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Efficient Data Broadcast Mitigation in Multisource Named-Content Discovery for Vehicular CPS

Safdar Hussain Bouk, Syed Hassan Ahmed, Kyung-Joon Park, and Yongsoon Eun

***Abstract*—Conventionally, a node or vehicle in the Named Data Networking (NDN) sends an interest packet to discover information and receives a single data packet in response. However, in the case of named data Vehicular Cyber-Physical System (VCPS), a vehicle may require content from multiple vehicles in the network. Therefore, NDN forwarding daemon must receive multiple data packets in response to a single interest. Moreover, the data broadcast storm worsens in the named data VCPS due to the broadcast nature of the wireless link. In this letter, we propose the data packet broadcast suppression method for any multisource content discovery in VCPS. The proposed scheme distributively selects the potential data forwarding vehicles based on the neighbor distance, node density, and the closeness to the data forwarding line of sight. Our simulation results show that the proposed scheme alleviates 55% data traffic, 17% average per-hop delay, and achieves 7% more data discovery ratio.**

***Index Terms*—NDN, VCPS, broadcast suppression, Multi-source Data.**

I. Introduction

Intelligent driving and smart transportation system (STS) have been at the center of research in the domain of smart cities, lately. The STS technologies blurred the boundaries of different fields, including, communication, control, computation, sensing, and actuation. This notion is commonly termed as the vehicular cyber-physical systems (VCPS) [1]. VCPS is simply characterized as "a system of systems (all mobile and infrastructure nodes, etc.) that brings a well-structured, organized, and close cooperation between the physical and the cyber worlds for vehicles through communication technologies to form a complete STS". VCPS has realized many applications and domains, including but not limited to, emergency vehicle preemption, smart traffic light system, intelligent cruise control system, dynamic and connected Eco-driving, smart parking, and many more.

In a typical VCPS, all vehicular network elements, such as, vehicle's onboard unit (OBU), roadside unit (RSU), sensory devices installed within the vehicle and on the road, servers at the regional transport centers, personal devices, and so forth, have communication, computation, control, decision making, and actuation capabilities. Having said that, the communication is the integral component of VCPS that transfers data or content among all the VCPS components to realize the impeccable STS. Mainly, the communication is presumed to be fast, secure, and error-free in VCPS control research, which is not a pragmatic assumption. The content communication and achieving a certain quality of communication among mobile devices, is still an active research topic. Thus, many researchers are continuously investigating different solutions to improve the efficiency and security of vehicular networks.

Recently, researchers have investigated one of the information-centric networking (ICN) architectures, called, Named-Data Networking (NDN), in the domain of vehicular networks. They demonstrated that NDN inherently provides content security and intrinsically deals with the mobility issues in the mobile networks [3]. NDN uses naming to communicate content along with the content's security credentials to focus on security and communication, over the content instead of the communication channel. Vanilla NDN communicates content in a pull-based manner using two packet types; *interest* and *data*. Information requesting node (*consumer*) sends an interest packet and the requested content holding or generating node(s) (*provider(s)* or *producer(s)*) send(s) the requested content in the data packet, one interest-one data. Interest and data communication between consumer and producer is achieved through employing the pending interest table (PIT), forwarding information based (FIB), and the content cache or store (CS). However, there are multiple VCPS applications, where a consumer expects content from multiple providers optimally by sending one interest packet and receiving multiple data packets. We named this process as multisource content discovery in VCPS. On the contrary, vanilla NDN does not support single interest multisource content, yet, it discovers multisource data by sending multiple interest packets with `exclude` filed. Using `exclude` field in successive interest packets, the consumer excludes all the previously received instances of the contents, refer Fig. 1(a). Next, the authors in [4] proposed the one-hope single interest multisource data retrieval, refer Fig. 1(b). The interest packet forwarder holds the packet for a longer time until it receives data from all the one-hop neighbors. In contrast, the authors in [5] proposed the multi-hop multisource content discovery in the VCPS scenario. In this work, when a vehicle receives an interest, first it replies with the content and then it blindly forwards the interest further in the network. Each node maintains a long PIT (LP) entry and also forwards all the respective data packet towards the consumer, as shown in Fig. 1(c). Due to the valid long PIT entry, each vehicle generates and forwards a distinct

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content instance towards the consumer via data packets, thus incurring a large data broadcast storm in the specific region, i.e., road segment, block area, etc., called an information discovery region. Thus, lots of data packets fail to reach the consumer and resulted in a very small information discovery ratio [5]. In this letter, we mitigate the data broadcast storm

