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Performance Optimization of Cluster-Based MAC Protocol for VANETs

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ABSTRACT Recently, a novel cluster-based medium access control (CB-MAC) protocol has been proposed for vehicular ad hoc networks (VANETs). Though performance of CB-MAC protocol is affected by cluster size, no mechanism is provided to manage cluster size efficiently. In this paper, the performance of CB-MAC protocol is optimized for VANETs by optimizing transmission probability with cluster size. Each vehicle should adopt the optimum transmission probability in the cluster which can be obtained by tuning the number of clusters in VANET. Therefore, optimum number of clusters is defined based on the number of vehicles in VANETs. An analytical study based on Markov chain model is provided. Optimum transmission probability, and optimum number of clusters expressions are derived. The microscopic mobility model is generated in SUMO for practical scenario. Simulation results are presented which verify analytical (theoretical) analysis and show that the performance of CB-MAC protocol is maximized in terms of throughput, packet dropping rate (PDR), and delay. Throughput is remarkably increased, whereas PDR and delay are decreased.

INDEX TERMS Clustering, CB-MAC, optimization, VANETs.

I. INTRODUCTION

For vehicle ad hoc networks (VANETs), a new cluster-based medium access control (CB-MAC) protocol has recently been introduced [1]. High relative mobility makes communication unstable in VANETs. Since neighbouring vehicles travelling along same direction with similar velocity form a cluster, clustering reduces the effect of high relative mobility and makes communication stable [2]–[7]. Moreover, clustering reduces delay by limiting channel contention and effectively regulating the topology of a network [1], [2]. Medium access control (MAC) as well as physical (PHY) layer specifications are described in IEEE 802.11 for VANETs [8]. Multi-channel operation is outlined in IEEE 1609.4 [9].

We proposed the CB-MAC [1] protocol to meet the performance criteria of safety messages (sm) as well as non-safety data (nsd) transmission in VANETs such as 100 ms strict delay limit of sm [10]–[14]. Sm is for safety or critical communication such as lane changing support, emergency warning etc. Sm have priority over nsd which are map update, web browsing etc. Sm is time sensitive and packet size is small about 100-300 bytes. Sm is transmitted through control channel (CCH) but nsd is transmitted through service channels (SCH). In our previous study, we showed that performance of CB-MAC protocol is better than existing schemes. In [15], a cluster-based MAC protocol is proposed for VANETs which is TDMA based and suffers from hidden terminal problem. The cluster based MAC protocol in [15] has high delay and low throughput because after a failed transmission during unreserved time slots, the sender waits for the next frame for retransmission even if the channel is idle. Real-time traffic management is discussed in [16]–[21]. In [22], [23], only sm is considered. The TDMA based MAC protocols [15], [22]–[24] cause wastage of time slots and can not utilize available resources because all time slots of a frame can not be utilized due to lack of nodes in VANET. Besides, when idle slot is unavailable, clustering and/or data transmission become impossible. Under the same network scenario, maximum throughput versus number of vehicles is about 1.1 Mbps, 1.3 Mbps, and 11 Mbps in [23], [25], and [2], respectively. Alternatively, CB-MAC protocol offers about 15 Mbps of overall throughput. Moreover, highest throughput versus transmission probability is around 800 kbps in [23] and

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throughput becomes negligible when transmission probability is more than 0.4. On the other hand, CB-MAC protocol increases throughput versus probability of transmission remarkably. In [24], average delay is 151 ms for sm which is higher than the strict delay requirement of sm. In [26], average delay is more than latency constraint too. Alternatively, CB-MAC protocol always meets the strict prime significant sm delay criteria.

Cluster size affects performance of CB-MAC protocol. Since channel contention, probability of collision, packet loss, etc. depends on cluster size i.e. vehicle number in cluster; performance depends on cluster size. If the cluster size is too large, performance decreases significantly because there will be a large number of packet collisions when the number of vehicles is too high. On the other hand, a small cluster could not use existing radio resources because of the insufficient number of vehicles i.e. cluster members (CMs) in the cluster. In CB-MAC, no mechanism is provided to manage cluster size efficiently. In this paper, performance of CB-MAC protocol is improved by optimizing transmission probability based on cluster size. The key objective of optimization is to increase communication quality by increasing throughput and decreasing delay, and to make more reliable communication by reducing packet dropping rate (PDR).

