Performance Evaluation of IEEE 802.11p MAC Protocol in VANETs Safety Applications

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***Abstract*—VANETs are becoming more and more popular as a way to increase the traffic safety and comfort. The IEEE 802.11p standard, especially the 802.11p MAC protocol, has attracted much attention as part of the WAVE protocol in VANETs. Safety applications, as one of the main categories of applications in VANETs, is very challenging for the design of a MAC protocol due to their low latency and high reliability requirements. The CCH interval is also a key parameter for the 802.11p MAC protocol since it can affect the performance of safety message delivery significantly. In this paper, a simulation based evaluation is proposed to evaluate the performance of the 802.11p MAC protocol with various vehicle densities and CCH interval settings. The evaluation results indicate that the 802.11p MAC protocol can be improved via extending the CCH interval. However, the reliability is still very challenging due to high collision rates.**

Keywords—Vehicular ad-hoc Networks; IEEE 802.11p; MAC; safety; evaluation; channel interval.

I. Introduction

Vehicular ad-hoc Networks (VANETs) have attracted much attention owing to our society transportation problems such as traffic congestion, traffic accidents, lack of mobility and accessibility etc. During the last two decades, several technical groups such as the IEEE 1609 working group [1], the IEEE 802.11p task group [2], the ISO TC204 Working Group 16 [3] and the ETSI [4] ITS Technical Committee, were created in an attempt to solve the said problems. From that perspective, three main categories of applications are targeted: (i) road safety, (ii) traffic efficiency, and (iii) value added applications. VANETs constitute the cornerstone of the envisioned Intelligent Transportation Systems (ITS). By enabling vehicles to communicate with each other via Inter-Vehicle Communication (IVC), alternatively known as Vehicle to Vehicle (V2V), as well as with roadside base stations via Roadside-to-Vehicle Communication (RVC), also known as Vehicle to Infrastructure (V2I), VANETs will contribute to safer and more efficient roads by providing timely information to drivers and the authorities concerned.

VANETs present a challenging environment for protocol and application design due to their low latency and high data rate requirements in a high mobility environment. The IEEE 1609 working group has defined the first version of the protocol stack IEEE 802.11p/1609.x protocol families [5], also known as WAVE (Wireless Access in a Vehicular Environment). The WAVE protocols are designed for the 5.850-5.925 GHz band, the Dedicated Short Range Communications (DSRC) spectrum band in the United States (US), known as intelligent transportation systems radio service (ITS-RS).

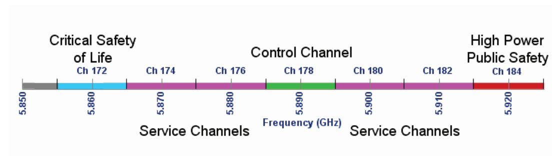

Fig. 1. The set of channels defined in the WAVE trial standard [6]

This 75 MHz band is divided into one central control channel (CCH) and six service channels (SCH) as depicted in Fig. 1. An overview of the WAVE protocol families is illustrated in Fig. 2. The IEEE 802.11p standard [2] defines the physical (PHY) and medium access control (MAC) layers based on earlier standards for Wireless LANs (Local Area Networks). The IEEE 802.11p uses the enhanced distributed channel access (EDCA) MAC sub-layer protocol designed based on the IEEE 802.11e with some modifications, while the physical layer is OFDM (Orthogonal Frequency Division Modulation) as used in IEEE 802.11a.

Safety applications are very challenging for the design of a MAC protocol in VANETs due to their low latency (less than 100*ms*) and high reliability requirements. Many evaluations were proposed for the 802.11p MAC protocol recently. However, the performance of the 802.11p MAC protocol is highly affected by some key parameters, such as the packet size of safety related message, the message generation function, the vehicle density, the communication range and etc. Some of these parameters are not set properly in the recent proposed evaluations. Furthermore, as stated in [8], this is a significant concern if BSMs (Basic Safety Messages) are constrained to be sent on the CCH during the 50*ms* CCH interval, since there could be hundreds of devices in a given area and the collision rate could be very high. A special safety Channel 172 for safety communication is also proposed in [9] and [8]. On the other hand, the 50*ms* CCH interval could be too long and wasted in a low vehicle density environment. The idea of adapting the intervals of CCH and SCH is proposed in [10]. The CCH interval is reduced in order to improve the SCH service, but it is not considered to extend the CCH interval for a high vehicle density environment in order to reduce the collision probability. The main purpose of this paper is to propose a simulation based evaluation for the 802.11p MAC protocol in terms of the safety applications in VANETs. Two questions will be addressed in this work: (i) how is the performance of the IEEE 802.11p MAC protocol in safety applications with various CCH intervals? (ii) how many