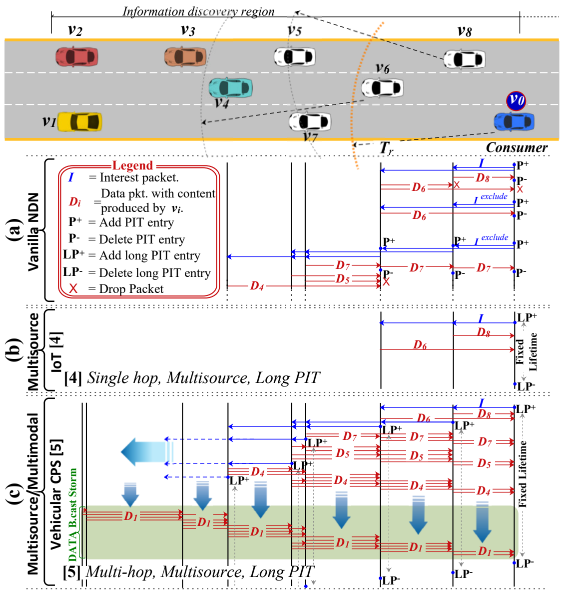

Fig. 1: Multisource named-content discovery in VCPS.

by considering multiple network characteristics, including the vehicle density, directional distance, and the closeness of potential data forwarding vehicle in the line of sight between consumer and the data forwarding vehicles. A vehicle that is closest to the direction of the consumer and has a large vehicle degree, will only further forward the data packet towards the consumer and the rest will defer the packet broadcast. As a result, the data broadcast storm is mitigated, which increases the information discovery ratio. Next section briefly discusses our proposed multisource named-content.

II. Proposed Multisource Named-Content Broadcast Storm Mitigation Scheme

In a single interest multisource content discovery scenario, the consumer requires current traffic or other traffic information from all the network elements of the specific information discovery region. Since vanilla NDN architecture is not suitable for this type of communication, therefore, the authors in [5] extended NDN to achieve multisource content discovery. The consumer in this discovery phase generates an interest packet, and each interest receiving vehicle performs two operations; (a) replies with the content in data packet, and (b) creates a long PIT entry and forwards the interest further in the network. Each interest and data packet are assigned a random number (NONCE) to avoid the interest and data routing loop. All the data packet receiving vehicles further forward it to the consumer(s), if they did not already forward the copy of that packet. In result, we face data broadcast storm, as illustrated in Fig. 1.

Our proposed method reduces the data broadcast storm by allowing only selected vehicles to forward copies of the data packet towards the consumer. The selection of potential data forwarding vehicle(s) take(s) into account the large node density, directional distance, and closeness of potential data forwarding vehicle to the line of sight between consumer and data forwarder vehicle. Based on these parameters, the potential forwarder computes the final score of Q. The vehicle that has a minimum Q will forward the data packet, otherwise, it defers the data packet forwarding. The potential forwarder selection parameters and process are discussed in the upcoming sections.

A. Potential data forwarder selection parameters

Let us assume that a data packet generator or forwarder, D_F, receiver, D_{v_i}, and a consumer, C, nodes are moving at the speed of s_F, s_{v_i}, and s_C, respectively. The approximate location of these nodes are denoted as (x_F, y_F, z_F), $(x_{v_i}, y_{v_i}, z_{v_i})$, and (x_C, y_C, z_C). Euclidean distance between receiver node v_i and F is denoted by $E_{(v_i,F)}$. All vehicles v_i are considered receivers vehicles, R, which are in the transmission range of s, T_{r_s} and satisfy the condition: $v_i \in R | E_{v_i,s} \le T_r$. In order to select the most suitable data forwarder among R, the following parameters and conditions are considered in this work. The closeness ratio of $v_i \in R$ towards the C, c_i, is computed as:

$$c_1 = \left(\frac{(T_r - E_{(F,C)}) + E_{(v_i,C)} \cos\phi_i}{T_r} \right), \tag{1}$$

where $\cos\phi_i = \frac{E^2_{(v_i,C)} + E^2_{(F,C)} - E^2_{(F,v_i)}}{2E_{(v_i,C)}E_{(F,C)}}$. In such a case, lower the value of c_1, better the v_i to be selected as a forwarder. The next parameter is the adjacency to the line of sight between F and C, and the v_i:

$$c_2 = E_{(v_i,C)} \sin\phi_i. \tag{2}$$

Smaller the c_2, the better the v_i to forward the data packet further to C. In addition to that, our proposed scheme also considers node degree of the data receiving vehicle, which is estimated as:

$$c_3 = |\cup v_j | T_r \le E_{(v_i,v_j)}|, \tag{3}$$

where $j \neq F$ and C. The receiver node with a large degree is intended to forward data to many nodes in the network. Hence, the larger node degree vehicle v_i is a suitable data forwarder. The parameters are shown in Fig. 2. All vehicles in R are the

