IEEE Access Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal
SPECIAL SECTION ON FUTURE NETWORKS: ARCHITECTURES, PROTOCOLS, AND APPLICATIONS

Received May 21, 2017, accepted June 7, 2017, date of publication June 26, 2017, date of current version July 24, 2017.

Digital Object Identifier 10.1109/ACCESS.2017.2717501

Enhancing Quality-of-Service Conditions Using a Cross-Layer Paradigm for Ad-Hoc Vehicular Communication

SABIH UR REHMAN[1], (Member, IEEE), M. ARIF KHAN[1], (Member, IEEE), MUHAMMAD IMRAN[2], (Member, IEEE), TANVEER A. ZIA[1], (Senior Member, IEEE), AND MOHSIN IFTIKHAR[1], (Member, IEEE)

[1]School of Computing and Mathematics, Charles Sturt University, Sydney, NSW 2127, Australia
[2]College of Computer and Information Sciences, King Saud University, AlMuzahmiyah 11692, Saudi Arabia

Corresponding author: Sabih ur Rehman (sarehman@csu.edu.au)

This work was supported by the Charles Sturt University ''Writing-Up'' Grant 2016. The work of M. Imran was supported by the Deanship of Scientific Research at King Saud University through Research Group under Grant RG. No 1435-051.

ABSTRACT The Internet of Vehicles (IoVs) is an emerging paradigm aiming to introduce a plethora of innovative applications and services that impose a certain quality of service (QoS) requirements. The IoV mainly relies on vehicular ad-hoc networks (VANETs) for autonomous inter-vehicle communication and road-traffic safety management. With the ever-increasing demand to design new and emerging applications for VANETs, one challenge that continues to stand out is the provision of acceptable QoS requirements to particular user applications. Most existing solutions to this challenge rely on a single layer of the protocol stack. This paper presents a cross-layer decision-based routing protocol that necessitates choosing the best multi-hop path for packet delivery to meet acceptable QoS requirements. The proposed protocol acquires the information about the channel rate from the physical layer and incorporates this information in decision making, while directing traffic at the network layer level. Key performance metrics for the system design are analyzed using extensive experimental simulation scenarios. In addition, three data rate variant solutions are proposed to cater for various application-specific requirements in highways and urban environments.

INDEX TERMS Internet of vehicles, vehicular ad hoc networks, multi-hop routing, cross-layer design, quality-of-service, multi-rate.

I. INTRODUCTION

Recent advancements in automotive, transportation, sensing, computing, wireless communication, and networking technologies have paved the way for the evolution of vehicular ad-hoc networks (VANETs) into the Internet of vehicles (IoV) [1]. The IoV introduces innovative applications and services, such as traffic management (e.g., congestion and collision avoidance, intelligent monitoring, and prediction), multimedia streaming, infotainment, and e-health, all of which rely on VANETs for inter-vehicle communication. Despite considerable advances in various aspects, routing in VANETs is challenging because finding a reliable data forwarding path from the source to the destination is difficult. This challenge is mainly attributed to the unique characteristics (e.g., frequent topology changes due to high-speed mobility, sparse network), and quality-of-service (QoS) requirements of these emerging applications. To fulfil QoS requirements, the Physical (PHY) and Medium Access Control (MAC) layer standards were compiled under the IEEE 802.11 framework with some minor changes to accommodate these key functionalities. Using the traditional ISO-OSI layering model [4], previous works have made several attempts to meet the QoS requirements and attain optimum functionality within an architecture comprising of several layers. Looking at the Physical layer, the QoS is mostly involved with achieving maximum data rate for nodes (i.e. vehicles). However the QoS at higher layers (e.g. MAC) also deals with parameters such as propagation delay and throughput. Designing a network architecture on the basis of individual layer attributes cannot be directly applied to a VANET architecture because of its stringent environment and exacting requirements to provide QoS for various applications. Nevertheless, these tough QoS requirements can still be met by employing a cross-layered approach. In this approach, the scheduler attains the required information from a combination of various layers to fulfill the QoS requirements for each node. The standard protocol stack for Wireless Access for Vehicular Environment (WAVE) has been established to illustrate the formation of this layered structure for VANET architecture [5]–[7]. To tackle this problem, what is required is a design that utilizes the values of various protocols from the PHY and MAC layers such as queue lengths, information of the channel state, wireless link capacity, and throughput as well as provides a suitably tailored solution to address application needs.

When it comes to establishing communication relative to these application requirements, information can be disseminated in different ways. A successful VANET architecture should not only be able to meet the requirements of its users that are constantly changing but should also comply with all available standards and architecture. In a typical VANET communication architecture, vehicles can capture localised information with relative ease; however distributing such information over long is challenging. For example, a critical safety/medical application [8] needs to successfully relay accident information to emergency services, that can be miles away from the accident site. The beaconing (or hello signals) approach [9] helps distribute accident information. Continuous network connectivity is not always possible within the Vehicular Ad-hoc Networks mainly because of their extremely dynamic nature. Previous studies [10], [11] have utilized concepts from Delay Tolerant Networks (DTN) [12], [13] such as *store-and-forward* approaches for a multi-hop architecture design of VANETs. Most existing routing schemes are either in context of Mobile Ad hoc Networks (MANETs) [18]–[20] or based on a single layer. For instance, the authors in [17] presented a multiple rate aware routing architecture to enhance resource sharing and distribution and to address power requirements within the architecture of MANETs. The idea was to use the rate allocation that has already been defined by the IEEE 802.11b architecture. The authors showed that the proposed routing architecture outperforms conventional approaches for delay in information delivery and average throughput. Studies have rarely considered a cross-layer design in the context of VANETs [15]. We designed a multi-hop routing framework based on a cross-layered architecture for VANETs [14]. The proposed architecture uses beaconing information in exchanging inter-layer parameters from the PHY and MAC layers. Unlike traditional (distance or pre- route based) algorithms, the proposed cross-layer routing protocol is based on true channel conditions (i.e., channel quality information). This study is the first to present a cross-layered framework for routing that attains information about the channel rate from the Physical layer and then integrates it with the routing decisions at the network layer. The contributions of this paper are highlighted below:

- Implementation of a multi-hop cross-layered routing framework for dynamic vehicular communication environment by considering system constraints from various layers, such as PHY-MAC to make efficient decisions.
- Exploration of a cross-layered routing design on the basis of channel quality information (i.e., data rate) and practical scheduling policy by using a realistic wireless channel model.
- Analytical investigation for the system design and its performance using extensive experimental simulation scenarios.
- Proposition of three variants of the rate specific scheduling policy to cater application specific requirements.

The remainder of this manuscript is organised as follows: Section II, provides a complete synopsis of the latest work in this field. Section III presents the system model and architecture considered in this paper. In Section IV we provide a thorough description of the proposed algorithm. Section V presents a mathematical examination of the suggested framework under varying simulation conditions. Finally, the paper is concluded in Section VI.

II. RELATED WORK

Initially, the problems in routing for VANETs were treated same as those established earlier for MANETs [18]–[20]. Later on, researchers recognized VANETs as a special class of MANETs but with a predetermined mobility pattern associated with each node (vehicle). One unique characteristic of VANET nodes is the high mobility of the vehicle. This attribute creates short network lifetime and frequent link failures. Moreover, establishing the QoS requirements in such a rigid environment is challenging. Hence, researchers have explored the real sense of provisioning QoS in terms of user needs to understand the true nature of requirements for a stringent VANET architecture. For instance, a recent study [21] has introduced the terminology of Quality of Experience (QoE) to gauge the user perspective. A detailed survey in relation to the challenges in a design of QoS architecture has been presented in [22]. The researchers have comprehensively analysed issues related to the provision of QoS solutions for VANET architecture. Another study [23] has presented a viable mechanism to provide QoS in a VANET environment by considering a compromise among various conflicting requirements. The authors have used well-known routing approach based on the cluster head mechanism, to establish the architecture of the proposed algorithm. The authors in [24] have highlighted the impact of the current channel access mechanism on QoS provisioning as per the IEEE WAVE standard. To present this effect, an analytical model has been formulated and a new solution to this problem has been proposed by dynamically adjusting the priority of the real-time data to avoid the collision. The results obtained for the proposed approach have shown an improvement in terms of channel utilization compared with the existing mechanism.

The authors in [25] have presented a Quality of Service aware and power control routing framework for MANETs.

The suggested framework manages to support the required bandwidth by regulating the quality of the channel for each link within an acceptable limit. The authors have used an effective route maintenance mechanism to evade link failure and avoid possible significant degradation in the performance of real-time applications such as live video or audio streaming. The effectiveness of the proposed algorithm has been validated through extensive simulations, especially for energy efficiency and end to end delay . The authors in [26] have proposed a QoS-aware multi-channel, MAC channel access scheme for VANETs that adaptively tunes the contention window according to the requirements of different user applications. The design has been tested for prioritised packet transmission environment, and simulation results have shown a high saturation throughput of the implementation.

