A Survey of IEEE 802.11p MAC Protocol

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Abstract— The 802.11p standard has attracted much attention as part of the WAVE protocol in VANETs. The 802.11p MAC protocol is very challenging owing to the characteristics of VANETs. In this paper, a survey of the IEEE 802.11p MAC protocol in vehicular environments is presented. Firstly, the existing evaluations of 802.11p are presented and classified, and subsequently, the enhancements which have been proposed for 802.11p MAC, are presented and discussed. Based on the above-mentioned evaluations and enhancements, a conclusion is reached regarding the present situation of this protocol. Finally, three suggested research directions are proposed: (i) throughput improvement, (ii) scheduling optimisation and (iii) traffic control.

Index Terms— **802.11p, collision, enhancement, latency, MAC, scheduling, throughput, traffic control, VANETs, WAVE.**

I. Introduction

Vehicular ad-hoc Networks (VANETs) have attracted much attention owing to the transportation problems of our society. 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, have been created to attempt to solve the said problems. From that perspective, three main categories of applications have been 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 Vehicular Environment). The WAVE protocols are designed for the 5.850-5.925 GHz band in the United States (US), known as Intelligent Transportation Systems Radio Service (ITS-RS). This 75 MHz band is divided into one central Control Channel (CCH) and six Service Channels (SCHs) 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. The IEEE 802.11p uses the Enhanced Distributed Channel Access (EDCA) MAC sub-layer protocol designed based on that of the IEEE 802.11e with some modifications, while the physical layer is OFDM (Orthogonal Frequency Division Modulation) as used in IEEE 802.11a.

In [7] the main MAC protocols for Mobile ADHOC Networks (MANETs) are presented. Subsequently, some MAC protocols suited for VANETs are compared and qualitatively analysed. Finally the authors of [7] indicate that IEEE 802.11p and ADHOC MAC [8] are the most likely two kinds of protocols that could be adapted by VANETs. ADHOC MAC works in a slotted frame structure, and uses a dynamic TDMA (Time Division Multiple Access) mechanism. However, it is indicated in [9] that TDMA-based protocols are not suited to VANETs because the high vehicular mobility renders MAC coordination much more difficult than the traditional distributed slot allocation scenarios. Hence the main purpose of our paper is to survey the existing evaluations of 802.11p and the enhancements of 802.11p MAC, furthermore the present situation and future research directions of 802.11p MAC will be presented. To the best of our knowledge, no survey focusing on the IEEE 802.11p MAC protocols has been conducted so far.

The rest of this paper is organised as follows. In Section II,

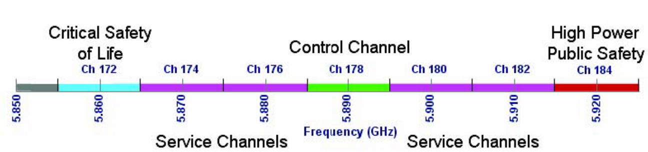

Fig. 1 The set of channels defined in the WAVE trial standard [6].

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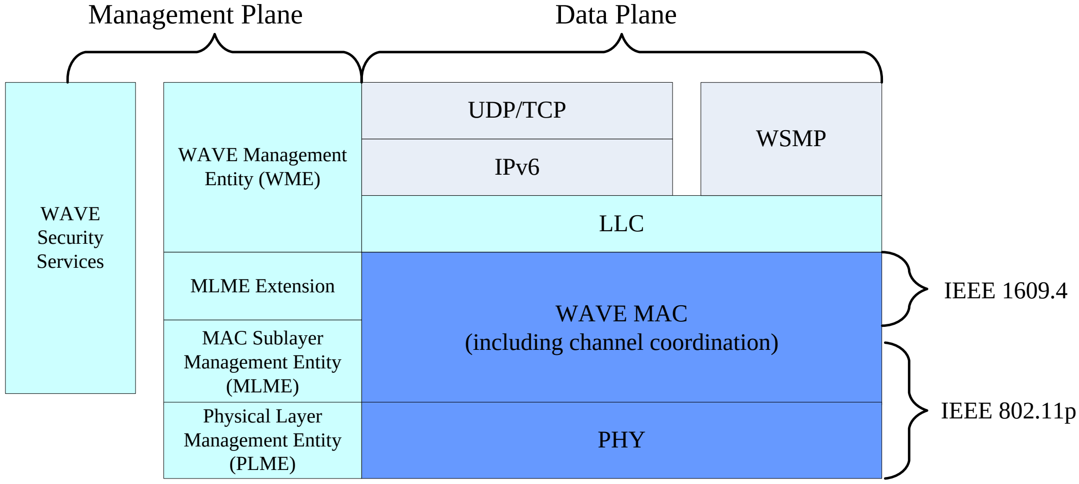

