

Joint Rate and Queue based Routing for Vehicular Ad-hoc Networks

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Abstract—In recent years, Vehicular Ad-hoc Networks (VANETs) have become important and critical part of the Intelligent Transport System (ITS). VANETs have brought the potential of new services and various applications for emergency, comfort and commercial use. However, designing a practical VANET architecture is still hindered with lot of challenges. One such challenge is to route the data packets from source to destination vehicle as per application specific need without sacrificing the Quality of Service (QoS) requirements. In order to design a practical system that meets the requirements of new applications for VANETs, we propose a new cross-layer approach for efficient and reliable routing. Our proposed model considers the wireless transmission parameters from Physical (PHY) layer as well as the system buffer capacities from the Medium Access Control (MAC) layer to make informed and accurate routing decisions at the network layer. This model can be used to cater for specific application requirements in VANET by applying varying routing decisions depending on node specific attributes such as *commodity data*, *queue backlog* and *rate allocation*. The model exemplifies a multi-hop backpressure architecture in VANET where each vehicle is trying to select the next-hop vehicle on the basis of buffer size (queue backlogs), the data to be send (commodity) as well as the channel rate allocated. The key objective here is the optimal selection of next hop vehicle for information dissemination by integrating these metrics. We classify this as a rational Constraint Driven Problem (CDP) and we explore an optimal solution to this problem. Using a systematic mathematical model formulation and extensive simulations, we present the performance analysis of our exemplary model by deriving values of relevant key performance indicators applicable in such an environment.

Index Terms—VANETs; Cross-layer; Routing; Rate; OBU Buffer

I. INTRODUCTION

Adopting wireless communication in vehicles has created unique opportunities for the transportation community. Since vehicles can easily communicate with each other, it has opened a totally new communication paradigm that can be used to provide new services to stakeholders [1], [21]. A key enhancement of research in vehicular communication is to provide these services by designing new and innovative applications. In stringent network conditions such as that of VANETs, communication between vehicles is not only limited by the intensity of the received signals but is also dependent on the available bandwidth. To facilitate such communication,

vehicles are equipped with a hardware known as On Board Unit (OBU). The typical design of OBU resembles a typical wireless node consisting of four key units namely, sensing, processing, radio/communicating and the power unit to process the information. The purpose of the sensing unit is to detect the change in any attribute associated with the car or traffic environment and pass on the relevant information to the processing unit. The processing unit captures the way the information/packets are gathered just before they are propagated via a radio unit. Generally this design formation follows a buffer state-based structure where packets are collected in a queue and distributed according to the queue structure adopted in IEEE 802.11p standard [5], [10]. Limited vehicle buffer sizes can also affect the overall communication quality. As most VANET applications work on the principle of broadcasting information to neighbouring vehicles, there is a need to create a controlled mechanism to ensure that the best possible performance is achieved. In order to accomplish such a mechanism in a multi-layer architecture such as represented by Open Systems Interconnection (OSI), a typical methodology is to work on layers individually where each layer is designed and adjusted independently [2]. Achieving an overall reliable network performance for throughput and delay cannot be obtained using such a design approach. An effective solution to this problem is to utilise a cross-layer design architecture.

Research has recently been focused on developing solutions to address and analyse the impact of node queue on the performance of ad-hoc wireless networks. An important research in relation to incorporating queue structure of each wireless node and its optimisation was established in [16]. In this paper, the authors have presented a structure of a *back-pressure* algorithm where nodes are informed about the queue length of the neighbouring nodes prior to dissemination of routing information. This approach can be adopted for dynamic environments such as VANETs.

In this paper, the proposed routing architecture as established earlier in [12], [13] is enhanced by integrating vehicle OBU buffer capacities. The proposed model considers jointly, wireless transmission parameters from the PHY layer and OBU buffer capacities from the MAC layer to make informed routing decisions at the network layer. This model can be

used especially to cater for specific application requirements in VANETs by applying varying routing decisions depending on node (vehicle) specific attributes such as *commodity data*, *queue backlog* and *rate allocation*. The model exemplifies a multi-hop back-pressure architecture for VANET where each vehicle is trying to select the next-hop on the basis of buffer size (queue backlogs), the data to be sent (*commodity*), and the rate allocated. The key objective here is the optimal selection of the next hop vehicle by integrating these metrics. This model will be used to cater for specific application requirements (*Objectives*) in VANET conditions by applying varying scheduling decisions depending on node specific properties (*Constraints*) such as commodity data, queue backlog and rate allocation. Using mathematical modelling and simulations, the performance of this model has been formulated and analysed by deriving values of relevant key performance indicators applicable for such an environment. In particular, this paper presents the following contributions:

- Discussion of cross-layer routing design architecture for multi-hop VANET by considering parameters from both the PHY and MAC layer to facilitate informed decision making;
- Enhancement of the proposed routing design by integrating OBU buffer capacity in the decision making;
- Identification of routing problems in a multi-hop VANET architecture as Constraint Driven - Multi Objective Decision Problem (CD-MODBP);
- Formulation of a mathematical model to present the performance analysis of routing architecture design.