In general, several studies have explored solutions based on cross-layered approaches to optimise routing for ad-hoc wireless networks [30], [31]. In [33], the authors have designed a cross-layered architecture under Rayleigh fading channel conditions for ad-hoc networks . They have demonstrated via simulations that the system performance parameters especially control overheads, packet drop ratio (PDR), and throughout are optimised after the implementation of the cross-layered architecture. In the absence of this architecture the system performance is degraded, the control packet volume becomes large and the packet drop ratio steeply increases. The performance of ad-hoc networks can be improved using a cross-layer approach while meeting certain guaranteed QoS requirements. However, adopting a cross-layer design in VANET is still in its infancy [20]. For example, the authors in [15], [16] have discussed the challenges of cross-layer design and the limitations imposed by the PHY and MAC layers in a VANET environment. The authors have proposed approaches M1 - M4 to tackle these issues. Moreover, the author in [39] presented a delay aware routing protocol based on cross-layer approach for VANET. This protocol uses beacon messaging to provide information about the chosen communication path. The authors in [34] presented a cross-layer optimisation framework for a multi hop environment for co-operative wireless networks. The proposed scheme employs network utility maximisation techniques to improve convergence, flow control, routing, scheduling, and relay assignment. In [35] the authors proposed a position based cross- layered framework named CLWPR for VANETs. Utilising a two-ray wireless channel model, the authors used weighted Signal to Interference plus Noise Ratio (SINR) and MAC frame error rate to enhance the efficacy of CLWPR. A cross-layer strategy based on the state-of-the-art Ad hoc On-demand Multipath Distance Vector routing protocol (AOMDV) [37] outperforms conventional schemes in both sparse and dense VANET environments. The authors in [38] presented a cross-layered architecture for cooperative VANETs. This architecture makes routing decisions on the basis of link capacity while adjusting the connectivity probability at the MAC layer. Recently, a resource allocation and fuzzy-based rate adaptation technique has been proposed for MANETs [28]. With the Markov model, free bandwidth is predicted on the basis of the current traffic load and the addition of new nodes depends on bandwidth availability. The proposed technique incorporates rate parameter by estimating the physical transmission rate using fuzzy logic, thereby improving the total throughput and performance of the entire network. In the context of VANETs, the authors in [27] have designed a video dissemination routing protocol under dynamic road traffic conditions in an urban environment. The proposed routing protocol uses the rate control mechanism to control the dissemination of information as per data traffic, thereby minimising channel overloading. To the best of our knowledge, the proposed cross-layer VANET scheme is the first to employ channel quality information and practical scheduling policy by using a realistic wireless channel model.

TABLE 1. Symbols and notations.

Symbol	Explanation
V	Number of vehicles
f_c	Carrier frequency
P_t	Total transmit power (W)
B	Bandwidth (Hz)
R	Transmission range (m)
ρ	Vehicle density (veh/m^2)
μ	Vehicle velocity (m/s)
$\mid A \mid$	Cardinality of set A
$\lfloor \cdot \rfloor$	Floor value
$\mathbf{E}[\cdot]$	Expected value
$\mathbf{A}$	Matrix notation s.t $\mathbf{A} \in \mathbf{C}^{m\times n}$
$\mathbf{a}$	Vector notation s.t $\mathbf{a} \in \mathbf{c}^{m\times 1}$
$< s, d >$	Source and destination pair
γ	Channel quality indicator (dB)
Υ	Allocated rate (bps/Hz)
λ	Packet arrival rate (pk/sec)
Ψ_{gen}	Packet generated at node
Ψ	Packets to send (for specific λ)
S	Packet size (byte)
T	Packet transmission time (sec)
Ψ_{dr}	Packet drop ratio
Π	Throughput (bps/Hz)
U	Channel utility

III. SYSTEM MODEL

This section summarizes the system model used in this work and presented earlier in our previous work [29]. Symbols utilised in this paper are presented in Table 1. The terms ‘‘node’’ and ‘‘vehicle’’ are used interchangeably afterwards. We assume a multi-hop communication model and it is illustrated in Figure 1. The total number of vehicles is assumed to be V so that $v = 1, 2, \cdots V$. Vehicles are simulated to move with a given velocity $u(m/s)$ in a freeway environment. Two-way traffic conditions where both directions of the road have two lanes are assumed. The vehicles are statistically deployed initially, in accordance with a homogeneous Poisson distribution having density ρ. Communication begins with the source node s aiming to deliver a particular number of packets to the destination node d via multi-hop communication. A common neighbourhood set of vehicles denoted by $\{CN\}$ is assumed where the neighbouring vehicles within the transmission range of the source node (s) are represented

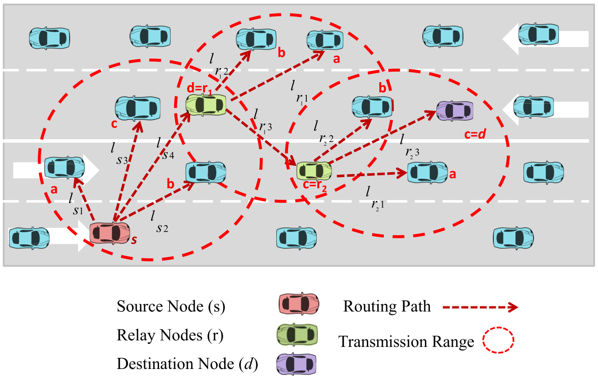

FIGURE 1. System model [29].

by the elements of $\{CN\}$. For instance, vehicles 1-5 are in the vicinity of the source s (i.e., $\{CN\} = \{1..5\}$) as shown in Figure 1. The set of transmission links is given as $\{\mathcal{L}\} = \{l_{s_1}, l_{s_2}, l_{s_3}, l_{s_4}, l_{s_5}\}$ where l_{s_1} is the communication link between the source s and node a. The cardinality of $\{\mathcal{L}\}$ is given by V i.e $|\{\mathcal{L}\}| = V$.

Moreover, a time slotted system is considered where data transmission between vehicles takes place from one block of time to the next. Each block comprises of a predefined number of time slots that can be represented by t. Within each slot of time, the scheduling scheme used, controls the transmission of one or more than one vehicles.

The features of the wireless channel determine the success of a wireless communication scenario. Wireless channel modeling for VANETs is difficult because of its dynamic environment. It is assumed that the number of vehicles within the transmit range of the source node s is given by V_s i.e. $j = 1, \cdots V_s$. In addition, the complex channel h_{sj} denotes a realistic wireless channel between the source s and a vehicle j. The channel h_{sj} features *Rayleigh* distribution [40] and is statistically distributed. This channel is generalised as $h_{s_j} \sim R_r(P')$ where R_r denoting the Rayleigh distributed random variable is given by $R_r = \sqrt{X^2 + Y^2}$. In this equation the independent normal random variables $X \sim N(0, \sigma^2)$ and $Y \sim N(0, \sigma^2)$ have σ^2 variance and a zero mean. The power received at vehicle j that is within the range of source node is represented by P'.

The wireless channel is assumed to remain constant for a clear interval of time so that communication can occur successful within each time slot t. The channel vector is modeled as per the above discussion. Furthermore for the sake of simplicity, each vehicle is assumed to be equipped with a single antenna for transmit and reception of data. Therefore the link between two vehicles can be categorised as a Single Input Single Output (SISO) wireless channel. A more sophisticated and advanced antenna system such as MIMO (Multiple Input and Multiple Output) can be considered for better transmission and reception of signal, however, this can make the overall system model more complicated to analyse. The channel vector $\mathbf{h}$ is defined such that $\mathbf{h} \in \mathbf{C}^{(V_s \times 1)}$ and is given as $\mathbf{h}$:

$$\mathbf{h} = \begin{bmatrix} h_{s_1} \\ h_{s_2} \\ h_{s_3} \\ \cdot \\ \cdot \\ \cdot \\ h_{sV_s} \end{bmatrix}_{V_s \times 1}. \tag{1}$$

Upon being selected for transmission, the source vehicle s delivers the information to the selected npde v^*. The complex signal y_{v^*} received at the receiving node is given as

$$y_{v^*} = h_{sv^*} x + n_{v^*}, \tag{2}$$

where x is the transmitted signal and n_{v^*} is symbolizes Additive White Gaussian Noise at the selected vehicle v^*.