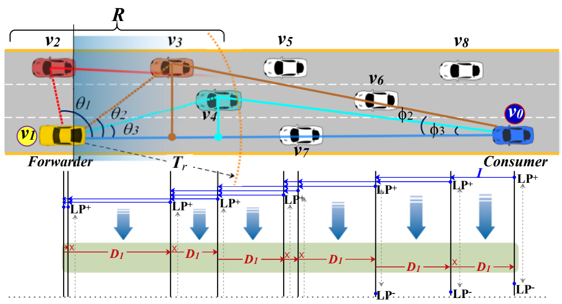

Fig. 2: Broadcast suppression in multisource named-content discovery.

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data packet forwarding candidates if they satisfy the following conditions:

$$\theta_i = \cos^{-1}\left(\frac{E^2_{(F,v_i)} + E^2_{(F,C)} - E^2_{(v_i,C)}}{2E_{(F,v_i)}E_{(F,C)}}\right) > 0 \text{ and } E_{(v_i,C)} < E_{(F,C)}.$$

The above conditions restrict all the vehicles that are out of the forwarding zone between F and C. In Fig. 2, v_2 is out of the forwarding zone.

B. Potential forwarder score computation

The following steps are used to distributively select the most suitable vehicle from the data receiving vehicles to further disseminate the message upstream in the network. Every vehicle maintains a neighborhood table that keeps track of the following parameters, the distance between vehicles and the speed of neighboring vehicles.

When a vehicle receives a data packet, it computes the relative overall weight of itself and its neighbors by using the following steps. Every vehicle maintains c_1, c_2, and c_3 of the neighboring vehicles in a table, as presented below.

$$\mathbf{d_{m,n}} = \begin{array}{c c} & \begin{array}{ccccc} c_1 & c_2 & c_3 & \cdots & c_n \end{array} \\ \begin{array}{c} v_1 \\ v_2 \\ \vdots \\ v_m \end{array} & \begin{bmatrix} a_{1,1} & a_{1,2} & a_{1,3} & \cdots & a_{1,n} \\ a_{2,1} & a_{2,2} & a_{2,3} & \cdots & a_{2,n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{m,1} & a_{m,2} & a_{m,3} & \cdots & a_{m,n} \end{bmatrix} \end{array}. \quad (4)$$

Next, it is important to get *ideal* solutions for the positive (c^+) and negative (c^-) criteria j, $1 < j < n$, respectively using the eq.(5) and (6).

$$A^+_j = (\underset{i}{max}(a_{i,j}) \mid \textit{if } j \in c^+;\ \underset{i}{min}(a_{i,j}) \mid \textit{if } j \in c^-\ ), \quad (5)$$

$$A^-_j = (\underset{i}{min}(a_{i,j}) \mid \textit{if } j \in c^+;\ \underset{i}{max}(a_{i,j}) \mid \textit{if } j \in c^-\ ). \quad (6)$$

After getting the ideal solutions, all criteria values in the $d_{m,n}$ are weighted normalized to the uniform scale and similar criteria trend, e.g., positive criterion, where higher the value of the criterion is the better. As a result, we get the weighted normalized matrix, $U_{m,n}$, where each element $u_{i,j}$ is computed as:

$$u_{i,j} = \left(w_j.\frac{A^+_j - a_{i,j}}{A^+_j - A^-_j}\right), \quad (7)$$

where w_j is the weighting factor to assign relative preference to each criterion c_j. The value of w_j are assigned by the decision maker or can be determined using entropy of the $d_{m,n}$ [6].