The rest of the paper is organised as follows: Section II provides an overview of some related work in this area. Section III presents the generalised system model utilised in this paper. Section IV presents the key enhancement on this system model by including joint rate and queue models in the architecture. Section V explains the proposed routing algorithm. Simulation results are presented in Section VI. Finally, the paper is concluded in Section VII.

II. RELATED WORK

This section presents a review of some well-known literature in this area. In [18], the authors have investigated a distributed cross-layer optimisation scheme for multi-hop wireless networks where different nodes can cooperate with each other. By using network utility maximisation technique the authors have shown an improvement in flow control, routing, scheduling and relay assignment for multi-hop wireless cooperative networks. The authors have concluded that their proposed approach gives enhanced network performance in terms of convergence, system throughput and performance of the scheduling algorithms. Cross-layer based architecture has been widely used in wireless networks especially to cater for a range of QoS metrics [3], [20]. A comprehensive tutorial concerning cross-layer optimisation methods for wireless networks has been presented in [8]. Additionally another comprehensive study in the context of VANETs highlighting the challenges in such stringent environment has been under

taken in [15]. By highlighting main challenges, the authors have presented an optimisation approach for joint congestion control and scheduling problems in multi-hop wireless networks. In another approach, the performance of vehicular wireless channel in terms of robustness and scalability has also been analysed in [9]. The authors have studied various congestion control methods for different possible conditions at intersections utilising simulations with realistic mobility patterns. In another interesting approach, the authors in [17] have proposed a cross-layer optimisation framework in order to maximise system throughput over the design variables such as wireless multicasting rate of the source nodes, the data flows and life time of nodes against various QoS constraints. The authors have modelled the optimisation problem as an NP-hard problem and have proposed heuristic network coding algorithm (LCRT). The authors have concluded that their proposed cross-layer design outperforms existing approaches reaching up to 50% increase in the system throughput. In order to tackle the network congestion problem in VANET communication, the authors in [7] have proposed an architecture to reduce the data load using data aggregation technique. The authors have utilised three basic aggregation schemes with varying complexity, which has resulted in achieving data precision within the framework. Using network simulations, the authors have shown that the proposed aggregation schemes allow for a flexible trade-off between competing resources within the network. Authors in [10] have investigated network transition from non-saturation to saturation regimes in VANETs. The authors developed an analytical model comprising of a Markov chain, queueing sub models and a probabilistic spatial model to study the performance of a vehicular network. They showed that the VANET architecture becomes unstable if the OBU buffer capacity is not incorporated in decision making. In addition to this, authors have shown that in order to avoid network saturation, Road Side Units (RSUs) deployment needs to be carefully considered. In another interesting study [5], the authors investigated the impact of queue size and scheduling mechanisms on the beaconing performance for IEEE802.11p. The authors conducted various simulations to gauge the impact of various transmission/scheduling mechanisms and its effect on beaconing reception. They also concluded that at a 25 Hz beaconing rate, buffering and scheduling techniques do not influence beacon reception rate. In [6], the authors investigated the problem of delay efficient scheduling in general multi-hop networks. They classified that using a max-weight type algorithm results in an increase in delay of information delivery. They proposed a Delay Efficient Scheduling (DESC) algorithm based on the notion of virtual queue formation that accelerates the propagation of information delivery. Using analytical and simulated results, the authors have shown that DESC results in reducing the overall service lag experienced in a multi-hop architecture.

III. SYSTEM MODEL

This section sets out the overall system model utilised in this paper that incorporates various cross-layer design parameters

Symbol	Explanation
s	source vehicle
d	destination vehicle
$\{CN\}$	Common neighbourhood set
V	Number of vehicles
ρ	Vehicle density (veh/m ²)
ν	Vehicle velocity (m/s)
$\mathcal{L}$	Transmission links
$ A $	Cardinality of set A
$[A]^T$	Transpose of set A
$\mathbf{A}$	Matrix notation s.t $\mathbf{A} \in \mathbb{C}^{m \times n}$
$\mathbf{a}$	Vector notation s.t $\mathbf{a} \in \mathbb{C}^{m \times 1}$
$\mathcal{T}$	Allocated rate (bps/Hz)
λ	Packet arrival rate (pk/sec)
Ψ_{gen}	Packet generated at node
Ψ	Packets to send (for specific λ)
Ψ_{size}	Packet size (byte)
T	Packet transmission time (sec)
Ψ_{dr}	Packet drop ratio
Π	Throughput (bps/Hz)
$Q_{max,i}$	Maximum queue size for vehicle i
v^*	Optimal selected vehicle
$\tilde{q}(t)$	Number of packets already in OBU buffer

TABLE I
SYMBOLS AND NOTATIONS

to establish a routing framework. The reader is encouraged to refer to the description of symbols described in Table I to comprehend the discussion in this section. The terms *node* and *vehicle* have been used interchangeably to describe the node (vehicle) structure throughout the discussion. The complete description of the system model that is the focus in this paper is categorically explained by defining *VANET Model*, *Queueing Model* and a *Joint Rate and Queue Model* separately in the following sections.

