

$$L = \frac{LCE^{-rh}}{Ce^{-rh} - 1} \quad (33)$$

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

$$L = \frac{CK}{C - Ke^{rh}} \quad (35)$$

$$h = 0,$$

$$L_0 = \frac{CK}{C - K} \quad (36)$$

Solving for $C$, we get:

$$C = \frac{L_0K}{L_0 - K} \quad (37)$$

By substituting the value of $C$ in eq.(35), we get:

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

After multiplying and dividing eq.(38) with $\frac{L_0 - K}{K}$ and simplifying, we get:

$$L = \frac{K}{1 + \left(\frac{K - L_0}{L_0}\right)e^{rh}} \quad (39)$$

or

$$L(h) = \frac{K}{1 + Ae^{rh}} \quad (40)$$

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

ACKNOWLEDGMENT

This work was supported by Institute for Information & communications Technology Promotion (IITP) grant funded by the Korea government (MSIT) (No.2014-0-00065, Resilient Cyber-Physical Systems Research).

REFERENCES