The next step is to find the group utility measure, G_i, that shows the overall benefit or gain and the regret measure H_i of each vehicle in the neighborhood, which indicates the individual deviation;

$$G_i = \sum_j^n u_{i,j}, \text{ where } \begin{array}{l} i = 1,\ldots,m, \\ j = 1,\ldots,n, \end{array} \quad G^* = \underset{i}{min}\,(G_i),\ \ G^- = \underset{i}{max}\,(G_i). \quad (8)$$

$$H_i = \max\,(u_{i,j}), \text{ where } \begin{array}{l} i = 1,\ldots,m, \\ j = 1,\ldots,n, \end{array} \quad H^* = \underset{i}{min}\,(H_i),\ \ H^- = \underset{i}{max}\,(H_i). \quad (9)$$

In last, the final score of each vehicle, Q_i, is computed that helps in ranking the more suitable vehicle to forward data among all the potential forwarding vehicles.

$$Q_i = \rho.\left(\frac{G_i - G^*}{G^- - G^*}\right) + (1-\rho)\cdot\left(\frac{H_i - H^*}{H^- - H^*}\right), \quad (10)$$

where ρ is the preference factor that prioritizes the group utility G and individual regret or deviation measure H. The value of ρ determines whether which rule has been applied in the decision; $\rho < 0.5$ (*veto rule*), grants preference to the individual vehicle, which dominates the final score. $\rho > 0.5$ (*majority voting rule*) gives more preference to the group utility measure. $\rho = 0.5$ (*consensus rule*) balances the priority between groups and individual vehicle measures. In the context of this letter, we used the consensus rule. The most preferable vehicle to forward data is the one that has the minimum final score, $min(Q_i)$.

C. Forwarding data packets

Unlike the traditional NDN forwarding daemon, the interest receivers in the proposed work, do not blindly forward data packet, but they first distributively compute Q_i. Furthermore, the vehicle(s) with $min(Q_i)$ forward(s) the data. If the receiver vehicle v_i's own Q_i is not less than its neighbors, then it holds the data packet to the duration of DH_i. Once the DH_i expires and the receiver v_i does not receive any other copy of the packet, it forwards the data packet. This condition ensures that only the potential forwarder(s) among the neighbors, forward the packet. As in Fig. 1, the forwarder v_1 broadcasts the data and the receivers v_2, v_3, and v_4, compute their respective DHs. Let, the neighbors of v_1 could not receive a copy of the data packet from v_1, then the neighbor with smaller DH that expires soon will forward the packet. Let v_4 has the lowest DH, then it will forward the data and rest will defer forwarding of the data packet. The DH_i is estimated as:

$$DH_i = tan(Q_i)(AIFS[j] + CW_d), \quad (11)$$

where $tan(Q_i)$ is the scaling factor for data holding time for v_i and $AIFS[j]$ is the access category j, $AC[j]$, arbitration inter-frame spacing value. The lowest the access category index, the highest the message forwarding priority, as in IEEE 802.11p [2]. The $AC[0]$ is assigned to data packets in order to ensure the highest priority. The $AIFS$ for $AC[0]$, $AIFS[0]$ is estimated as:

$$AIFS[0] = aSD \times AIFSN[0] + aSIFS, \quad (12)$$

where $AIFSN[0] = 2$, aSD is a slot duration that is $13\mu s$ in IEEE 802.11p with 10MHz channel spacing, and finally, the $aSIFS$ is the short inter-frame space duration that is $32\mu s$. In eq.(11), the term contention window for the data packet, CW_d, is estimated as $CW_d = (HC \times rand\,(0, CW_{max}[0])) \times aSD$. Here, $CW_{max}[0] = \left(\left(\frac{CW^{min}+1}{2}\right) - 1\right)$ with $CW^{min} = 15$. For further information, please refer [2].

III. Simulation Analysis

The performance of the proposed scheme is validated through simulations to its most relevant conventional scheme [5]. To ensure the fairness in our analysis, we considered similar simulation parameters as of the conventional

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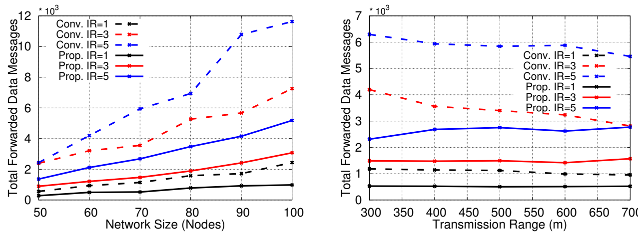
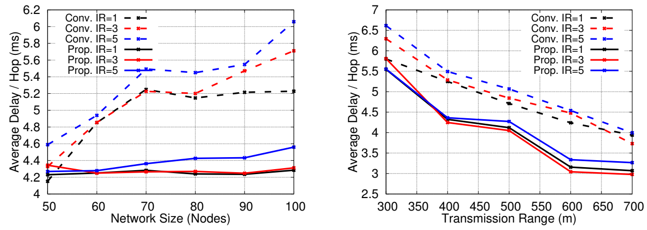