Below is an investigation of the actual rate supported by the links. The data rate supported by the links must be incorporated in the routing architecture to evade the risk of transmission breakdown. This process also minimises the control overheads. The data rate supported by a wireless link for the nodes s and j at any time slot t is given as $\Upsilon_{s_j}(t)$. Further explaining the convention, it is classified that $\Upsilon_{s_j}(t) = 0$ for links (s,j) when no direct communication is possible amid vehicles s and j. Rate is measured in units of bps/Hz. Average data rate, $\hat{\Upsilon}_{s_j}(t)$, is calculated as

$$\hat{\Upsilon}_{s_j}(t) = \mathbf{E}[\log_2(1 + \gamma_{s_j})] \quad \text{bps/Hz}, \tag{3}$$

where γ_{s_j} denotes the SINR between vehicles s and j and is given as below as previously mentioned in [29]

$$\gamma_{sj} = \frac{h_{sj} P_{sj}}{n_{sj} + \sum_{i=1, i \neq j}^{V_s} h_{si} P_{si}}, \tag{4}$$

where P_{si} signifies the transmission power between vehicles s and i. For sake of clarity, it is assumed that all transmitting vehicles transmit with a consistent transmission power P_t of $1W$ and $\boldsymbol{\Upsilon}(t)$ is a vector of data rates:

$$\boldsymbol{\Upsilon}(t) = \begin{bmatrix} \Upsilon_{s_1} \\ \Upsilon_{s_2} \\ \Upsilon_{s_3} \\ \cdot \\ \cdot \\ \cdot \\ \Upsilon_{sV_s} \end{bmatrix}_{V_s \times 1}. \tag{5}$$

A. SCHEDULING

Scheduling an appropriate vehicle for transmission during each time slot plays a critical role in establishing application-specific communication requirements. For the source s to select an appropriate node for transmission, vehicle-specific attributes such as location, distance and wireless channel conditions or supported data rate are required. Depending on these elements, we schedule the communication for a particular time slot. The key purpose of the scheduler is to deliver the promised QoS by attaining a higher system throughput value while assuring successful transmission of packets. In the following subsections, we review commonly used scheduling schemes in wireless communications and apply them for the VANET communication scenario under discussion.

1) ROUND ROBIN SCHEDULING

Round Robin (RR) scheduling is a simple approach in which a vehicle is randomly selected from the $\{CN\}$ irrespective of their data rates or any other information. This scheduling scheme can be represented as:

$$v^*(t) = \underset{i\in\{1,\cdots,V_s\}}{\text{argrand}} \{1 : V_s\}. \tag{6}$$

Corollary: A special case of (6) can be achieved for $N \rightarrow \infty$ such that

$$\lim_{N\rightarrow\infty} \frac{v_r^*}{v_{rr}^*} \Rightarrow 1 \tag{7}$$

where v_r^* and v_{rr}^* represent the optimal selected vehicle using random and Round Robin approaches respectively.

2) MAX-RATE(MR) SCHEDULING

In Max-Rate (MR) scheduling, the selection of relay vehicle is based on the highest data rate at each time slot. We consider that the current data rate sustained between nodes s and j by the wireless channel at a time slot t is $\Upsilon_{sj}(t)$ where $j = 1 \cdots V_s$. The selection of vehicle v^* for transmission in MR scheduling is as follows:

$$v^*(t) = \underset{j\in\{1,\cdots,V_s\}}{\text{argmax}} \{\boldsymbol{\Upsilon}(t)\}. \tag{8}$$

The MR scheduling algorithm selects a vehicle with the best data rate, thereby providing QoS with an increased likelihood of success. This algorithm is well suited for applications requiring strict QoS measures such as multimedia streaming.

3) WEIGHTED ROUND ROBIN(W-RR) SCHEDULING

In the Weighted Round Robin (W-RR) scheduling, the relay vehicle is selected on the basis of scale or weight associated within the routing decision i.e.

$$v^*(t) = \underset{j\in\{1,\cdots,V_s\}}{\text{argmax}} \{\kappa(t) \times \boldsymbol{\Upsilon}(t)\}, \tag{9}$$

where $\kappa(t)$ is the weight associated with the scheduling decision. The value of $\kappa(t)$ can be derived as per application requirement or can be utilised to gain the trade off between performance efficiency and computational complexity.

IV. PROPOSED ALGORITHM DESIGN

As mentioned earlier, the current paper aims to further develop the architecture previously presented in [14] to explore the possibilities of creating an optimised routing architecture for VANETs. In order to design such an architecture, we would like to model the design to cater QoS requirements for application-specific needs by considering accessible information from all layers of the OSI architecture.

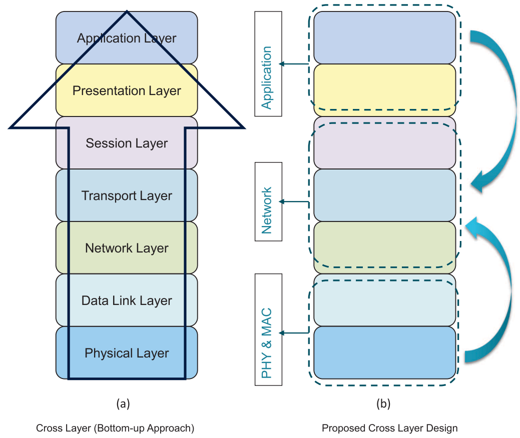

FIGURE 2. Cross-layer approach for VANETs [32].

The design of a Cross Layer Decision Based Routing Protocol *CLDBRP* is proposed in this paper, which links the channel rate information from the PHY-MAC layer to establish correct routing decisions within the network. In a conventional OSI-layered architecture, individual layers use their own set of variables. Conversely, a cross-layered approach utilises the bottom-up method, where the upper layers are optimized accordingly after considering parameters from the lower layers. On the basis of the WAVE protocol stack and as illustrated in Figure 2, the OSI layer model is sub-divided into three main sub-layers, namely PHY-MAC, Network and Application. The communication range is calculated by considering PHY-MAC layer parameters such as SINR, channel rate and channel dynamics at the network layer. The major variable at PHY layer that can be utilized at the upper layers is the data rate (throughput) information. Data rate is dependent on signal strength, i.e., available bandwidth, SINR, transmit/receive power and wireless channel dynamics with respect to time. An overall efficient system can be designed by varying the routing parameters consistent with the PHY-MAC layer variables, [33].

On the basis of the PHY-MAC layer parameters, a source node receives SINR information as a feedback. The nodes at the border of the transmission range of the source are expected to have low SINR values. However, to ensure that they are included in the selection process, their SINR can be improved by using a weighting factor when required. As a result of adjusting SINR values, the source node may end up selecting a weak wireless link that cannot support the transmission effectively. Therefore, realistic SINR values must be incorporated in decision making. This process is useful in calculating the allocated channel rate as per equation (3). The proposed algorithm *CLDBRP* is illustrated in a flow diagram presented in Figure 3. As mentioned in the previous section, this proposed architecture is an enhancement of our previous work referred in the flow diagram as Case I [14]. In this proposed routing scheme implemented at the network layer level, key metrics used to optimize the performance are average transmission delay, packet drop ratio, throughput

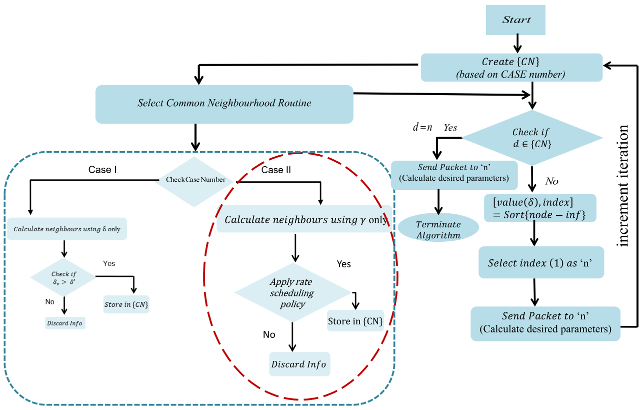

FIGURE 3. Flow diagram: ***CLDBRP***.

and channel utilization. These performance metrics are an important measure to validate the efficiency of the proposed routing.

A. CLDBRP - DESCRIPTION

In the *CLDBRP* algorithm when packets are sent to the target and if the target or destination vehicle is out of the reach, the packets are transmitted to the next best hop node. A variable i is randomly used to control the iteration number in the algorithm. Highest value for i is represented as M. At the beginning when $m = 1$, a set of common neighbourhood {CN} is formed by the source node s by using intermittent beaconing signals from other nodes. The creation of $\{CN\}$ is the key element in the propositioned routing scheme. This study focuses on utilising data rates to establish the $\{CN\}$. Upon the formation of {CN} the source node s determines whether d belongs to {CN}. The presence of d in the {CN} indicates the successful delivery of the packet to it using the allocated Υ after which the algorithm terminates. However, the absence of the destination node d within the {CN}, prompts the algorithm to search for the next best hop node v^* for packet transmission depending on the rate scheduling policy being used. The function "*Gatherstats*" computes the desired performance metrics as discussed above. The procedure is summarised in the pseudo-code as shown in Table 2.

V. NUMERICAL RESULTS

This section presents the results obtained through the implementation of the proposed architecture. These results are methodically described in the subsequent subsections.

A. PRELIMINARIES

The simulations, involve a highway model consisting of two lanes and featuring a simulation area of 1000*meters* × 100*meters* which mimics the architecture of a linear VANET model. In each step, all vehicles construct their {CN} from the same distribution of nodes in their vicinity. We assume that beacon packets are transmitted by each vehicle using an equal amount of transmit power $P_t = 1W$ with a beacon interval of 1 Hz in 1D Freeway environment. This method,

TABLE 2. Description of algorithm.