A. VANET Model

A multi-hop VANET architecture that can be modelled as a graph $G = (\mathcal{V}, \mathcal{L})$ where $\mathcal{V}$ denotes the set of vertices and $\mathcal{L}$ describes the set of edges of the graph, is illustrated in Figure 1. For this model, $\{\mathcal{L}\}$ represents the set of links within the communicating vehicles for the total number of V vehicles such that $v = 1, 2, \dots, V$. Note that the cardinality of $\{\mathcal{L}\}$ is V i.e. $|\{\mathcal{L}\}| = V$. These vehicles are assumed to be moving with a certain velocity $\nu(m/s)$ on a stretch of road resembling a freeway or highway. Two-way traffic conditions for a linear VANET where traffic is travelling in two lanes, one for each direction has been assumed in this model. The vehicles are statistically deployed at the beginning, following a homogeneous Poisson distribution with density ρ . A time slotted system has been considered where the transmission occurs among vehicles from one block of time to another. Each block consists of a predefined number of time slots denoted by t . During each time slot, transmission of a single or multiple vehicles can be scheduled depending on the scheduling scheme used.

The communication starts with the source node s wanting to send a certain number of packets to the destination node d via multi-hop communication. A key aspect of establishing this communication is the formation of a common neighbourhood

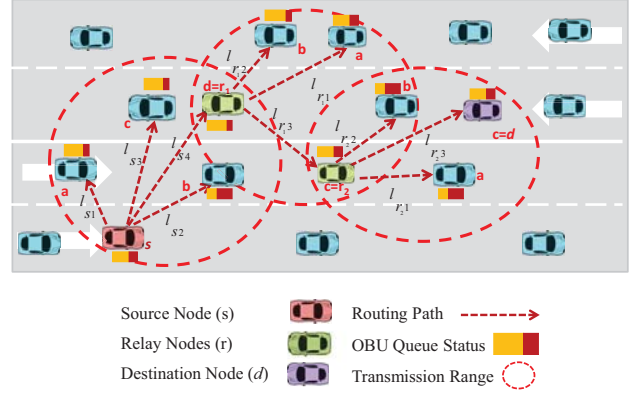


Fig. 1. Transmission model for VANET

set of vehicles denoted by $\{CN\}$. The members of $\{CN\}$ represent the neighbouring vehicles in the transmission range of the transmitting vehicle. $\{\mathcal{L}\}$ defines a set of transmission links for $\{CN\} = \{1, 2, 3, 4, 5\}$ such that $\{\mathcal{L}\} = \{l_{s1}, l_{s2}, l_{s3}, l_{s4}, l_{s5}\}$ where l_{s1} represents the transmission link between the source vehicle s and vehicle 1. The Single Input Single Output (SISO) wireless channel model already proposed and discussed in [14] has been utilised in its original structure to formally devise the system model. Following the same nomenclature, as established in our work [12], the data rate that wireless link can support between vehicles s and j at a particular time slot t is given by $\Upsilon_{sj}(t)$ and data rate vector $\Upsilon(t)$ as per the formation of $\{CN\}$ is given by equation (5) of [12] that can be rewritten here as:

$$\Upsilon(t) = [\Upsilon_{s1}, \Upsilon_{s2}, \Upsilon_{s3}, \dots, \Upsilon_{sV_s}]^T. \quad (1)$$

B. Generalised Queueing Model

Understanding the queue structure is important in order to define the system design. This section defines the queueing model adopted that is integrated with the proposed architecture. This is important to incorporate since successful transmission depends on the capability of a vehicle to store packets in its buffer until they are scheduled for transmission to the next hop. It is assumed that each vehicle in the $\{CN\}$ such as $\{a, b, c, d, e\}$, has a predefined buffer size with a certain storage capacity. A simplified queue structure of a particular vehicle is illustrated in Figure 2. The terms buffer and queue size are used interchangeably in this paper. Let us define $Q_{max,i}$ as the maximum buffer storage capacity of vehicle i . The values of Q_{max} are taken as integer units of *packets* in this model. It is considered that the packets arriving at vehicle i are stored in the buffer and the available buffer size is reduced with the packet accumulation. Let us define $q_{aval,i}(t)$ as the available buffer space of vehicle i at time t . This available space can be calculated as:

$$q_{aval,i}(t) = Q_{max,i} - q_i(t), \quad (2)$$



Fig. 2. Generalised queue structure of OBU

where $q_i(t)$ represents the current queue status of vehicle i at time t . The overall set of queues for all vehicles in $\{CN\}$ can be represented as:

$$\{\mathbf{Q}(t)\} = \{q_a(t), q_b(t), q_c(t), q_d(t), q_e(t)\}, \quad (3)$$

where $q_a(t)$ representing the queue status of vehicle a in $\{CN\}$. By defining the structure of queues further, it is assumed that the packets are gathered as per standard queue formation for data networks [4]. The arrival rate of packets associated with each vehicle is λ_v (packets/sec). The service rate at the output of each queue is defined as the rate at which packets are scheduled for transmission and is represented by μ_v (packets/sec). The queue status of vehicle i at a particular time t is given as

$$q_i(t) = \max\{q_v(t-1) + \lambda_v(t) - \mu_v(t), 0\}. \quad (4)$$

It should also be noted that the service rate $\mu_i(t)$ of vehicle i depends on the supported data rate Υ_i of the vehicle i as given in equation (3) of [12]. But the arrival rate of packets is only dependent on the data rate of the previous vehicle. It is important to mention that in the proposed routing scheme, the service rate (also the transmission strategy) depends on multiple factors such as data rate of the wireless channel and buffer/queue size of the next hop vehicle.