The novelty of this paper is outlined as follows: performance of CB-MAC protocol is optimized by optimizing transmission probability with cluster size for both sm and nsd. To achieve optimized performance each vehicle should adopt the optimum transmission probability in the cluster which can be obtained by tuning the number of clusters in the VANET. Therefore, optimum number of clusters is defined based on number of vehicles in VANETs. An analytical analysis based on Markov chain model is provided. Optimum probability of transmission, optimum number of clusters expressions are derived. Simulation results are presented which verify analytical analysis. The model of microscopic mobility is generated in simulation of urban mobility (SUMO) [27], then the output of SUMO is used in MATLAB as input and simulation results are achieved. Simulation results prove that performance of CB-MAC protocol is optimized.

The remainder of the paper is structured like this: Section II sketches an overview on CB-MAC protocol, optimization mechanism of CB-MAC protocol is detailed out in Section III. Analytical and simulation results are illustrated in Section IV. The article is concluded in Section V.

II. OVERVIEW OF CB-MAC PROTOCOL

System model of CB-MAC protocol is presented in Fig. 1. Vehicles traveling in the identical direction will be in the same cluster because clustering with moving vehicles in different direction causes signalling overhead due to frequent re-clustering. Therefore, clustering mechanism of CB-MAC protocol is stable. Fig. 2 presents the finite state machine (FSM) of CB-MAC protocol. To join in a cluster an isolated vehicle will send RTCF (Request To Cluster Formation). If there is a cluster, CH will send ReTCl (Registration To Cluster) and the isolated vehicle will join in that cluster. If there is no cluster, a cluster will be formed by the isolated vehicle and it will be the CH. Algorithms to transmit sm and nsd are given in Algorithm I and Algorithm II, respectively.

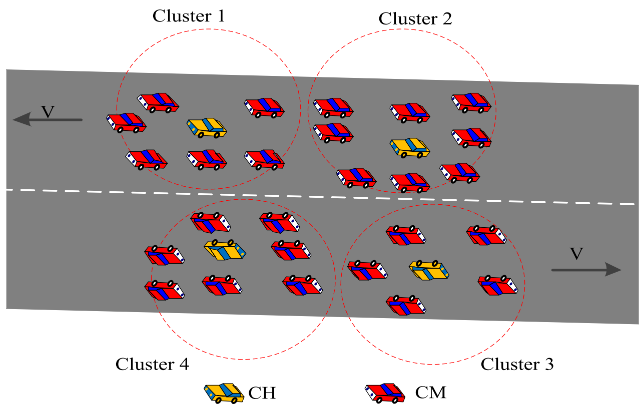

FIGURE 1. System model of CB-MAC protocol [1].

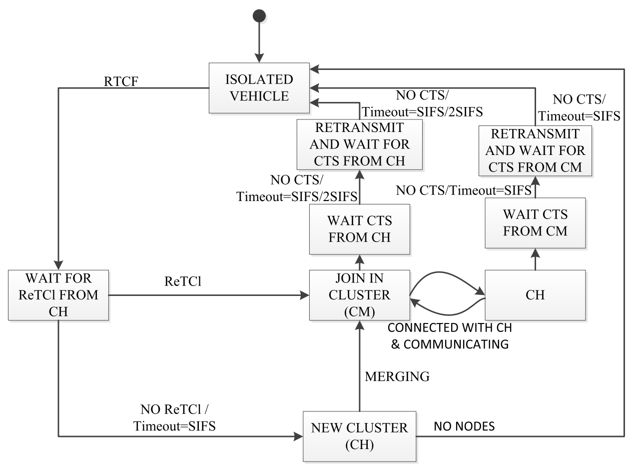

FIGURE 2. FSM of CB-MAC protocol [1].