Algorithm: *Cross Layered Decision Based Routing Protocol (CLDBRP)*

Notations:
s = source vehicle, d = destination vehicle
v_{nhop} = next hop , v^* = optimal next hop vehicle,
Υ = channel rate, M = total number of iterations.
Output:
drop ratio (Ψ_{dr}), Average transmission delay ($T_{\Psi_{tx}}$),
Π, Channel utility (U), Hop count (HCOUNT = i).
Bold (words) = Actions.

1 i = 1 to M do
2 if $i = 1$ then
3 $x == s$
4 endif
5 else
6 if i $\neq$ M
7 $x == v_{nhop}$
8 endif
9 **Create** $\{\text{CN}\}_i$ % Rate based $\{\text{CN}\}$ creation
10 if $d \in \{CN\}_i$ then
11 $d == v_{nhop};$
12 **Send** Packets to d using Υ_{sd} available
13 **Gatherstats**
14 endif
15 else
16 if $d \notin \{\text{CN}\}_i$ then
17 $\mathbf{H} = [\mathbf{h}_{s_1}, \mathbf{h}_{s_2}, \cdots, \mathbf{h}_{sv}]^T$
18 **Calculate** $\{R(t)\} = \{\Upsilon_{s_1}(t), \Upsilon_{s_2}(t), \cdots, \Upsilon_{sv}(t)\}$
19 **Select** v^* using scheduling technique
20 **Send** Packets to v^*
21 **Gatherstats**
22 **Assign** $v_{nexthop} == v^*$
23 i = i + 1 % Increment i
24 if i $\neq$ M
25 GO BACK TO LINE 9
26 endif
27 else
28 if i $\leq$ M
29 **Send** Packets to v^*
30 **Gatherstats**
30 endif
31 endif
32 endfor

which has been verified via simulations for a one dimensional Freeway setting, can be implemented in 2D Grid scenarios, such as the Manhattan model demonstrated in [7]. In addition, all participating vehicles are assumed to have an adequate capacity in their queue to ensure that each vehicle is able to store the data packets being received without having to discard them before they are transmitted successfully to the next hop. The self generation of packets at each node can further complicate the scenario. Thus, we initially assumed that no vehicle is producing the packets such that $\Psi_{gen} = 0$ in this paper. The self-generation of packets for each node and its effects are topics in future studies.

We assume the packet size $S = 512$ bytes in each simulation scenario. This selection is aimed at testing the architecture at maximum network capacity as suggested by [16]. Simulation parameters are tabulated in Table 3 . Unless stated otherwise, this default setting has been used in all the simulation scenarios, presented in subsequent sections.

The complete model is based on the packets being transmitted from one vehicle to another in a multi-hop communication scenario. The system performance depends on the

TABLE 3. Parameters of simulation.

Parameters	Value
Area of Simulation (meters)	1000m x 100m
Centre frequency f_c	5.9 GHz
Transmission power (P_t)	1W
Bandwidth (B)	10 MHz
Range of transmission (R)	200m
Vehicle Numbers (V)	20
Channel Quality Indicator (CQI) (γ)	10dB
Packets to be sent Ψ	20
Size of Packet S	512 bytes

volume packets being generated and transmitted at each node. We adopt the packet generation from exponential distribution. Assuming that $''X''$ represents the random variable following the exponential distribution, we can describe the probability distribution function (pdf) of packet generation for this system as

$$f(x;\lambda) = \begin{cases} \lambda e^{-\lambda x}, & x \geq 0, \\ 0, & x < 0, \end{cases}$$

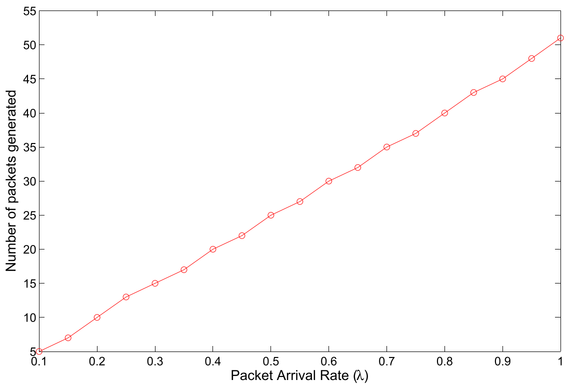

FIGURE 4. Packet generated vs packet arrival rate (simulation runs = 5000).

where the parameter of interest λ, denotes the arrival rate of packets within the simulation scenarios. We use Monte-Carlo simulations with several runs to achieve accuracy in packet generation. True results are depicted in Figures 4 and 5. Figure 4 shows the total number of packets generated at various packet arrival rates. Figure 5 illustrates the statistical distribution of data generated by packets in a box plot format. For each set of data with a certain arrival rate, a box is plotted from the 1st to 3rd quartile and the median is plotted with a solid red line. Extra whiskers cover the lowest and highest values of the data set for the specific arrival rate. This steps helps to select a reasonable number of packets generated for associating with a particular vehicle i.

B. ANALYTICAL DERIVATION OF KEY PERFORMANCE METRICS

We first define the PDR in the network. Then we calculate the PDR at each node and then add it at subsequent vehicles to

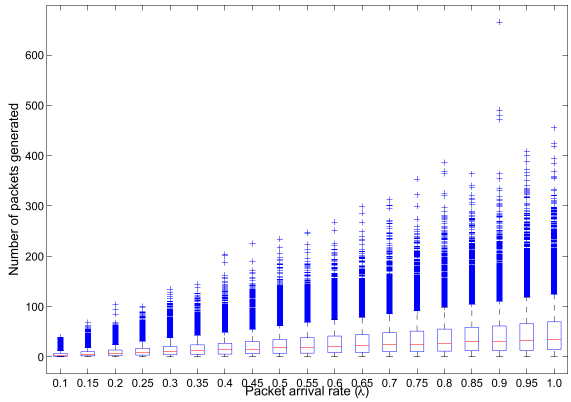

FIGURE 5. Packet arrival statistics (simulation runs = 5000).

calculate the end-to-end (from the source to the destination) PDR. In this paper we define the PDR as the ratio between the total number of packets received and transmitted. Let us define Ψ_{dr_i} as the PDR at vehicle i and is given as:

$$\Psi_{dr_i} = \frac{\Psi_{Rx_i}}{\Psi_{Tx_i}}, \tag{10}$$

where Ψ_{Rx_i} and Ψ_{Tx_i} define the total number of packets sent and received respectively.

Furthermore Ψ_{Rx_i} is defined as

$$\Psi_{Rx_i} = \left\lfloor \frac{\Upsilon_i}{S} \right\rfloor, \tag{11}$$

where Υ_i represents the allocated channel data rate and S represents the size of a packet and is given as $S = 8 \times \Psi_{size}$. The end-to-end PDR denoted by Ψ_{dr} is given as:

$$\Psi_{dr} = \frac{1}{M}\sum_{i=1}^{M} \Psi_{dr_i}. \tag{12}$$

The total time taken by a packet to be successfully transmitted at the destination is an important performance metric to be considered because it is directly related to the Time to Live (TTL) of the packet. In these scenarios, the total transmission time T for a packet is defined as

$$T = \sum_{i=1}^{M} T_i, \tag{13}$$

where T_i is given as:

$$T_i = \frac{\Psi_i}{\Upsilon_i}. \tag{14}$$

We define the average throughput of the overall system as Π where

$$\Pi = \frac{1}{M}\sum_{i=1}^{M} \Pi_i. \tag{15}$$

In this equation Π_i is the throughput of vehicle i. In the simulation scenarios, we calculate the actual data rate of the wireless channel between nodes and denote it as R_i. This data rate depends on the wireless channel characteristics. Notably this is not the transmission rate allocated to a node for data transmission. The transmission rate (allocated rate) is further defined as Υ_i where $\Upsilon_i \le R_i$. To achieve the Υ_i, node i must have sufficient data packets that need to be sent. $\Phi_i(bps/Hz)$ is the total available data rate at node i to be transmitted. Mathematically Φ_i is given as $\Psi_i \times S$, (bits/sec/Hz) i.e.

$$\underbrace{\Phi_i}_{\text{(bits/s/Hz)}} = \underbrace{\Psi_i}_{\text{(Number of packets)}} \times \underbrace{S}_{\text{(bits/s/Hz)}} . \tag{16}$$

We define the throughput of node i as follows:

$$\Pi_i = \begin{cases} \Phi_i & \Phi_i < \Upsilon_i \\ \Upsilon_i & \Phi_i \geqslant \Upsilon_i . \end{cases} , \tag{17}$$

The above discussion on the throughput of each vehicle provides an insight into the amount of actual data rate that can be efficiently utilised in the system. We can use the channel utility model to analyse how much channel is actually being utilised. Let us define the wireless channel utility for each vehicle i as U_i and is given as

$$U_i = \frac{\Pi_i}{R_i}. \tag{18}$$

As previously mentioned $\Upsilon_i \le R_i$. To measure the overall system performance, we can further define the percentage of utilisation as the overall system efficiency denoted as η.