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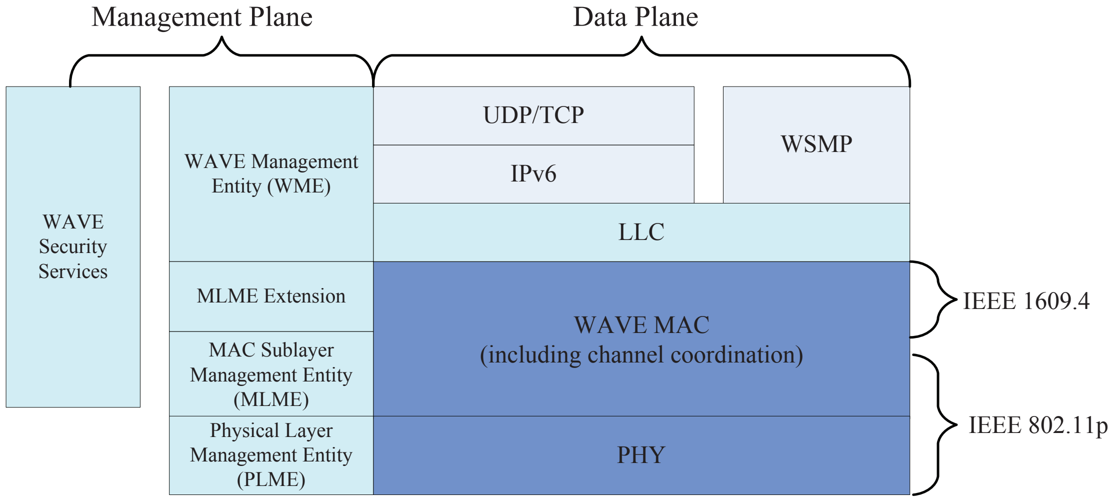

Fig. 2. The WAVE protocol suit [7]

vehicles can be accommodated in VANET safety applications with various CCH intervals? To the best of our knowledge, no work focusing on the IEEE 802.11p MAC protocols has been conducted to focus on the above mentioned issues.

The rest of this paper is organised as follows. In Section II, the overview of the 802.11p MAC protocol is described. The related work is discussed in Section III. In Section IV, the performance evaluation of the 802.11p MAC are presented and analysed. Finally, the conclusions and future works are given in Section V.

II. Overview of 802.11p MAC

In this section an overview of the IEEE 802.11p MAC protocol is presented. Just the information relevant to this paper is provided. Further information can be found in [2] and [6].

The IEEE 802.11p employs HCF (Hybrid coordination function) contention-based channel access EDCA (Enhanced Distributed Channel Access) as the MAC method, which is an enhanced version of the distributed coordination function (DCF) of 802.11. EDCA uses Carrier Sense Multiple Access (CSMA) with collision avoidance (CSMA/CA). The basic EDCA access method is depicted in Fig. 3. In EDCA scheme, a node willing to transmit will sense the medium, and if the medium is idle for greater than or equal to a AIFS[AC] (Arbitration Inter-Frame Space [Access Class]) period, the node starts transmitting directly. If the channel becomes busy during the AIFS[AC], the node will defer the transmission by selecting a random backoff time. The backoff procedure in

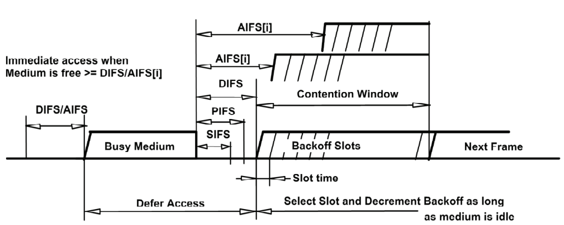

Fig. 3. A basic EDCA access method [11]

TABLE I. Parameter settings for different application categories in IEEE 802.11p [2].