IV. JOINT RATE AND QUEUE BASED MODEL

This section presents the joint rate and queue model used in this paper. The main objective behind the designing of this model is to help formulate the best routing decision considering rate and queue state of a vehicle together. The solution to this problem can be formulated by utilising a constraint driven approach while making decisions based on objectives derived by application specific needs [19]. One parameter of interest, is the allocated rate $\Upsilon_{ij}(t)$ which represents the transmission rate allocated over link (i, j) during time slot t . Both, rate and queue vectors are shown below.

$$\mathbf{r}(t) = \begin{bmatrix} \Upsilon_{s1} \\ \Upsilon_{s2} \\ \Upsilon_{s3} \\ \vdots \\ \Upsilon_{sV_s} \end{bmatrix}, \quad \mathbf{Q}(t) = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ \vdots \\ q_{V_s} \end{bmatrix}.$$

The maximum number of vehicles in the range of a particular source vehicle is $V - 1$ and the indexes of these vehicles

are elements of the $\{CN\}$. Furthermore, p_i represents the *commodity data* destined to reach each selected vehicle via the wireless link. The unit of p_i is taken as the number of packets. Each vehicle maintains its own *queue backlog* information as well as backlog information for its neighbouring vehicles. When packet transmission occurs from one vehicle to another, the packets transmitted are removed from the queue of the first vehicle and are added to the next. Once packets reach the destination they are removed from the network. To keep the model simple and easy to understand, it is assumed that no external packets can take part in the communication. Furthermore, it is also assumed that there are no transmission errors within the communication. Only a certain number of packets can be transmitted at a particular rate, that defines the *optimal commodity* $p_{ij}^*(t)$ (packets). Since the optimal commodity has been determined for each link, the next step is to calculate the weight W_p associated with the optimal selection for the scheduling technique. The objective is to maximise the rate at which the communication can take place by using the optimal commodity as well as selecting the vehicle with the minimum queue backlog, hence $q_i \geq p_i$ but $p_i \not\geq q_i$ and $p_i = \Upsilon_i$. So the priority weighting factor W_p for the scheduling decisions is selected in an increasing fashion and given as:

$$W_p = \{1, 2, 3\},$$

where

$$W_p = \begin{bmatrix} W_1 & \rightarrow & \text{Best effort} \\ W_2 & \rightarrow & \text{Middle} \\ W_3 & \rightarrow & \text{Guaranteed} \end{bmatrix}.$$

In order to derive the solution, each mode selects the best possible route as per the following equation:

$$v^*(t) = \arg \max_{j \in \{1, \dots, V_s\}} \{W_p \Upsilon_v p_v\}, \quad (5)$$

such that

$$\min\{q_i\} \text{ for } j \in \{1, \dots, V\} \text{ and } j \neq v.$$

This formulates the complete design solution for a *Constraint Driven - Multi Objective Protocol (CD-MODBP)*. CD-MODBP is based on sequential search methods where the algorithm searches for the best available solution. A step-by-step narrative of this protocol and how it is integrated into the current architecture [12] is provided in the next section along with an illustration of the flow diagram in Figure 3.

V. PROPOSED ROUTING ALGORITHM

This section describes an extended version *Cross-Layer Decision Based Protocol - v3 (CLDBP-v3)* of our proposed architecture previously presented in [11] and [12]. The proposed routing architecture is formulated by integrating channel conditions described by allocated rate as well as vehicle queuing information, to make informed routing decisions. A step-by-step instruction for the formation of this protocol is

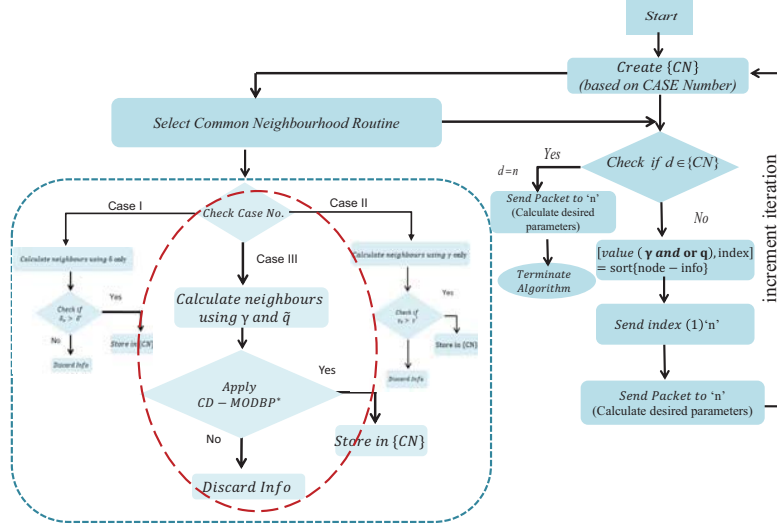


Fig. 3. Flow diagram: CLDBP-v3

provided in Table II. The main algorithm works on establishing communication between source and destination vehicles by sending beaconing information. This beaconing information helps to establish the $\{CN\}$ for neighbouring vehicles. In an attempt to transmit packets to the destination node when the destination is unreachable, packets are transmitted to the next best hop vehicle. The next best hop vehicle is selected based on the CD-MODBP subroutine as highlighted in Table IV. The objective is to select the best hop based on available rate, queue (backlog) and the commodity data at that particular time instance.