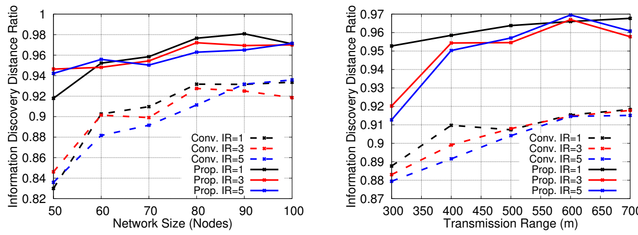
(a) $T_r = 400m$, C=3, IR=1, 3, 5 (b) $N = 70$, C=3, IR=1, 3, 5

Fig. 3: Total forwarded data packets (a) N and (b) T_r.



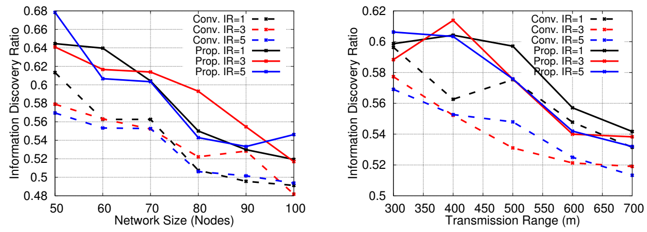
(a) $T_r = 400m$, C=3, IR=1, 3, 5 (b) $N = 70$, C=3, IR=1, 3, 5

Fig. 5: Avg. per hop delay (a) N and (b) T_r.



(a) $T_r = 400m$, C=3, IR=1, 3, 5 (b) $N = 70$, C=3, IR=1, 3, 5

Fig. 4: Information discovery distance ratio (a) N and (b) T_r.



(a) $T_r = 400m$, C=3, IR=1, 3, 5 (b) $N = 70$, C=3, IR=1, 3, 5

Fig. 6: Interest discovery ratio (a) N and (b) T_r.

scheme. The simulations are performed in a traditional Ubuntu based Network Simulator (v.2), where we considered the highway mobility scenario. In simulations, a 4-lane two-way highway of $10km$ long is mapped, where vehicles move at the average speed of $15m/s$. The network and transmission ranges are varied from 50 to 100 nodes and 300 to $900m$, respectively. The information discovery region is $1000m$. Finally, the number of consumers $C = 3$ and the interest rate $IR = 1$, 3, and 5 interest/s have been used in the simulations.

Figure 3 shows the total number of data packets processed in the network. The results show that the proposed scheme process far less number of data packets compared to the conventional scheme because it allows only potential nodes to forward the messages in the information discovery region. On average, the proposed scheme processes 55.7% and 54.7% data packets compared to the conventional scheme, for varying network sizes (Fig. 3a) and transmission ranges (Fig. 3b), respectively.

Next, we analyzed the information discovery distance ratio, shown in Fig. 4, which indicates the information discoverability of the scheme from the distant nodes in the region. It is evident from the results that the proposed scheme reduces the data broadcast storm in the network, which enables the successful communication of the contents generated by the distant vehicles, towards the consumer. Furthermore, results clearly depict that information from the extreme edge vehicles is also discovered by the proposed scheme. The other performance metric that we investigated is the average per hop delay, as shown in Fig. 5. The proposed scheme forwards data through the vehicles that are at the edge of the transmission range and near the beeline between consumer and the data generating vehicle. As a result, the content quickly reaches the consumer vehicle. Respectively, the proposed scheme reduces 17.6% and 18.4% per hop delay contrast to the conventional scheme for varying N and T_r scenarios. Finally, Fig. 6 shows the overall information discovery ratio, which is the number of vehicles with successfully discovered information and the total number of vehicles in the region. Owing to the low data broadcast traffic by the proposed scheme, it successfully discovers information from 6.5% more vehicles in the discovery region than the conventional scheme. After comparing all the results, we can easily comprehend that our proposed scheme outperforms the conventional scheme in all aspects.

IV. Conclusion

In this letter, we proposed a distributed multimodal named data broadcast storm mitigation scheme for VCPS. The proposed scheme minimizes the broadcast storm by selecting the potential forwarder(s) based on the distance, vehicular density, and vehicle's proximity information. The results show that the proposed scheme performs better in terms of less data broadcast, low per hop day, and higher information discovery ratio. In future,we plan to extend our proposed scheme to optimize the data forwarder selection process to minimize the delay and data broadcast storm.

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