AC	CWmin	CWmax	AIFSN
BK	15	1023	9
BE	15	1023	6
VI	7	15	3
VO	3	7	2

EDCA functions is as follows: (i) The node selects a backoff time uniformly from the interval [0, CW[AC]] where the initial CW[AC] (Contention Window) value equals CWmin[AC]. (ii) The interval size will increase (double), if the subsequent transmission attempt fails, until the CW[AC] value equals CWmax[AC]. (iii) If no medium activity is indicated for the duration of a particular backoff slot, then the backoff procedure shall decrement its backoff time by aSlotTime. If the medium is determined to be busy at any time during a backoff slot, then the backoff procedure is suspended. The medium shall be determined to be idle for the duration of AIFS[AC], before the backoff procedure is allowed to resume. (iv) When reaching a backoff value of 0, if the medium is sensed to be idle, the node will send immediately; If the medium becomes busy, the node will go to backoff again. However, in this scenario, the value of the CW[AC] is left unchanged. In order to ensure that highly relevant safety messages can be exchanged timeously and reliably, even when operating in a dense scenario, the 802.11p MAC protocol accounts for the priority of the messages using different Access Classes (ACs). There are four available data traffic categories with different priorities: background traffic (BK or AC0), best effort traffic (BE or AC1), video traffic (VI or AC2) and voice traffic (VO or AC3). A set of distinct channel access parameters, including AIFSN (Arbitration Inter-Frame Space Number) and CW, are selected for different ACs, as illustrated in Tab. I. A multiple AC access scheme is illustrated in Fig. 4. Each AC has a queue where messages are queued based on their priorities. If packets from different queues in the same station contend for the access, the message with higher priority will get more opportunity to access the channel due to the small value of AIFSN and CW.

According to the IEEE 1609.4 coordination scheme [7], as shown in Fig. 5, the channel time is divided into synchronization intervals with a fixed length of 100*ms*, consisting of 50*ms* (including 4*ms* guard interval) alternating CCH and SCH intervals. All vehicles stay in the control channel during the CCH period and switch to one of the six service channels during the SCH interval.

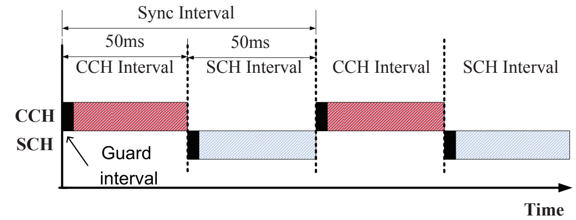

Fig. 5. Channel interval

III. Related Work

In this section, related evaluations of the IEEE 802.11p MAC protocol are presented and discussed. Certain analytical evaluation models are proposed based on Markov chains in [12] [13] [14] [15]. In [12], an analytical model is proposed to compute the successful reception rate, collision probability and throughput of IEEE 802.11p within VANET safety applications. The proposed model is based on a highway scenario on which the vehicles send status and emergency packets according to a Poisson distribution. However, in the backoff process calculation, a wrong parameter DIFS (DCF Inter-Frame Space) is used which should be AIFS[AC]. As a result, the evaluation may not be very accurate. In [13], a two-dimensional novel Markov chain analytical model for IEEE 802.11p is proposed, which takes AIFS, CW for different ACs (AC0-AC3), while the internal collisions inside each station are accounted for. This analytical model is used to investigate the performance of the IEEE 802.11p MAC sub-layer in terms of throughput. However, it is analysed in a saturated scenario which does not model a realistic network. In [14], a discrete-time Markov chains based model is proposed for the EDCA MAC protocol, which considers the specific conditions of the control channel of a WAVE environment. The proposed model captures the fact that EDCA can establish priorities among the stations. The important metrics of QoS, such as throughput, losses, buffer occupancy and delays, are presented and analysed in this paper. However, the AIFS duration after a busy slot as well as the busy medium time are not counted in the delay calculation. Herewith, the delay obtained in [14] is not accurate and much shorter than the real value. In [15], the authors propose an analytic model for safety message delivery when using the channel coordination mechanism defined in the 802.11p standard. The 802.11p standard is evaluated based on both heavy traffic and light traffic conditions. The evaluation results derived from the proposed model indicate that 802.11p standard can satisfy the needed latency requirements (less than 100*ms*), but cannot satisfy the required reliability for the safety of the message delivery (greater than 99.9%). It is also indicated that the 45*ms* sub-interval value defined in the standard is a good choice, since increasing the sub-interval value more than that does not improve the performance on the CCH. However, the heavy traffic conditions which contain only 26 nodes are not explained clearly in the paper and hence the evaluation results based on the heavy traffic conditions are questionable and unreliable. In addition, the packet size of safety related message, which could affect the evaluation accuracy, is not well considered in these related works. The packet size is set as 250, 500, and 1000*bytes*. As defined in [16], the message size for the BSM (Basic Safety Message) part I is 39*bytes* and for the Part II, the VehicleSafetyExtension frame of the BSM which is less than 100*byte*. Hence, the packet size of safety related message should be less than 140*bytes*.