C. SIMULATION STUDY

This subsection, presents a number of simulated scenarios that constitute the real VANET models. The simulation parameters, results and analysis for each study are given in the relevant simulation scenario below.

Scenario I: In the proposed algorithm, a key requirement is to form the $\{CN\}$ at each vehicle until the destination is reached. In this scenario, we discuss the formation of $\{CN\}$ for the proposed algorithm. The scenario I commences with arbitrary selection of source and destination vehicles as 1 and 14 respectively. This type of communication can be achieved with either a direct link between nodes 1 and 14 or through a multi-hop scenario depending on the formation of {CN}. In Scenario I, node 1 must form the CN set of its neighbouring vehicles and select the best possible next hop vehicle because this node cannot communicate with node 14 directly. The total number of packets available for transmission at the source vehicle is selected from the packet generator as discussed above. At this point, (20) packets are available at the source vehicle for transmission.

Communication initiates by the source vehicle (1) searching for a $\{CN\}$ in its vicinity. The established {CN} has a cardinality of three i.e | {CN} |. The destination node i.e (14) is absent from this {CN}. Hence the source chooses the next hop vehicle 6 with the best available transmission rate of 47265 bps. Overall this rate allows vehicle 1 to send 11 packets, leading to a reduction of 9 packets. The transmit time T_1 needed for these 11 packets to be transmitted from vehicle 1 to 6 is 0.95 sec. In the next step, after successfully receiving the 11 packets, vehicle 6 conducts a search for its own $\{CN\}$ and establishes a {CN} with a | {CN} | of four. Because the destination node (14) is absent within the second $\{CN\}$, it selects the next best possible hop with the highest possible transmission rate. This selected vehicle is (9). Using the available rate, node (6) sends the all available 11 packets, resulting in no packet drop at the second hop. Node 9 then searches for its own $\{CN\}$ after receiving 11 packets and finds destination 14 with a channel rate of 42056 bps. This phenomenon results in a reduction of 1 packet. Once the destination is located within the $\{CN\}$, it is chosen as the next best hop node regardless of its associated data rate. The reason behind using this approach is to meet the requirements of the packet expiry time or TTL within a realistic value [14]. The formation of $\{CN\}$ along with the transmission path taken for this setting are presented in Table 4 .

TABLE 4. {CN} formation for MR algorithm.

Vehicle 1		Vehicle 6		Vehicle 9	
Vehicle ID	Rate	Vehicle ID	Rate	Vehicle ID	Rate
3.0	45667	5.0	45624	12.0	35642
5.0	35687	7.0	48652	14.0	42056
6.0	47265	8.0	38975	18.0	47823
–	–	9.0	49989	–	–

Scenario II: This scenario focuses on the effect of increasing packet arrival rate λ on desired performance metrics such as end-to-end transmission time T and overall packet drop ratio Ψ_{dr}. Other related parameters such as channel quality indicator γ and number of vehicles V are kept constant throughout this scenario to focus the study on the effects of the above-mentioned performance metrics.

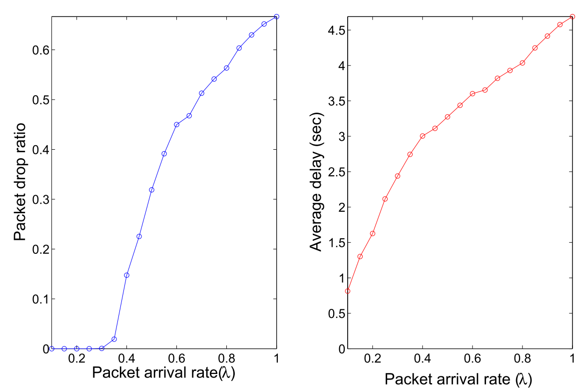

FIGURE 6. Packet drop ratio and average packet delay against packet arrival rate (V = 20).

The description and values associated with the new parameters for this scenario are tabulated in Table 5. The remaining parameters are kept constant as given in Table 3. Figure 6 shows the overall packet drop ratio and overall average delay vs various packet arrival rates. At low arrival rates, the PDR is almost zero because a small number of packets are generated

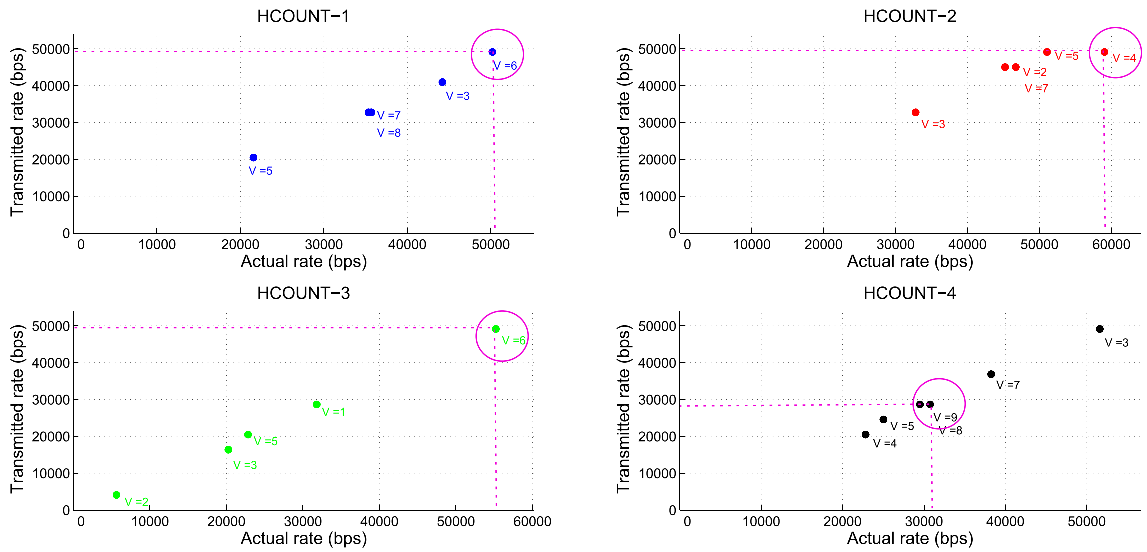

FIGURE 7. Actual rate vs transmitted rate hop to hop communication .

TABLE 5. Simulation parameters - scenario III.

Parameter Description	Value
(s, d)	$(4, 9)$
Ψ	25

and available at the source node for transmission. However at higher arrival rate values, the effects of PDR and average delay are eminent as shown in Figure 6. We define the average delay as the only transmission delay from the source to the destination. Hence the processing times at each node are not included in this result.

Scenario III: This scenario focuses on, the effect of transmission rate on the actual rate associated with each selected vehicle. Analysing of this aspect in the simulation provides an insight into the effect of PDR degradation within the communication. The simulation parameters for this scenario are shown in Table 5. This scenario starts with a random selection of source and destination as 4 and 9 respectively. The source has 25 packets to transmit towards the destination. The step by step formation of rate degradation is visually presented via scatter plots in Figure 7 . The entire communication took four HCOUNTs to complete. For the first HCOUNT, the $\{CN\}$ was established for the source node and five vehicles were found with in the range. The key aspect to observe here is the difference in rates on which the packets were sent as opposed to the actual rates that were supported by the wireless channels of each vehicle with in the $\{CN\}$.

For example, in HCOUNT-2, the actual rate for $V = 4$ (the selected next hop node) is 59038 bps but packets were transmitted at the allocated rate of 49152 bps. This rate degradation is primarily due to the random rates supported by the wireless channel for each vehicle and the number of packets to be transferred at each hop. This study shows an important insight about the operating point of the network. Figure 7 illustrates that even though the wireless channels between vehicles can support higher data rates, the overall system may be working at lower data rates because of limiting factors such as packet size restriction and packets availability at the transmitting vehicle. This scenario particularly highlights the practical operating point of the system.