Algorithm 1 Algorithm of CB- MAC Protocol for sm

1. CM sends sm to CH via RTS/CTS handshake
2. CH broadcasts sm
3. $T_{wait} = T_{ACK}$
4. IF ACK is received from all CM
5. Then broadcast is successful
6. End IF
7. ELSE IF ACK is not received and $R_t \leq m_{rsm}$
8. Then retransmit to the CM who's ACK is not received
9. ELSE IF Discard
10. End ELSE IF
11. End ELSE IF

If CH wants to broadcast a sm, it will broadcast immediately. If a CM has a sm to transmit, the CM will send to the CH through RTS/CTS handshake. Since other CM may transmit to CH, to avoid collision and hidden node

Algorithm 2 Algorithm of CB- MAC Protocol for NSD

CM sends nsd to CH with RTS/CTS handshake
CH unicast nsd to a CM/CH
$T_{wait} = T_{ACK}$
IF ACK is received from the CM/CH
Then transmission is successful
End IF
ELSE IF ACK is not received and $R_t \leq m_{rnsd}$
Then retransmit to the CM/CH
ELSE IF Discard
End ELSE IF
End ELSE IF

problem, RTS/CTS handshake is utilized. After receiving the sm, the CH will broadcast sm. Let T_{wait} be the waiting time to receive acknowledgement (ACK) from all CMs. If all ACKs are received, the transmission is successful. Otherwise, the sm will be retransmitted. Let R_t and m_{rsm} are number of retransmission for the particular transmission and maximum retransmission limit for sm, respectively. The sm will be retransmitted if $R_t \leq m_{rsm}$. The sm will be retransmitted to only the CM who's ACK is not received.

If CH wants to transmit a nsd, it will unicast the nsd directly. If a CM has a nsd to transmit, the CM will transmit to the CH using RTS/CTS handshake. To avoid collision and hidden node problem, the RTS/CTS handshake is utilized because anyone of other CMs may transmit to CH in the same time slot. After receiving the nsd, the CH will transmit to a CM/CH. After sending the nsd, CH waits for T_{wait} to receive an ACK. If ACK is not received, nsd is retransmitted. The nsd will be resent until maximum retransmission limit for nsd (m_{rnsd}). CH and CM handshake for sm and nsd is presented in Fig. 3 and Fig. 4, respectively.

Algorithm 3 Algorithm for P_{t-cl} Optimization

Begin
Initialize x, N
Calculate S
$\frac{dS}{dP_{t-cl}} = 0$
Obtain the root of P'_{t-cl}
IF root of $P'_{t-cl} > 0$ then
$\frac{dS^2}{dP^2_{t-cl}} = 0$
End IF
Obtain the root of P''_{t-cl}
IF root of $P''_{t-cl} > 0$ then
$\frac{dS^3}{dP^3_{t-cl}} = 0$
ELSE IF root of $P''_{t-cl} < 0$ then
P'_{t-cl} is the optimum
End ELSE IF
End IF
End

CH broadcasts a sm to CMs and receives ACK after successful transmission is shown in Fig. 3(a). When ACK is not successfully received, CH will send the sm to the CM. In Fig. 3 (b), how a CM send a sm to the CH and CH broadcasts in the cluster is shown. A CM send sm to the CH via RTS/CTS handshake. Then CH broadcasts and waits for ACK from all CMs. When any ACK is missing, CH resend to that CM.

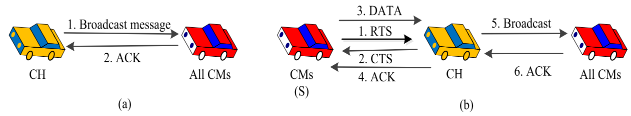

FIGURE 3. Handshake for sm. (a) CH broadcasts to CMs, (b) After receiving sm from a CM, CH broadcasts to CMs.