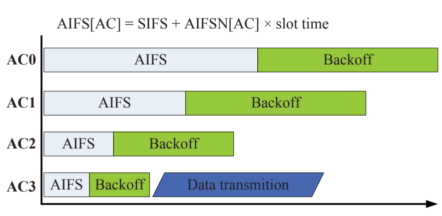

Fig. 4. A multiple AC access scheme

The effect of time allocations on CCH and SCH in IEEE 802.11p are analysed in [10] and [17]. In [10], the effect is analysed while the CCH/SCH duty cycle is changing. The results obtained show that the performance on CCH and SCH change significantly following the changing of the CCH/SCH duty cycle. Three various CCH intervals (9, 27 and 45*ms*) are considered, the tradeoff between the numbers of users on CCH and SCH are described. However, the effect is not analysed when the interval of CCH is greater than 45*ms*. In [17], an algorithm is proposed to improve the channel access scheme by adapting the intervals of CCH and SCH. However, the proposed algorithm cuts off CCH in order to extend SCH; hence it only improves the service channel utilisation without considering the control channel utilisation.

IV. Performance Evaluation

The performance of the IEEE 802.11p MAC protocol in VANETs safety applications is evaluated in the OMNeT++ network simulator [18] with the model of INET-2.0.0 [19]. The evaluation configurations and results are given in this section.

A. Evaluation Configurations

The simulation scenario is built on a highway segment of length 1000*m*. The vehicles speed ranges from $[60, 120] km/h$. The communication range is set as 1000*m* since the expected radio range for highway is up to 1000*m* [20]. Each vehicle sends only one safety message every 100*ms* in AC0. The safety message is generated randomly during $[0, T_{CCH}]ms$ for each vehicle, where T_{CCH} denotes the CCH interval. The T_{CCH} is set as $[10, 20, 30, 40, 50, 60, 70, 80, 90, 100]$ respectively in order to evaluate the performance of 802.11p MAC with various CCH interval. In this model, the safety messages can also be sent during SCH interval if there are still some safety messages remaining in the queue. Since the vehicle density $D_{vehicle}$ could vary widely in realistic network for different road and time period, the $D_{vehicle}$ is set from 0.01 to 0.5*vehicles/m*. As discussed in Section III, the packet size of

TABLE II. PARAMETER SETTINGS FOR EVALUATION.

Parameter	Value
Packet size L_{Safety}	140 bytes
MAC header $L_{MACheader}$	70 bytes
Message sending interval	10/s
Simulation time	10 s
Modulation and Data rate R	QPSK 6 Mbps
Communication range	1000 m
Transmission power P_t	800 mw
Transmitter&Receiver antennas heights	1.5 m
Transmiter&Receiver antennas Gain	0
aSlotTime	13 us
aSIFSTime	32 us
Signal to Noise plus Interference Ratio (SNIR) threshold	4 dB
Mobility model	BaseMobility
Propagation model	FreeSpace

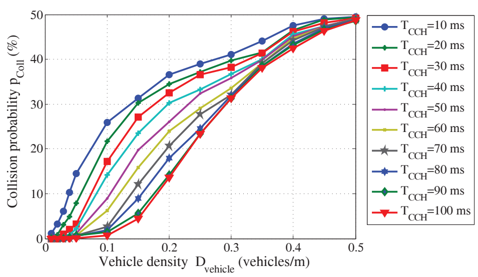

Fig. 6. Collision probability

safety message L_{Safety} is set as 140*bytes*. The other parameter settings used in this evaluation are listed in Table. II.

B. Evaluation Results

The IEEE 802.11p MAC protocol is evaluated in terms of collision, reliability, MAC delay and throughput respectively. The evaluation results are presented and discussed in this section.