Scenario IV: This scenario focuses on the effect of vehicle density on the performance of the proposed protocol. Performance metrics including system throughput Π and channel utility U are investigated closely. These parameters define the overall efficiency of the system. Figure 8 , illustrates the findings in this scenario. Figure 8(a) shows that increasing the number of vehicles in the system decreases the PDR. This result is mainly due to the high availability of a large number of vehicles in the vicinity of transmitting nodes. A large number of neighbors gives a high probability that a vehicle will almost always be available to be considered as next hop. Hence the PDR in the system is reduced. A decrease in PDR indicates successful packet delivery suggesting that the transmission delay of the system also decreases. This trend is shown in Figure 8(b). To illustrate further the overall system performance, Figure 8 (c) shows that the system throughput gradually increases with the increasing vehicle density. Given the large number of vehicles available for transmission, the probability of selecting a node with a high channel data rat is always present. This gives a high overall system throughput. Figure 8 (d) shows that channel utilisation also increases when the system throughput is hugh. To strengthen the above arguments, we study the number of elements in the $\{CN\}$ with increasing vehicular density. Figure 9 shows the total number of nodes in the $\{CN\}$ set vs number of vehicle. This result clearly shows that the cardinality of $\{CN\}$ increases as the number of vehicles increases. Accordingly with the large number of vehicles in the system, each transmitting node

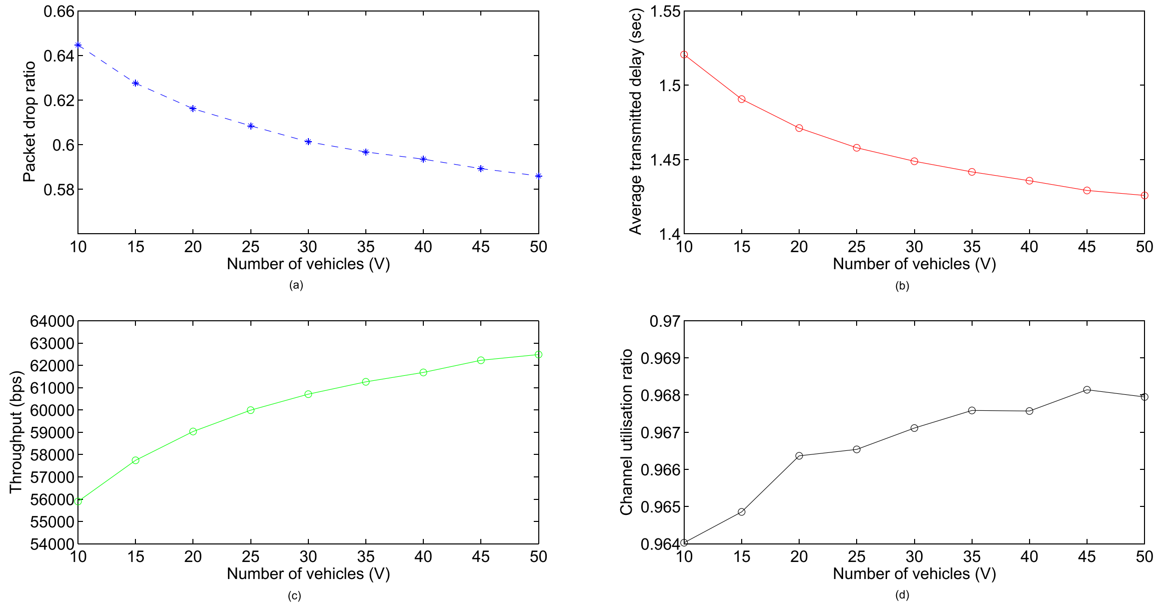

FIGURE 8. **Influence of changing vehicle density.**

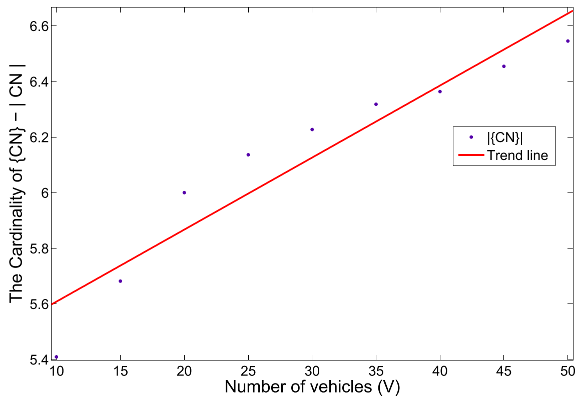

FIGURE 9. **Effect of varying vehicle numbers on | {*CN*} |.**

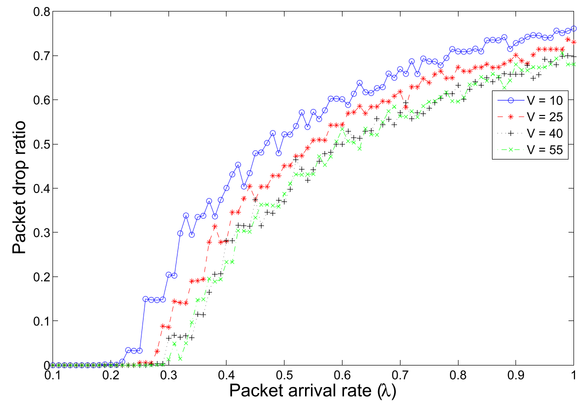

FIGURE 10. **Effect of changing *V* on PDR .**

will have additional routing potentials for successful communication. This argument is verified by using Monte-Carlo simulation to attain a plot of | {CN} | against V as shown in Figure 9 . The result clearly validates the aforementioned argument.

Scenario V: Close observation of the plot of Ψ_{dr} against vehicle density in Figure 8(a), indicates that the decreasing trend shown by Ψ_{dr} demonstrates a small percentage of change for a higher value of node density around the value 40 to 50. This observation encourages us to examine further the effect of this increasing vehicle numbers in simulation verses Ψ_{dr}. We ran the simulation using smaller step values of λ and plotted Ψ_{dr} against different values of V. The results are shown in Figure 10. Notably the small change in PDR for $V = 40$ and $V = 55$ is smaller compared with that for $V = 10$ and $V = 25$. Thus, increasing the values of V after a certain point will not improve routing possibilities. In Figure 8(a), clearly shows that the PDR curve has a smaller slope at a higher vehicle density and a larger slope at a small node density.

Scenario VI: As described in Section III, the key aspect of the proposed solution lies in the scheduling mechanism that can be adopted as per the application requirement. In this simulation scenario, we describe the total throughput results of the three rate variant approaches. The simplest and least complex among the three is the RR scheduling algorithm, where each vehicle receives an equal share of rates available to them. In W-RR scheduling the throughput remains under an acceptable level. To simulate and observe this effect, we arbitrary used a value of $\Pi \leqslant 0.65$ in this simulation. The RR scheduling method significantly reduces the total capacity as compared with the other algorithms. The design aspect highlighted here is to translate the results depending on the demand of the user application and find the trade-off between

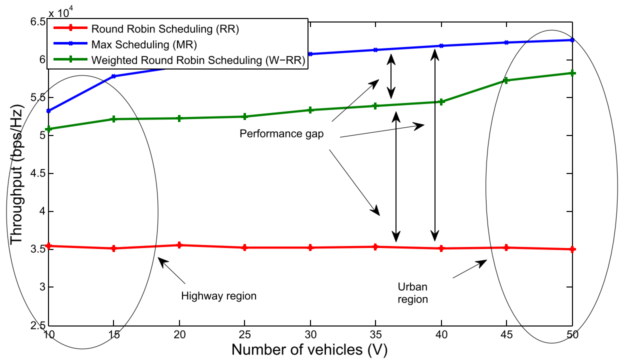

FIGURE 11. Rate variants design for app-specific requirement.

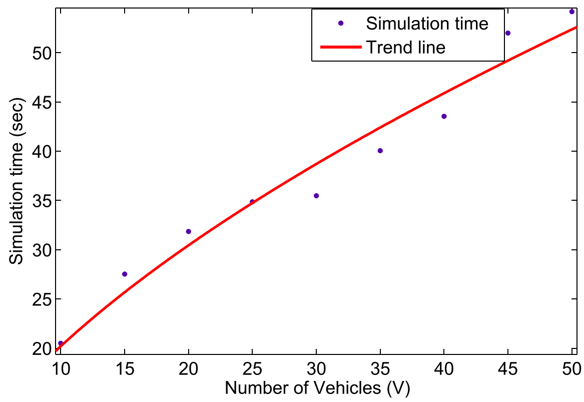

FIGURE 12. Algorithm performance - (path fixed).

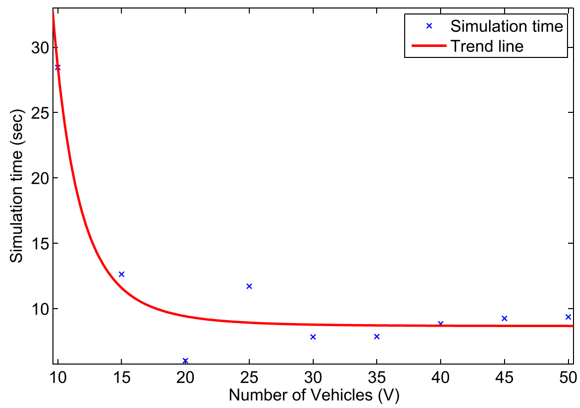

FIGURE 13. Algorithm performance - (path not fixed).

the performance drop and the complexity of the scheduling mechanism as attributed in Figure 11.