It is considered that each node has a buffer with the maximum queue capacity $Q_{max,i}$ and can store packets for a very short period of time. In order to avoid the packet drop and to improve the overall packet drop ratio¹, the node should have space in its buffer to store at least one packet for the duration of that time. If the transmitting node does not have the information about OBU buffer capacity and it sends a packet to the next node while the next node doesn't have space in its buffer to store the packet, then in this scenario the next node will discard that packet. This will also result in the transmission failure and hence increase the congestion in the network. It is assumed that each node sends the information about its queue backlogs $q_i(t)$ as well as the allocated rate $\hat{\gamma}_{ij}$ to the source node.

VI. SIMULATION RESULTS

This section presents simulation results for CLDBP-v3 utilising a discrete event simulator. A linear VANET environment in a simulation area of 1000 m $\times$ 100 m with two lanes of traffic where vehicles are travelling in both directions is assumed. One of the main aspects to observe in this paper is to

¹In this paper, we define packet drop ratio, Ψ_{dr} , as the ratio between the total number of packets received to the total number of packets transmitted for a given vehicle, i .

enhance the proposed design by incorporating OBU buffer capacities. Therefore contrary to, our previous approach in [12], the first step here is to enable self generation of packets Ψ_{gen} at each node. To assist in comprehension of implementation of the proposed structure, a number of simulated scenarios are presented below. The simulation parameters for these scenarios are defined in Table III.

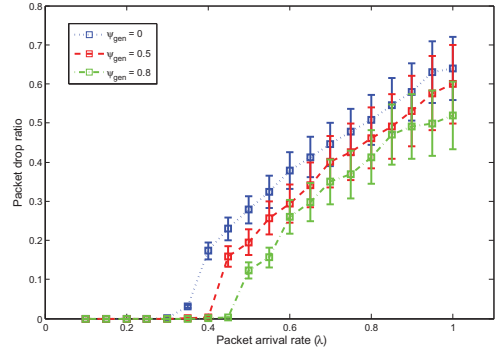


Fig. 4. Effect of varying Ψ_{gen} on packet drop ratio

Scenario I: This scenario presents the effect of self generation of packets Ψ_{gen} by individual node (vehicle) on the multi-hop communication environment. The two key performance metrics discussed here are *packet drop ratio* (Ψ_{dr}) and *transmission time for packet delivery* (T) experienced by the packet while going through such a multi-hop network. Please note that Ψ_{gen} was kept at zero in our previous work [12]. These packet generations follow Poisson distribution that is same as used earlier to generate actual source packets. The value of Ψ_{gen} was slowly increased and the simulation results are captured for 1500 simulation runs. The values of Ψ_{dr} and T are plotted for 95% confidence interval at the mean and

TABLE II
ALGORITHM DESCRIPTION

Case III - Algorithm: Cross-Layer Decision Based Protocol (CLDBP-v3)	
Notations:	
s	= source vehicle, d = destination vehicle
v_{nhop}	= next hop vehicle, v^* = optimal next hop vehicle,
γ	= channel rate, M = total number of iterations.
Output:	
Packet drop ratio (Ψ_{dr}), Average transmitted delay ($T_{\Psi_{tx}}$),	
Throughput II , 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 $\{CN\}_i$ % Rate based $\{CN\}$ creation
10	if $d \in \{CN\}_i$ then
11	$d == v_{nhop}$
12	Send Packets to d using γ_{sd} available
13	Gatherstats
14	endif
15	else
16	if $d \notin \{CN\}_i$ then
17	$H = [h_{s1}, h_{s2}, \dots, h_{sv}]^T$
18	Calculate $\{\gamma(t)\} = \{\gamma_{s1}(t), \gamma_{s2}(t), \dots, \gamma_{sv}(t)\}$
19	Select v^* using CD-MODBP routine
20	Send Packets to v^*
21	Gatherstats
22	Assign $v_{nhop} == v^*$
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
31	endif
32	endfor

TABLE III
SIMULATION PARAMETERS

Parameter description	Value
Simulation Area (meters)	1000m x 100m
Centre frequency f_c	5.9 GHz
Transmit power (P_t)	1W
Bandwidth (B)	10 MHz
Transmission range (R)	200m
Number of vehicles (V)	60
Channel quality indicator (δ)	10dB
Number of packets to send (Ψ)	20
Packet size (S)	512 bytes
Maximum OBU buffer capacity ($Q_{max,i}$)	20 packets

observations for this scenario are presented in Figures 4 and 5. The results clearly indicate a deterioration in packet drop ratio (Ψ_{dr}) and transmitted delay (T) with an increase of Ψ_{gen} .