Fig. 6 shows the average collision probability P_{Coll} obtained from simulations, where P_{Coll} is determined as $P_{Coll} = \frac{number\ of\ collision}{number\ of\ collision+number\ of\ successful\ received}$ for each vehicle. It can be observed that the collision probability increases significantly according to the increasing of vehicle density and the decreasing of CCH interval. In this simulation scenario, each vehicle sends one safety message every 100*ms*. The increasing of vehilce density means more vehicle will content and try to send a message on each CCH interval. As a result, more collision will be caused. On the other hand, the decreasing of CCH interval will furthermore increases the contention due to the shorter CCH interval. It can also be concluded that the extending of CCH interval can reduce the collision probability significantly when the vehicle density is lower than a threshold $D_{Threshold}$ which is 0.2*vehicles/m* obtained in this simulation scenario.

Fig.7 shows the average MAC delay T_{MAC} for different vehicle density and CCH interval settings, where T_{MAC} means the delay occurred in MAC layer. The T_{MAC} is the time since the safety message arrived to MAC layer till the time that the message is sent out. The end-to-end delay T_{E2E} is mostly depending on the MAC delay and it can be derived from T_{MAC} as $T_{E2E} = \frac{L_{Safety}+L_{MACheader}}{R} + T_{MAC} + \delta$, where δ is the propagation delay. We only focus on T_{MAC} in this work. It can be observed from Fig.7 that the T_{MAC} increases according to the increase in vehicle density and a decrease of the CCH interval. The MAC delay is mostly caused by the Backoff time. The increase of vehicle density as well as the decrease of the CCH interval will cause more contention and more Backoff. As a result, longer MAC delay is caused. In addition, the MAC delay is always less than 100*ms* in all these simulation scenarios. It indicates that IEEE 802.11p MAC protocol can satisfy the latency requirement (less than 100*ms*) in VANET safety applications.

Fig. 8 shows the average safety messages delivery reliability $P_{Reliability}$ for different vehicle density and CCH interval setting. It can be observed that the reliability decreases according to an increase in vehicle density and a decrease in CCH interval. The reliability is highly related to the collision probability. As discussed before, the increase of vehicle density as well as the decrease of the CCH interval will cause more collisions and herewith a worse reliability. It can also be seen that the reliability is lower than 90% when the vehicle density is greater than 0.15*vehicles/m*. Hence, the reliability for the domain $0 \leq D_{Vehicle} \leq 0.15$ is selected and shown in Fig. 9. The number of vehicles that can be accommodated in a network can then be derived from Fig. 9. The result obtained is shown in Table. III. In addition, as shown in Fig. 7, the corresponding MAC delay for all the vehicles listed in Table. III is less than 4*ms*. As discussed in Section II, there is a 4*ms* guard interval between CCH and SCH. Hence, for the accommodated number of vehicles, the safety messages can be sent out before the SCH interval.

The network throughput and successful throughput are shown in Fig. 10 and Fig. 11 respectively. Since the channel time in VANETs is divided into synchronization intervals with a fixed length of 100*ms*, the throughput for one synchronization interval rather than 1*s* is considered in this work. It can be observed that the bigger T_{CCH} and $D_{Vehicle}$, the bigger of throughput until the channel is getting saturated. The successful throughput can be improved significantly by extending the CCH interval before the network is getting saturated ($D_{Vehicle} = 0.2vehicles/m$). The point that the network is getting saturate is just the threshold $D_{Threshold}$ mentioned in the former collision analysis.

In conclusion, in VANET safety applications, the performance of the IEEE 802.11p MAC protocol can be improved significantly in terms of collision, reliability, delay and throughput via extending the CCH interval when the vehicle density is lower than the threshold $D_{Threshold}$. As shown in

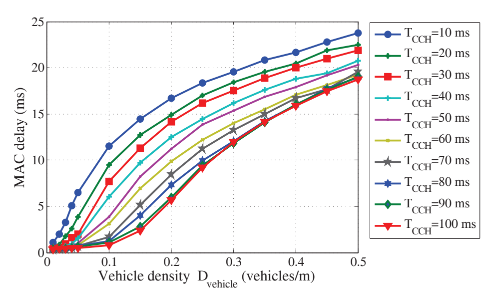

Fig. 7. MAC delay

TABLE III. ACCOMMODATED NUMBER OF VEHICLES

$T_{CCH}(ms)$	10	20	30	40	50	60	70	80	90	100
Number of vehicles ($P_{Reliability} \geq 99\%$)	0	10	20	20	30	30	40	40	40	50
Number of vehicles ($P_{Reliability} \geq 95\%$)	10	25	35	45	55	60	70	80	90	125
Number of vehicles ($P_{Reliability} \geq 90\%$)	18	30	47	55	65	73	105	120	130	140