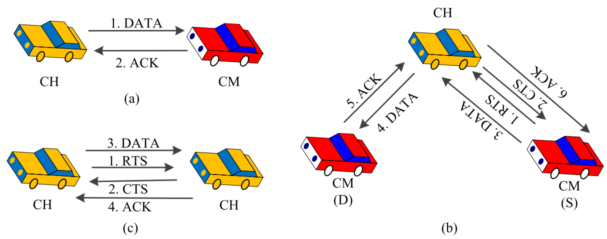

FIGURE 4. Handshake for nsd between (a) CH and CM, (b) CH and CH, (c) CM and CM.

CH transmits nsd to a CM, then expects ACK to realize the the successful transmission which is shown in Fig. 4 (a). A CM will always transmit a nsd to the CH via RTS/CTS handshake to avoid collision, after that CH will transmit the nsd to the destination CM which is illustrated in Fig. 4 (b). The transmission of data between CHs is demonstrated in Fig. 4 (c). If a CH wants to exchange data with another CH, data will be sent via RTS/CTS handshake to escape collision and hidden node problem.

III. OPTIMIZATION OF CB-MAC PROTOCOL

A VANET comprising of N randomly distributed vehicles is considered. Saturation condition, i.e. each vehicle always has a packet to transmit is assumed. Let M be the number of clusters in VANET. Clusters consist of adjacent vehicles heading in the same direction. Let S be normalized system throughput which is ratio of mean transmitted payload length and average duration of a slot time that can be written as [1]

$$S = \sum_{k=1}^{M} S_k, \tag{1}$$

where S_k is throughput of k^{th} cluster which can be expressed as [1]

$$\begin{aligned} S_k &= \frac{P_s P_{busy} L}{T_e} \\ &= \frac{P_s P_{busy} L}{(1-P_{busy})T_{slot} + P_{busy} P_s T_s + P_{busy}(1-P_s)T_c}, \end{aligned} \tag{2}$$

where T_e, T_{slot}, T_c and T_s are period of each Markov state, slot time, collided packet and successful transmission, respectively. L represents data length. P_s and P_{busy} are probability of successful transmission and channel busy, respectively which can be written as [1]

$$P_s = \frac{(x-1)P_{t-cl}\,(1-P_{t-cl})^{x-2}}{P_{busy}} = \frac{(x-1)P_{t-cl}\,(1-P_{t-cl})^{x-2}}{1-(1-P_{t-cl})^{x-1}}, \tag{3}$$

$$P_{busy} = 1-(1-P_{t-cl})^{x-1}, \tag{4}$$

where x is cluster size and P_{t-cl} is the transmission probability that a CM transmits a packet in a slot time in the cluster. x can be given as

$$x = \frac{N}{M}. \tag{5}$$

Since each cluster contains a CH, average number of CMs in a cluster is

$$y = x-1 = \frac{N-M}{M}. \tag{6}$$

Therefore, P_{t-cl} can be written as [1]

$$P_{t-cl} = \frac{y}{x} = \frac{N-M}{N}. \tag{7}$$

Equation (2) can be rearranged as:

$$S_k = \frac{L}{T_s - T_c + \frac{P_{busy}(T_c-T_{slot})+T_{slot}}{P_sP_{busy}}}. \tag{8}$$

Since L, T_s, T_c and T_{slot} are constants, S will be maximum when the following quantity is optimized:

$$\frac{P_sP_{busy}}{P_{busy}+\frac{T_{slot}}{(T_c-T_{slot})}} = \frac{(x-1)P_{t-cl}\,(1-P_{t-cl})^{x-2}}{\left(1-(1-P_{t-cl})^{x-1}\right)+t} \tag{9}$$

where $t = \frac{T_{slot}}{T_c-T_{slot}}$ with $t > 0$. Taking the derivative of (9) with respect to P_{t-cl} and solving to 0:

$$t(x-1)P_{t-cl} - t + (1-P_{t-cl})^{x-1} + (x-1)P_{t-cl} - 1 = 0. \tag{10}$$

Under the condition $P_{t-cl} \ll 1$, the series expansion as [28]