Scenario VII: This scenario focuses on the multi-hop communication when the path between the source and the destination is fixed and not fixed. The performance metric of interest in this scenario is the simulation time vs vehicle density. When the communication path between the source and the destination is not fixed, then the source node in the large vehicle domain finds the destination in a short time span, thereby reducing the overall simulation time. As shown in Figure 12, the simulation time of the algorithm prolongs as the number of vehicles in the system is increased. This result is due to the fact that each transmitting vehicle has a large search space to form the $\{CN\}$. Searching this large vehicle regime prolongs the overall simulation time. Figure 13 shows the scenario when the communication path between the source and the destination is not fixed. In the large vehicle regime, the source node finds the destination node in its $\{CN\}$ with high probability. This scenario results in a single hop communication and shortens the overall simulation time for the algorithm.

VI. CONCLUSION

We investigated the performance of the *CLDBRP* routing protocol in a multi-hop VANET communication environment. While implementing the proposed routing protocol in a linear VANET architecture, we used channel quality(data rate) in making the routing decisions. We used various simulations to model realistic scenarios and analysed performance of the proposed routing protocol within these scenarios. In Scenario I, we formulated the establishment of $\{CN\}$ and its effect on the routing protocol. In Scenario II, we explored the effect of increasing packet arrival on packet drop ratio under the proposed *CLDBRP*. In Scenario III, we analysed the effect of channel quality (data rate) on packet drop ratio. Results show that incorporating the data rate information in routing decisions improves the system performance in terms of packet drop ratio. The impact of vehicle density on routing decisions was also studied. More vehicles in the system means higher probability of finding the neighborhood in the communication. This probability was studied in Scenarios IV, V, and VI. Results highlighted the adaptability of the proposed protocol for dense urban environments. In future works, we will explore packet statistics such as TTL closely and their effect on the proposed scheme. We will also enhance the proposed model by integrating vehicle queue buffer state to obtain an optimal routing scheme.

ACKNOWLEDGMENTS

The authors would also like to thank the Faculty of Business for organising the "Writing Retreat" that provided a conducive writing environment.

REFERENCES

[1] M. Gerla, E.-K. Lee, G. Pau, and U. Lee, "Internet of vehicles: From intelligent grid to autonomous cars and vehicular clouds," in *Proc. IEEE World Forum Internet Things (WF-IoT)*, Mar. 2014, pp. 241–246.
[2] M. Al-Doori, *Directional Routing Techniques In Vehicular Ad Hoc Networks*, Germany: LAP Lambert Academic Publishing, 2012.
[3] M. Watfa, *Advances in Vehicular Ad-Hoc Networks: Developments and Challenges*, Hershey, PA, USA: IGI Publishing, 2010.
[4] A. S. Tanenbaum, *Computer Networks*, 5th ed. Upper Saddle River, NJ, USA: Pearson, 2010.
[5] J. B. Kenney, "Dedicated short-range communications (DSRC) standards in the United States," *Proc. IEEE*, vol. 99, no. 7, pp. 1162–1182, Jul. 2011.
[6] R. A. Uzcategui, A. J. D. Sucre, and G. Acosta-Marum, "WAVE: A tutorial," *IEEE Commun. Mag.*, vol. 47, no. 5, pp. 126–133, May 2009.
[7] S. ur Rehman, M. A. Khan, T. A. Zia, and R. Khokar, "A synopsis of simulation and mobility modeling in vehicular ad-hoc networks (VANETs)," *IOSR J. Comput. Eng.*, vol. 15, no. 2, pp. 1–16, Dec. 2013.

[8] D. Lin, Y. Tang, F. Labeau, Y. Yao, M. Imran, and A. V. Vasilakos, "Internet of vehicles for E-health applications: A potential game for optimal network capacity," *IEEE Syst. J.*, doi: 10.1109/JSYST.2015.2441720.

[9] J. Mittag, F. Thomas, J. Härri, and H. Hartenstein, "A comparison of single- and multi-hop beaconing in VANETs," in *Proc. 6th ACM Int. Workshop Veh. Internetw.*, 2009, pp. 69–78.

[10] I. Leontiadis and C. Mascolo, "Opportunistic spatio-temporal dissemination system for vehicular networks," in *Proc. 1st Int. MobiSys Workshop Mobile Opportunistic Netw. (MobiOpp)*, 2007, pp. 39–46.

[11] J. Zhao and G. Cao, "VADD: Vehicle-assisted data delivery in vehicular ad hoc networks," in *Proc. 25th IEEE Int. Conf. Comput. Commun. (INFOCOM)*, Apr. 2008, pp. 1–12.

[12] M. K. Nasir *et al.*, *A Framework and Mathematical Modeling for the Vehicular Delay Tolerant Network Routing*. Cairo, Egypt: Hindawi Publishing Corporation, 2016.

[13] A. Vasilakos, Y. Zhang, and T. Spyropoulos, *Delay Tolerant Networks: Protocols and Applications, Wireless Networks and Mobile Communications*. Boca Raton, FL, USA: CRC Press, 2011.

[14] S. U. Rehman, M. A. Khan, and T. A. Zia, "A multi-hop cross layer decision based routing for VANETs," *Wireless Netw.*, vol. 21, no. 5, pp. 1647–1660, Jul. 2015.

[15] B. Jarupan and E. Ekici, "A survey of cross-layer design for VANETs," *Ad Hoc Netw.*, vol. 9, no. 5, pp. 966–983, 2011.

[16] B. Jarupan, "Cross-layer design for location-and delay-aware communication in vehicular networks," Ph.D. dissertation, Dept. Elect. Comput. Eng., Columbus, OH, USA: Ohio State Univ., 2011.

[17] Y. S. Y. Seok, J. P. J. Park, and Y. C. Y. Choi, "Multi-rate aware routing protocol for mobile ad hoc networks," in *Proc. 57th IEEE Semiannual Veh. Technol. Conf. (VTC-Spring)*, vol. 3, Apr. 2003, pp. 3–6.

[18] J. Härri, F. Filali, and C. Bonnet, "Performance comparison of AODV and OLSR in VANETs urban environments under realistic mobility patterns," in *Proc. 5th Annu. Medit. Ad-Hoc Netw. Workshop (Med-Hoc-Net)*, 2006, pp. 14–17.

[19] B. Li, Y. Liu, and G. Chu, "Improved AODV routing protocol for vehicular Ad hoc networks," in *Proc. 3rd Int. Conf. Adv. Comput. Theory Eng. (ICACTE)*, vol. 4, 2010, pp. 337–340.

[20] Z. Ning, Y. Jung, Y. Jin, and K.-C. Kim, "Route optimization for GPSR in VANET," in *Proc. IEEE Int. Adv. Comput. Conf. (IACC)*, Mar. 2009, pp. 569–573.

[21] T. A. Q. Pham, K. Piamrat, and C. Viho, "QoE-Aware routing for video streaming over VANETs," in *Proc. 80th IEEE Veh. Technol. Conf. (VTC Fall)*, Sep. 2014, pp. 1–5.

[22] R. Daher and D. Tavangarian, "QoS in vehicular communication networks," in *Quality of Service Architectures for Wireless Networks: Performance Metrics and Management*. USA: IGI Publishing, 2010, pp. 300–325.

[23] O. A. Wahab, H. Otrok, and A. Mourad, "VANET QoS-OLSR: QoS-based clustering protocol for vehicular ad hoc networks," *Comput. Commun.*, vol. 36, no. 13, pp. 1422–1435, 2013.

[24] C.-Y. Chang, H.-C. Yen, and D.-J. Deng, "V2V QoS guaranteed channel access in IEEE 802.11p VANETs," *IEEE Trans. Depend. Sec. Comput.*, vol. 13, no. 1, pp. 5–17, Jan./Feb. 2015.

[25] Z.-K. Lee, G. Lee, H. R. Oh, and H. Song, "QoS-aware routing and power control algorithm for multimedia service over multi-hop mobile ad hoc network," *Wireless Commun. Mobile Comput.*, vol. 12, no. 7, pp. 567–579, 2010.

[26] Q. Wang, S. Leng, Y. Zhang, and H. Fu, "A QoS supported multi-channel MAC for vehicular ad hoc networks," in *Proc. 73rd IEEE Veh. Technol. Conf. (VTC Spring)*, May 2011, pp. 1–5.

[27] G. Maia, L. A. Villas, A. C. Viana, A. L. Aquino, A. Boukerche, and A. A. Loureiro, "A rate control video dissemination solution for extremely dynamic vehicular ad-hoc networks," *J. Perform. Eval.*, vol. 87 (C), pp. 3–18, May 2015.

[28] P. Sivanesan and S. Thangavel, "HMM based resource allocation and fuzzy based rate adaptation technique for MANET," *Int. J. Light Electron Opt.*, vol. 126, no. 3, pp. 331–336, 2015.

[29] S. ur Rehman, M. A. Khan, T. A. Zia, and M. Jafer, "Quality of service based cross layer routing protocol for VANETs," in *Proc. 16th IEEE Int. Conf. Softw. Eng., Artif. Intell., Netw. Parallel/Distrib. Comput. (SNPD)*, Jun. 2015, pp. 1–6.