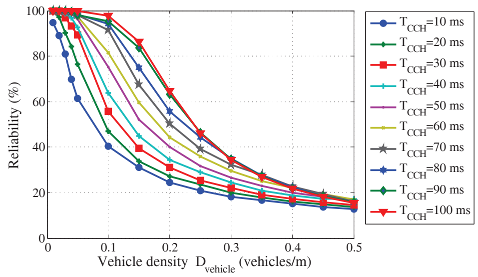

Fig. 8. Safety messages delivery reliability

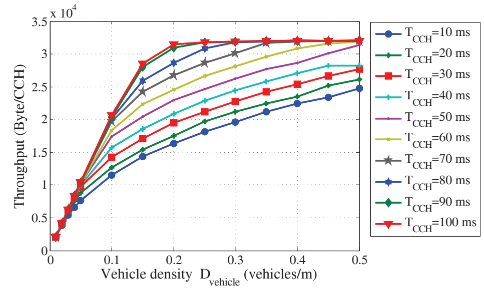

Fig. 10. Throughput

Fig. 10, the threshold $D_{Threshold}$ is just the point that the network is getting saturates for the whole synchronization interval ($T_{CCH} = 100ms$). The evaluation results indicate that the 802.11p MAC protocol can satisfy the latency requirement (less than 100*ms*). However, it is still very challenging in terms of message delivery reliability. The number of vehicles that can be accommodated in a network is derived and shown in Table. III, in which, the setting of $T_{CCH} = 100ms$ is just a special scenario where that the safety messages are delivered in a special safety channel as presented in [9]. The 50*ms* CCH interval setting is not appropriate for the network with a very low or high vehicle density. The 802.11p MAC would perform better if the CCH interval could be adjusted according to the vehicle density.

V. Conclusions

In this paper, a simulation based evaluation of the IEEE 802.11p MAC protocol in VANET safety applications is proposed. The 802.11p MAC protocol is evaluated in terms of collision, reliability, delay and throughput in the OMNeT++ network simulator. The evaluation covers various vehicle densities (0.01-0.5 *vehicles/m*) and CCH interval (10-100*ms*) settings. The evaluation results indicate that: (i) the performance of the IEEE 802.11p MAC protocol can be improved via extending the CCH interval; (ii) the IEEE 802.11p MAC protocol can satisfy the latency requirement in VANET safety applications; (iii) the delivery reliability is still very challenging due to the high collisions, even considering delivering the safety messages during a special safety channel. In addition, the number of vehicles that can be accommodated in a network is also proposed according to the reliability requirement in VANET safety applications.

Some of the future studies include: (1) proposing a analytical model to evaluate the performance of the IEEE 802.11p MAC protocol with different CCH interval setting; (2) evaluating the network capacity of IEEE 802.11p standard for both of the CCH and SCH interval.

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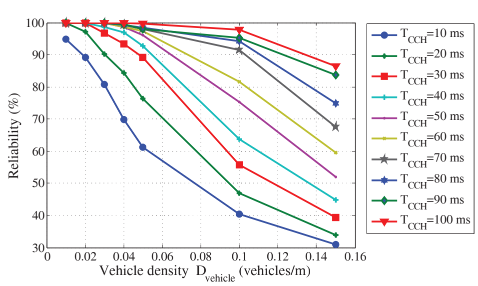

Fig. 9. Safety messages delivery reliability-selected domain

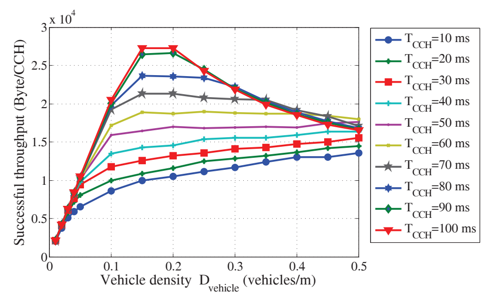

Fig. 11. Successful throughput

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