Scenario II: The inclusion of self generated packets within the multi-hop communication network and its impact on the overall performance has resulted in a need to further refine the scheduling mechanism. This has been achieved by incorporating key constraints in the routing decisions by redefining the criteria for next-hop selection as described in Section V. In order to achieve the understanding of the complete procedure, this scenario presents the step-by-step formation of $\{CN\}$ based on refined technique. The communication starts by a random selection of source and destination vehicles, as 2 and

TABLE IV
CD-MODBP ROUTINE DESCRIPTION

Constraint Driven - Multi Objective Decision Based Protocol (CD-MODBP)	
Notations:	
(i, j)	= Communicating vehicles pair
W_p	= Application specific objectives, p_i = Commodity packets for vehicle i
$Q_{max,v}$	= Maximum buffer(queue) capacity of vehicle v ,
$q_i(t)$	= Queue status of vehicle v at time t
$q_{aval,v}(t)$	= $Q_{max,v} - q_v(t)$
Output:	
v^* = Optimal next hop vehicle,	
Bold (words) = Actions.	
START	
1. Get priority W_p (predefined)	
2. Get rate $\gamma_{i,j}(t)$ for all vehicles in transmission range	
3. Get $q_{aval,i}(t)$ using above equation for all vehicles	
4. Calculate p_i for all vehicles in transmission range	
5. Solve routing problem defined in equation 5	
6. Get the best hop vehicle v^*	
7. Terminate algorithm	
END	

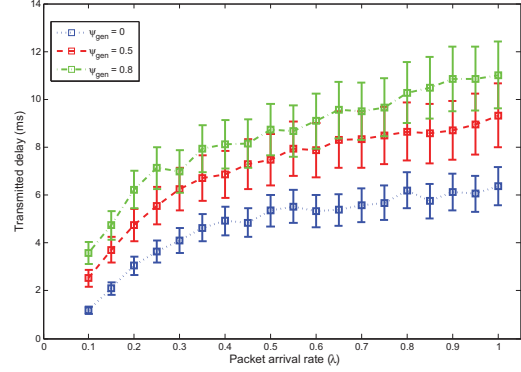


Fig. 5. Effect of varying Ψ_{gen} on transmitted delay

18 respectively. The source node has a total of 20 packets to transmit. Since the source vehicle cannot communicate directly with the destination, it needs to form $\{CN\}$ with its neighbouring vehicles to select the next best hop vehicle. The cardinality of $\{CN\}$ in the first hop is found to be 4. Since the destination vehicle 18 is not present in $\{CN\}$, therefore using CD-MODBP routine the source vehicle selects the next best hop node. Vehicle 12 was found in the $\{CN\}$, however, was rejected since it had a higher queue backlog of 10 packets. Additionally the rate of 59567 bps/Hz was resulting in a loss of 6 packets. Node 7 was considered to be the best hop node as it not only had a queue backlog of 5 packets but due to its allocated rate of 63285 bps/Hz only results in a drop of 5 packets. Moreover, due to the low queue backlog, there was no additional packet loss. This results in source vehicle 2 to transmit 15 packets to vehicle 7.

Now vehicle 7 will follow the same process to establish its $\{CN\}$ in order to locate the destination vehicle 18. The cardinality of this $\{CN\}$ as shown in Table V is 4. Node vehicle 3 is one possible next hop vehicle however it is rejected, as selection of this vehicle will result in a packet

TABLE V
 $\{CN\}$ FORMATION FOR *CLDBP-v3*

Node 2				Node 7				Node 13			
Node ID	γ	p^*	q	Node ID	γ	p^*	q	Node ID	γ	p^*	q
5.0	60715	14.0	7.0	3.0	51466	12.0	11.0	5.0	48797	11.0	7.0
7.0	63285	15.0	5.0	8.0	50912	12.0	9.0	9.0	54678	13.0	14.0
9.0	58150	14.0	4.0	11.0	56976	13.0	8.0	14.0	49345	12.0	4.0
12.0	59567	14.0	10.0	13.0	62234	15.0	5.0	17.0	47812	11.0	6.0
—	—	—	—	—	—	—	—	18.0	62612	15.0	3.0

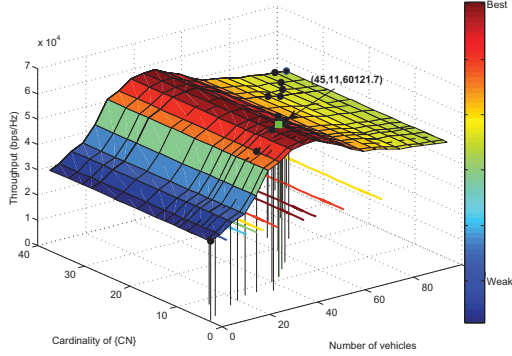


Fig. 6. 3D Visualisation of II , $|\{CN\}|$ and V (CD-MODB)P

drop of 3 packets based on its allocated rate of 51466 bps/Hz. Furthermore, its queue backlog of 11 packets will also result in a packet drop of 1 additional packet. Based on the criteria, node 13 is found to be the best next hop vehicle with a queue backlog of only 5 packets and allocated rate of 62234 bps/Hz, that results in no packet loss and the transmission of 15 packets to vehicle 13. Utilising the same routine as above, vehicle 13 now establishes its $\{CN\}$ with a cardinality of 5. The destination vehicle 18 forms a part of this $\{CN\}$ with a queue back log of 3 and allocated rate of 62612 bps/Hz that results in successful transmission of 15 packets to the destination.