[30] J. Yuan, Z. Li, W. Yu, and B. Li, "A cross-layer optimization framework for multihop multicast in wireless mesh networks," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 11, pp. 2092–2103, Nov. 2006.

[31] K. Ghada, J. Li, and Y. Ji, "Cross-layer design for topology control and routing in MANETs," *Wireless Commun. Mobile Comput.*, vol. 12, no. 3, pp. 257–267, 2012.

[32] S. U. Rehman, M. A. Khan, and T. A. Zia, "Cross layer routing for VANETs," in *Proc. IEEE Int. Symp. World Wireless, Mobile Multimedia Netw. (WoWMoM)*, Jun. 2014, pp. 1–4.

[33] P. P. Pham, S. Perreau, and A. Jayasuriya, "New cross-layer design approach to ad hoc networks under Rayleigh fading," *IEEE J. Sel. Areas Commun.*, vol. 23, no. 1, pp. 28–39, Jan. 2005.

[34] S. Yang, Z. Sheng, J. A. McCann, and K. K. Leung, "Distributed stochastic cross-layer optimization for multi-hop wireless networks with cooperative communications," *IEEE Trans. Mobile Comput.*, vol. 13, no. 10, pp. 2269–2282, Oct. 2014.

[35] K. Katsaros, M. Dianati, R. Tafazolli, and R. Kernchen, "CLWPR—A novel cross-layer optimized position based routing protocol for VANETs," in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Nov. 2011, pp. 139–146.

[36] B. Karp and H. T. Kung, "GPSR: Greedy perimeter stateless routing for wireless networks," in *Proc. ACM/IEEE Int. Conf. Mobile Comput. Netw. (MobiCom)*, 2000, pp. 243–254.

[37] Y. Chen, Z. Xiang, W. Jian, and W. Jiang, "A cross-layer AOMDV routing protocol for V2V communication in urban VANET," in *Proc. 5th Int. Conf. Mobile Ad-Hoc Sensor Netw. (MSN)*, Dec. 2009, pp. 353–359.

[38] L. Zhou, B. Zheng, B. Geller, A. Wei, S. Xu, and Y. Li, "Cross-layer rate control, medium access control and routing design in cooperative VANET," *Comput. Commun.*, vol. 31, no. 12, pp. 2870–2882, 2008.

[39] B. Jarupan and E. Ekici, "PROMPT: A cross-layer position-based communication protocol for delay-aware vehicular access networks," *Ad Hoc Netw.*, vol. 8, no. 5, pp. 489–505, 2010.

[40] S. ur Rehman, M. A. Khan, and T. A. Zia, "Wireless transmission modeling for vehicular ad-hoc networks," in *Proc. 20th IEEE Int. Conf. Parallel Distrib. Syst. (ICPADS)*, Dec. 2014, pp. 398–403.

SABIH UR REHMAN (M'11) received the bachelor's (Hons.) degree in electronics and telecommunication engineering from the University of South Australia, Adelaide, and the Ph.D. degree in vehicular ad-hoc networks from Charles Sturt University. He has combined experience in the field of information technology/telecommunication of over 16 years in both enterprise and educational sector environments. He has also extensive expertise in delivering solutions for large scale networking, systems administration, helpdesk operations, IT security, and data integration environments. He is currently a Lecturer in Computing with the School of Computing and Mathematics at Charles Sturt University. His broader research interests are in the areas of wireless communication, network planning/designing, routing and switching, and information security. His expertise lies in the areas of quality-of-service, cross-layer protocol architecture designing, wireless propagation modeling using mathematical/stochastic models and conducting performance analysis. His current research is focused on the emerging area of Internet of Things especially in the context of intelligent transport systems and precision agriculture. He is a member of the Institute of Engineers Australia and the Institute of Electrical and Electronic Engineers Computer Society. He was a recipient of a competitive scholarship from Charles Sturt University for his Ph.D. He is also a reviewer for a number of respected journals and conferences.

M. ARIF KHAN (M'17) received the B.E. degree from the University of Engineering and Technology, Lahore, in 2000, the M.S.E. degree from the GIK Institute of Engineering Sciences and Technology in 2002, and the Ph.D. degree from Macquarie University, Sydney, in 2010. He is currently the Course Director and a Lecturer with the School of Computing and Mathematics, Charles Sturt University, Australia. His research interests are in wireless ad hoc networks, cyber security and 5G technologies. He was a recipient of an International Macquarie University Research Scholarship for his Ph.D., a Research Scholarship from ICT CSIRO Center Marsfield Sydney, and a Competitive Scholarship for his M.S.E. degree from the GIK Institute.

MUHAMMAD IMRAN (M'11) was a Post-Doctoral Associate on joint research projects between King Saud University (KSU) and the University of Sydney, Australia. He has been an Assistant Professor with the College of Computer and Information Sciences, KSU, since 2011. He is currently a Visiting Scientist with Iowa State University, USA. He has authored a number of research papers in refereed international conferences and journals. His research is financially supported by several grants. His research interest includes mobile ad hoc and sensor networks, WBANs, M2M, Internet of Things, SDN, fault tolerant computing, and security and privacy. Recently, the European Alliance for Innovation (EAI) has appointed him as an Editor-in-Chief of the *EAI Transactions on Pervasive Health and Technology*. He also serves as an Associate Editor of the IEEE ACCESS, the *IEEE Communications Magazine*, the *Wireless Communication and Mobile Computing Journal*(SCIE, Wiley), the *Ad Hoc and Sensor Wireless Networks Journal* (SCIE), *IET Wireless Sensor Systems*, the *International Journal of Autonomous and Adaptive Communication Systems* (Inderscience), and the *International Journal of Information Technology and Electrical Engineering*. He served or is serving as a Guest Editor of the *IEEE Communications Magazine* (SCIE), *Computer Networks* (SCIE, Elsevier), *Future Generation Computer Systems* (Elsevier), *MDPI Sensors* (SCIE), the *International Journal of Distributed Sensor Networks* (SCIE, Hindawi), the *Journal of Internet Technology* (SCIE), and the *International Journal of Autonomous and Adaptive Communications Systems*. He has been involved in over 50 conferences and workshops in various capacities, such as the Chair, Co-Chair, and Technical Program Committee Member. These include the IEEE ICC, Globecom, AINA, LCN, IWCMC, IFIP WWIC, and BWCCA. He has received a number of awards, such as the Asia Pacific Advanced Network Fellowship.

TANVEER A. ZIA (M'04–SM'15) received the B.Sc. degree in computer sciences from Southwestern University, Philippines, the Masters of Interactive Multimedia degree from the University of Technology Sydney, the M.B.A. degree from Preston University, USA, and the Ph.D. degree from the University of Sydney. He is currently an Associate Professor of Computing with the School of Computing and Mathematics, Charles Sturt University, NSW, Australia. His broader research interests are in ICT security. Specifically, he is interested in security of low powered mobile devices. He is also interested in biometric security, cyber security, Internet of Things security, cloud computing security, information assurance, trust management, and forensic computing.

MOHSIN IFTIKHAR (M'07) received the B.Sc. degree in electrical engineering from the University of Engineering and Technology Lahore, Pakistan, the M.Eng.Sc. degree in telecommunications from UNSW Australia, and the Ph.D. degree from the University of Sydney, Australia, in 1999, 2001, and 2008, respectively. He was the Consultant for National Information, Communication and Technology Australia (NICTA) and Seoul Communications Australia from 2007 to 2009. He was also a Visiting Research Fellow at NICTA and an Honorary Research Associate at the School of IT, University of Sydney. Furthermore, he used to train Ericsson Australia employees on different Cisco networking products. He has been an Associate Professor with the Computer Science Department, Kind Saud University, Riyadh, Saudi Arabia. He is currently a Senior Lecturer with the School of Computing and Mathematics, Charles Sturt University, Australia. He has authored several high-quality papers in international conferences and journals. He has been the first person to produce closed-form expressions for the G/M/1 queueing system for multiple classes of self-similar traffic under variety of scheduling mechanisms. His current research interests include quality-of-service (QoS), traffic modeling, polling models, 3G/4G networks, Markov chains, stochastic processes, WiMAX network, and network calculus. He is a member of ACM and IET. He has served as TPC of many international conferences. His work has been acknowledged by both academia and industry and has received different industrial and academic prizes/awards. The most prominent ones are the Siemens Prize for solving an industry problem 2006, Networks and Systems Prize in research project work, School of IT, 2007. His Ph.D. dissertation was nominated for the Core Dissertation Award at the University of Sydney in 2008. He received an Endeavor Postgraduate Fellowship by the Australian Government in 2008. Furthermore, he has been nominated for inclusion in *Who is Who in the World* in 2010, 2011, and 2012 editions. He has been the TPC Co-Chair for the 9th IEEE Joint International Conference of Computer Science and Software Engineering (Bangkok, Thailand). He is a technical reviewer of many international conferences and high-quality ISI journals.