$$(1-P_{t-cl})^{x-1} \approx 1-(x-1)P_{t-cl} + \frac{(x-1)(x-2)P_{t-cl}^2}{2}, \tag{11}$$

then (10) can be written as

$$t(x-1)P_{t-cl} - t + \frac{(x-1)(x-2)P_{t-cl}^2}{2} = 0. \tag{12}$$

Therefore, optimum P_{t-cl} can be derived as

$$P'_{t-cl} = \frac{\sqrt{t(x-1)(t(x-1)+2(x-1)-2)} - t(x-1)}{(x-1)(x-2)} = \frac{t\sqrt{1+2/t-2/(t(x-1))}-1}{(x-2)}, \tag{13}$$

where $x > 2$. After taking second derivative of (9) with respect to P_{t-cl}, we get negative value of P_{t-cl} as

$$P''_{t-cl} = -\frac{t}{x-2}, \tag{14}$$

which shows it is the maximum P'_{t-cl}. Algorithm for P_{t-cl} optimization is presented in Algorithm III. To achieve the maximum S, each vehicle has to transmit with the optimum P_{t-cl}. The optimum S can be achieved by sizing P_{t-cl} in relation to cluster size. From equation (7), it is obvious that P_{t-cl} depends on N and M where N is not directly controllable. The only technique to have maximum S is to tune M. Using from (7) and (13), the optimum number of cluster M is found as

$$M_{opt} = \left\lceil N\left(1-\frac{t\sqrt{1+2/t-2/(t(x-1))}-1}{(x-2)}\right)\right\rceil, \tag{15}$$

where $\lceil . \rceil$ denotes ceil operation.

Let Z be average number of vehicles in the road segment. According to Little's law [29], Z can be written as

$$Z = \lambda T_e, \tag{16}$$

where λ is the mean vehicles arrival rate which can be written as

$$\lambda = n_L k_{density} v, \tag{17}$$

where n_L is number of lanes on the road, v is average velocity of vehicular node and $k_{density}$ is traffic density (vehicles/distance/lane). $k_{density}$ changes linearly with v as

$$k_{density} = k_{jam}\left(1-\frac{v}{v_f}\right), \tag{18}$$

where k_{jam} denotes the intensity of traffic jam that stops traffic flow and v_f presents free-flow speed.

Using eq. (17) to (18) in (16), the Z can be rewritten as

$$Z = n_L k_{jam}\left(1-\frac{v}{v_f}\right) v T_e. \tag{19}$$

The average number of vehicular nodes in transmission range (R_t) [30] can be given as

$$E[N] = ZR_t. \tag{20}$$

Therefore, the optimum number of cluster M can be written as

$$M_{opt} = \left\lceil n_L k_{jam}\left(1-\frac{v}{v_f}\right) vT_eR_t \times \left(1-\frac{t\sqrt{1+2/t-2/(t(x-1))}-1}{(x-2)}\right)\right\rceil. \tag{21}$$

A packet is dropped if it can not be transmitted until maximum retransmission limit (m_r). Therefore, PDR can be written as [1]

$$PDR = (1-P_s)^{m_r}. \tag{22}$$

The optimum PDR can be achieved by getting optimum P_s that can be obtained by using optimum P_{t-cl}.

TABLE 1. Parameter values utilized in simulation.

Symbols	Values
$T_{slot}, T_{SIFS}, T_{DIFS}, T_{delay}$ (μs)	20, 10, 50, 1
L_{sm}, L_{nsd}, L_h (bytes)	100, 512, 50
RTS, CTS, ACK (bytes)	26, 20, 14
R_c, R_d, λ (Mbps)	1, 11, 0.5
$W, N,$	64, 0 – 50
m_r(sm), m_r(nsd)	2, 7
Maximum vehicle velocity *(m/s)*	19.81

Average packet delay $E[D]$ can be given as [1]

$$E[D] = T_e\left(N - \frac{P_{drop}}{1-P_{drop}} \times \frac{2}{1+W+m_rW/2}\right), \quad (23)$$

where P_{drop} and W are probability that a packet will be finally dropped, and contention window size, respectively. The optimum $E[D]$ can be attained by obtaining optimum T_e that can be achieved by using optimum P_{t-cl}.