Scenario III: This scenario presents the performance analysis of *CLDBP-v3* protocol. Mainly this discussion is built to observe the behaviour of total throughput obtained. As mentioned previously the key aim of the proposed design architecture is to achieve reliability and robustness within the routing design. The key parameter associated with establishing reliability is to gauge the effect of Ψ_{dr} on network performance. A higher number of packet drops within a communication architecture corresponds to unsteadiness in the network. Additionally, in order to devise an efficient routing mechanism, it is important to keep transmission delay to acceptable levels.

Looking into the design architecture, another important metric devised earlier is the cardinality of $\{CN\}$ i.e. $|\{CN\}|$. A higher value of $|\{CN\}|$ corresponds to more routing opportunities within the communication environment. The key aspect to observe is the overall behaviour of throughput when vehicle density is varied. In addition to this, it is also interesting to observe the relationship of varying vehicle density and the cardinality of $\{CN\}$. These observations and

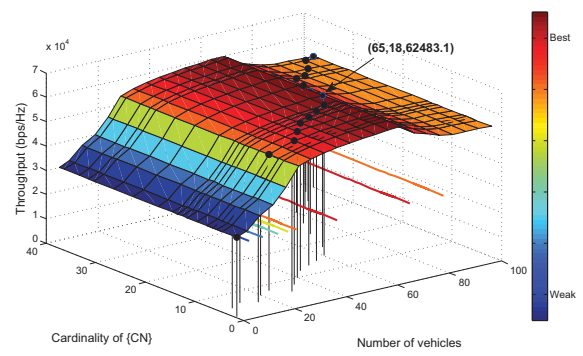


Fig. 7. 3D Visualisation of II , $|\{CN\}|$ and V (MR Algorithm)

relationships for *CLDBP-v3* have been pictorially illustrated via a 3D plot in Figure 6. One key observation is to observe the gradual increase in throughput until it reaches a specific peak as highlighted in the figure. It is evident from the plot that after reaching the peak, throughput starts to hold a consistent value even for increasing values of vehicle density. This point, as attributed in the figure, describes the operating point after which the influence of interference takes over. This observation helps to establish an operating point after which the throughput values should be ignored. This is due to the interference from adjacent vehicles within the communication range. This coincides well with the observation obtained in rate specific solution as highlighted in equation (6) of [12].

Comparison of these results with Max-Rate (MR) scheduling algorithm is illustrated in Figure 7 and shows a slight decrease in throughput for *CLDBP-v3*. To investigate these observations further, let us explore the behaviour of PDR with the increase in packet arrival rate and is illustrated in Figure 8. It is clear from the figure that overall PDR shows a balanced performance as compared to what was achieved with self packet generation level of $\Psi_{gen} = 0.5$ and $\Psi_{gen} = 0.8$ earlier. The key reason behind this is the reliability that the proposed *CD-MODB*P has been able to achieve by incorporating all possible influencing factors in decision making. Additionally, there is a slight compromise when it comes to transmitted delay as shown in Figure 9, however once again the levels are within an acceptable range. These results show that for a routing design to be robust and reliable, it is important to have a balance between various design parameters. Applying a cross-layer routing paradigm helps to formulate this balance as per application specific needs.

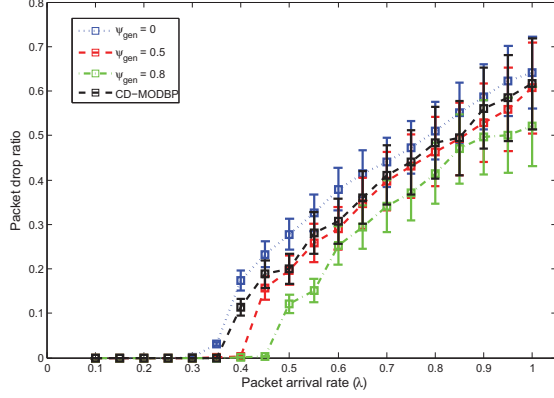


Fig. 8. Packet drop ratio vs packet arrival rate for CD-MODBP

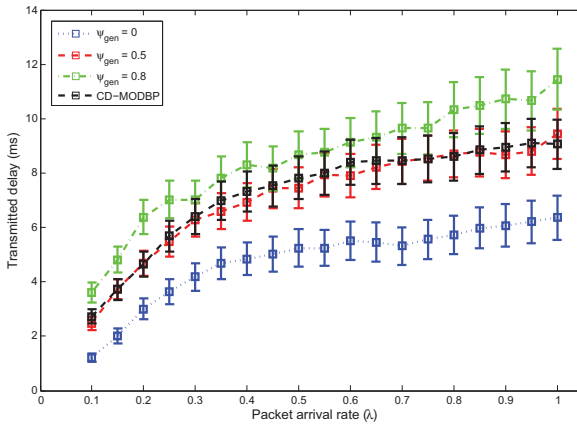


Fig. 9. Transmitted delay vs packet arrival rate for CD-MODBP

VII. CONCLUSION

This paper presented a detailed architecture of cross-layer routing framework for multi-hop VANET environment. The key focus in this paper has been to present the enhancement of our previously proposed routing architecture by incorporating OBU buffer capacities of vehicles. A joint rate and queue model was presented by incorporating constraint specific objectives of user applications. Simulation results were utilised to validate the expectations and we conducted a detailed performance analysis of the proposed model. Utilising cross-layer parameters in routing decision making can help in achieving reliability and robustness in the design. It was shown that the key aspect is to establish a balance between various cross-layer parameters according to application specific objectives. In this design, we have based the discussion on some selected parameters of interest such as packet drop ratio, throughput and cardinality of $\{CN\}$. Future extension of this work is to explore the attractive proposition of PHY layer security for multi-hop VANET environment. Having a vertical coordination among layers can help to devise a secure and more scalable and robust routing scheme for VANETs.

REFERENCES

- [1] K. Alam, M. Saini, D. Ahmed, and A. El Saddik, "VeDi: A vehicular crowd-sourced video social network for VANETs," *IEEE 39th Conference on Local Computer Networks Workshops (LCN Workshops)*, pp. 738–745, 2014.
- [2] J. R. Aschenbrenner, "Open systems interconnection," *IBM Systems Journal*, vol. 25, no. 3.4, pp. 369–379, 1986.
- [3] K. Ghada, J. Li, and Y. Ji, "Cross-layer design for topology control and routing in MANETs," *Wireless Communications and Mobile Computing*, vol. 12, no. 3, pp. 257–267, 2012.
- [4] D. Gross, J. Shortle, J. Thompson, and C. Harris, *Fundamentals of Queueing Theory*. Wiley, 4th edition, 2008.
- [5] L. Hendriks, "Effects of transmission queue size, buffer and scheduling mechanisms on the IEEE 802.11p beaconing performance," *15th Twente Student Conference on IT, University of Twente, Faculty of Electrical Engineering, Mathematics and Computer Science*, 2011.
- [6] L. Huang and M. J. Neely, "Delay efficient scheduling via redundant constraints in multihop networks," *An International Journal of Performance Evaluation*, vol. 68, no. 8, pp. 670–689, 2011.
- [7] J. Jiru, L. Bremer, and K. Graffi, "Data aggregation in VANETs: a generalized framework for channel load adaptive schemes," *39th Annual IEEE Conference on Local Computer Networks (LCN)*, pp. 394–397, 2014.
- [8] X. Lin, N. Shroff, and R. Srikant, "A tutorial on cross-layer optimization in wireless networks," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 8, pp. 1452–1463, 2006.
- [9] N. Nasiriani and Y. P. Fallah, "Performance and fairness analysis of range control algorithms in cooperative vehicle safety networks at intersections," *IEEE 37th Conference on Local Computer Networks Workshops (LCN Workshops)*, pp. 848–855, 2012.
- [10] S. Öztürk, J. Mišić, and V. B. Mišić, "Reaching spatial or networking saturation in VANET," *EURASIP Journal on Wireless Communications and Networking*, vol. 2011, no. 1, p. 174, 2011.
- [11] S. u. Rehman, M. A. Khan, and T. A. Zia, "A multi hop cross-layer routing protocol for vehicular adhoc networks," *Wireless Networks*, vol. 8, no. 5, pp. 489 – 505, 2014.
- [12] —, "Quality of Service Based Cross layer Routing Protocol for VANETs," *16th IEEE/ACIS International Conference on Software Engineering, Artificial Intelligence, Networking and Parallel/Distributed Computing (SNPD)*, 2015.
- [13] —, "Cross layer routing for vanets," *15th IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, pp. 1–4, 2014.
- [14] —, "Wireless Transmission Modeling for Vehicular Ad-hoc Networks," *20th IEEE International Conference on Parallel and Distributed Systems - (ICPADS)*, 2014.
- [15] M. R. J. Sattari, R. M. Noor, and H. Keshavarz, "A taxonomy for congestion control algorithms in Vehicular Ad Hoc Networks," *IEEE International Conference on Communication, Networks and Satellite (ComNetSat)*, pp. 44–49, 2012.
- [16] L. Tassiulas and A. Ephremides, "Stability properties of constrained queueing systems and scheduling policies for maximum throughput in multihop radio networks," *IEEE Transactions on Automatic Control*, vol. 37, no. 12, pp. 1936–1948, 1992.
- [17] Q. T. Vien, W. Tu, H. X. Nguyen, and R. Trestian, "Cross-layer optimisation for topology design of wireless multicast networks via network coding," *39th Annual IEEE Conference on Local Computer Networks (LCN)*, pp. 466–469, 2014.
- [18] 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 Transactions on Mobile Computing*, vol. 13, no. 10, pp. 2269–2282, 2014.
- [19] C.-H. Yeh, "A problem-based selection of multi-attribute decision-making methods," *International Transactions in Operational Research*, vol. 9, no. 2, pp. 169–181, 2002.
- [20] J. Yuan, Z. Li, W. Yu, and B. Li, "A cross-layer optimization framework for multihop multicast in wireless mesh networks," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 11, pp. 2092–2103, 2006.
- [21] H. Zhou, L. Gui, Q. Yu, and X. S. Shen, *Cooperative Vehicular Communications in the Drive-thru Internet*. Springer, 2015.