IV. ANALYTICAL AND SIMULATION RESULTS

This section examines the performance of the CB-MAC optimized protocol and verifies analytical study through Monte-Carlo simulations. Table 1 provides value of parameters utilized in simulation. Ideal channel condition is assumed. Simulation results are conducted in SUMO and MATLAB. Firstly, microscopic mobility model is produced in SUMO, then output of SUMO is used as input to MATLAB. Simulation results are achieved by 1000 Monte-Carlo iterations. In the CB-MAC [1] study, parameters related to mobility such as number of vehicles, vehicle velocity, etc. are assumed. In this study practical mobility parameters are taken from SUMO which makes the analysis realistic. To generate realistic mobility model SUMO is also used in [31]–[33]. Fig. 5 shows the area map and traffic simulation of the area considered in SUMO. The comparison of the CB-MAC protocol, optimized CB-MAC protocol and traditional MAC protocol which is based on IEEE 802.11 is presented. The cluster size is assumed to be 10 for CB-MAC.

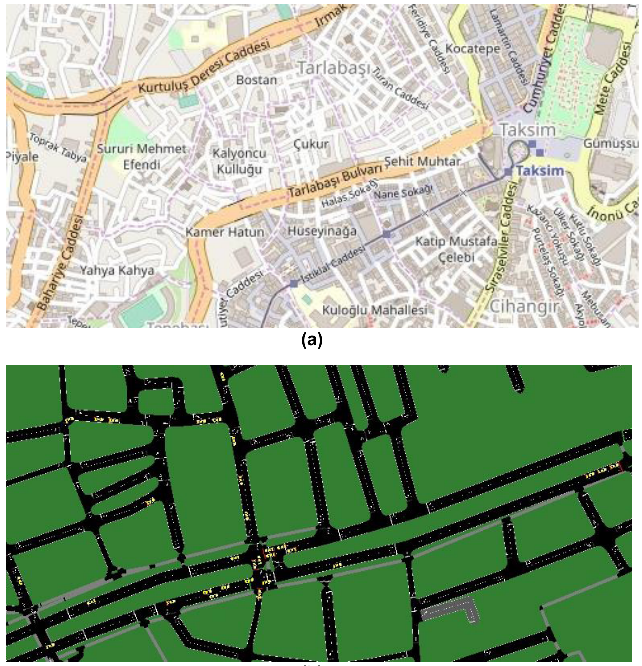

FIGURE 5. (a) Traffic map at Taksim square in Istanbul. (b) Traffic simulation of Taksim square, Istanbul in SUMO 1.2.0.

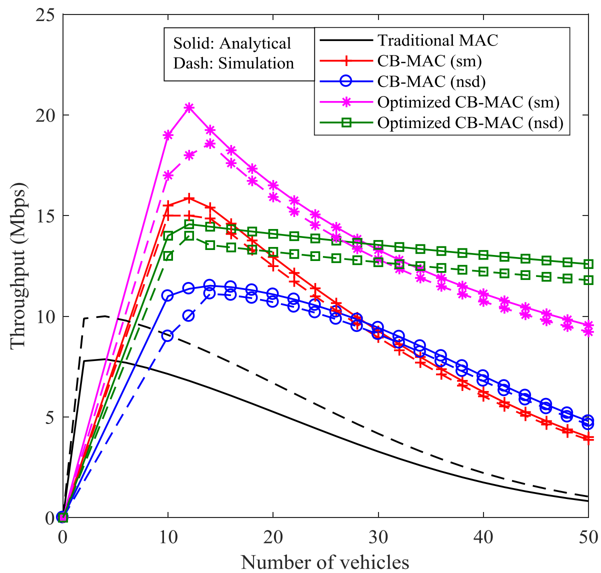

FIGURE 6. Throughput versus number of vehicles.

Fig. 6 shows throughput versus number of vehicles. Throughput is increasing with the increase of the number of vehicles until more packets contend which results in more collisions and degrades the performance. The throughput of optimized CB-MAC protocol is better than both traditional MAC and CB-MAC protocols. Since clustering limits the channel contention and controls the network topology efficiently, CB-MAC protocol has higher throughput than traditional MAC protocol. P_{t-cl} is maximized with M_{opt}, and the throughput is optimized.

Fig. 7 presents *PDR* against number of vehicles. *PDR* rises with the number of vehicles which reduces reliability of transmission. When number of vehicles is increased, number of packets contending for the transmission is increased which increases collision as well as *PDR*. *PDR* of proposed optimization mechanism is lower than the CB-MAC and traditional MAC protocol. Clustering makes communication stable, CB-MAC protocol has lower *PDR* than traditional MAC protocol. Since successful transmission probability is optimized by using optimum transmission probability with optimum cluster size, *PDR* is lower than CB-MAC in optimized CB-MAC which makes communication more reliable.

Fig. 8 demonstrates average packet delay against number of vehicles. With increase of the number of vehicles, delay

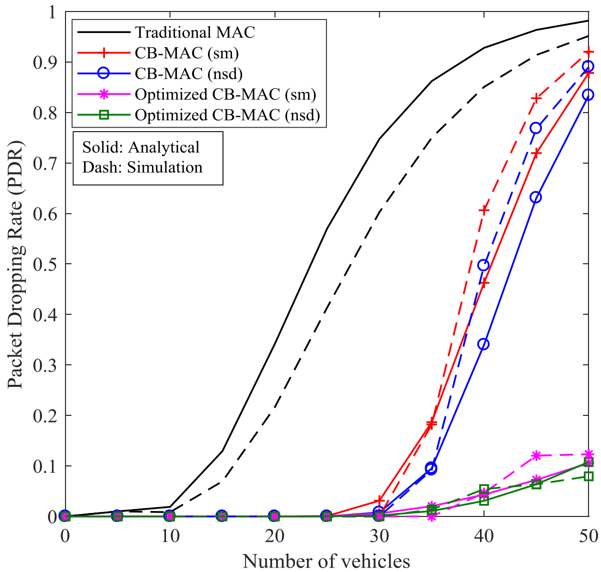

FIGURE 7. PDR versus number of vehicles.

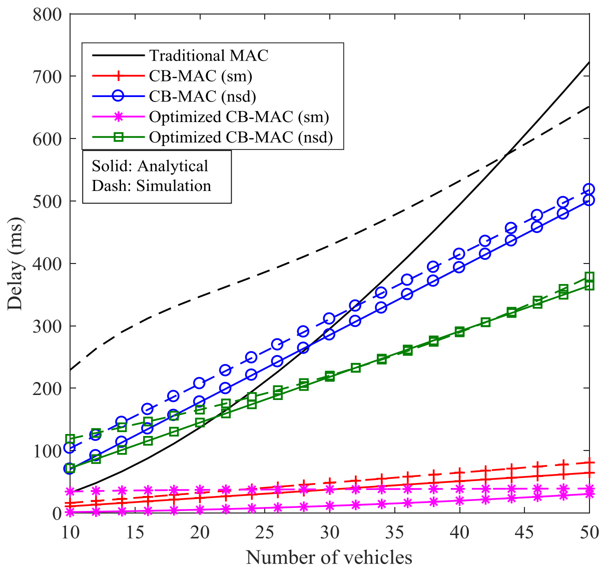

FIGURE 8. Delay against number of vehicles.

increases because probability of channel busy and collision increase. The delay for optimized CB-MAC is less than CB-MAC and traditional MAC. Clustering limits the channel contention which reduces probability of channel busy and collision that decreases delay. Thus, CB-MAC has lesser delay than traditional MAC. Optimized CB-MAC limits channel contention more efficiently than CB-MAC protocol by optimizing cluster size which results in lower delay than CB-MAC.

The analytical analysis supports the simulation results. It is also noticeable that high priority sm has higher throughput and lower delay than nsd. CB-MAC protocol fulfills the performance criteria of VANETs, and the performance can be optimized. Table 2 presents optimum number of cluster under different traffic conditions which is obtained from simulation. To design stable clustering, a range of the number of vehicle

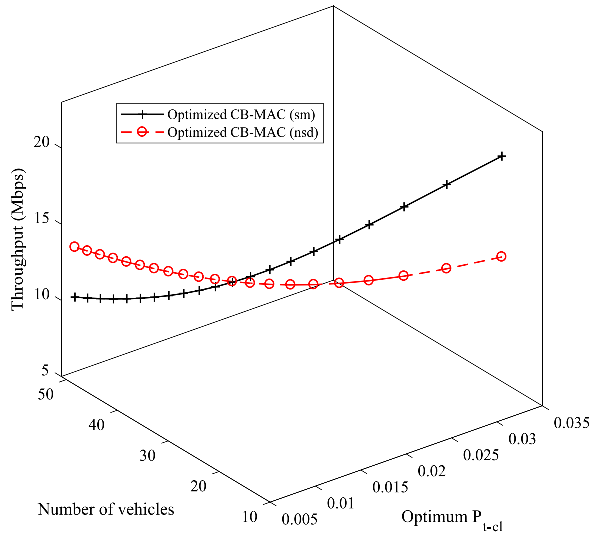

FIGURE 9. Throughput, number of vehicles, and optimum transmission probability in 3D.

TABLE 2. Optimum number of cluster for different number of vehicles.

N	M_{opt}
1-19	1
20-30	2
31-40	3
41-50	4
51-60	5
61-70	6
71-80	7
81-90	8
91-100	9

TABLE 3. Optimum P_{t-cl} and Maximum Throughput Values under Different Number of Vehicles for Optimized CB-MAC.

N	Optimum P_{t-cl}	S (sm) **Mbps**	S (nsd) **Mbps**
10	0.0298	19	14.0013
20	0.0168	16.5244	14.0929
30	0.0111	13.5433	13.5448
40	0.0083	11.1272	13.0474
50	0.0066	9.5588	12.5934

is provided. If clusters are formed as Table 2, i.e. optimum number of clusters are formed for particular number of vehicles, then the performance will be optimized. Table 3 presents the optimum P_{t-cl} and maximum S for both sm and nsd under different number of vehicles. For a particular number of vehicles if each vehicle adopts the optimum transmission probability then optimum throughput is achievable. Designing of VANET clustering to achieve optimum performance is understandable from Table 2 and Table 3. For example, if 2 clusters are formed for 20 vehicles that adopt optimum P_{t-cl} 0.0168, maximum throughput 16.5244 Mbps for sm and 14.0929 Mbps for nsd is achieved. From the simulation, obtained maximum optimum P_{t-cl} is 0.0311 which supports the assumption optimum $P_{t-cl} \ll 1$. Throughput, number of vehicles, and optimum transmission probability in 3D is presented in Fig. 9.

V. CONCLUSION AND FUTURE WORKS

In this paper, performance of CB-MAC protocol is optimized by optimizing transmission probability with cluster size for both sm and nsd cases. To achieve optimized performance each vehicle should adopt the optimum transmission probability in the cluster which can be obtained by tuning the number of clusters in the VANET. Therefore, optimum number of clusters is defined based on number of vehicles in VANETs. An analytical study based on Markov chain model is provided. Optimum probability of transmission, optimum number of clusters expressions are derived. Simulation results are presented which support and verify analytical analysis. The microscopic mobility model is generated in SUMO. Optimum number of clusters for different number of vehicles is presented. Moreover, optimum transmission probability and maximum throughput for different number of vehicles is provided. It is obvious that the optimization mechanism improves performance of CB-MAC protocol by increasing throughput and decreasing delay and PDR. Therefore, optimized CB-MAC protocol improves communication quality and increases reliability of communication and achieves stated objectives. Non-saturated condition will be considered in future research works. Channel fading and capture effect will be included too.

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