Fig. 2 The WAVE protocol suit.

the overview of the 802.11p MAC protocol is presented. The existing evaluations of the 802.11p protocol are described in Section III, and subsequently in Section IV, the enhancements of the 802.11p MAC are presented and discussed. The present situations and future research directions of the 802.11p MAC protocol are identified in Section V. Finally, the conclusion is given in Section VI.

II. Overview of 802.11p MAC

In this section an overview of the IEEE 802.11p MAC protocol is presented. Further information can be found in [2] [6]. Its latest version [2] was approved by IEEE on 17 June 2010.

The IEEE 802.11p employs the contention-based channel access EDCA as the MAC method, which is an enhanced version of the basic Distributed Coordination Function (DCF) from 802.11. EDCA uses Carrier Sense Multiple Access (CSMA) with Collision Avoidance (CSMA/CA), meaning that a node willing to transmit will sense the medium first, and if it is free for an AIFS (Arbitration Inter-frame Space), the node shall defer the transmission by selecting a random backoff time. The backoff procedure in 802.11 functions as follows: (i) the node selects a backoff time uniformly at random from the interval [0,CW +1] where the initial CW (Contention Window) value equals CWmin; (ii) the interval size will increase (double), if the subsequent transmission attempt fails, until the CW value equals CWmax; (iii) the backoff value will be decreased only when the channel is free; (iv) when reaching a backoff value of 0, it will send immediately. 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). Different AIFSN (Arbitration Inter-Frame Space Number) and CW values are chosen for different ACs, as illustrated in Table. I.

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

III. Evaluations of 802.11p

In this section, the existing evaluations of this protocol are presented and discussed. The existing evaluations can be divided into three categories according to the evaluation method: (i) Analysis-based evaluation, (ii) Simulation-based evaluation and (iii) Test-based evaluation.

A. Analysis-based evaluation

In analysis-based evaluation, only the analytical models can be used to analyse the performance of the 802.11p protocol for different network environments are presented. In [10], an analytical model is proposed to compute the successful reception rate, collision probability and throughput of IEEE 802.11p within VANETs 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. In this model, two one-dimensional Markov chains are proposed to calculate the transmission probabilities of both the status and emergency packets. Subsequently, the recommended maximum range is derived from this model which can be used to keep the delay as short as possible while achieving maximum throughput. Finally, the recommended maximum range is validated by means of simulation. In [11], a two-dimensional novel Markov chain analytical model for IEEE 802.11p is proposed, which takes AIFS, CW for different ACs (AC0-AC3), and 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. Thereafter, it is validated against simulation results in order to demonstrate its accuracy.

In [12], the authors propose a model for the EDCA MAC protocol, which considers the specific conditions of the control channel of a WAVE environment. The model is based on discrete-time Markov chains, and it captures the fact that EDCA can establish priorities among stations. The important metrics of QoS (Quality of Service), such as throughput, losses, buffer occupancy and delays, are presented and analysed in this paper. In [13], the effect of time allocations on CCH and SCH in IEEE 802.11p is investigated. The affection is analysed while the CCH/SCH duty cycle is changing, and the tradeoff between the numbers of users on CCH and SCH are presented. However, these two papers only propose analytical models and are not validated by simulation or realistic experiments.

B. *Simulation-based evaluation*

In [14], the authors present a model to analyse the characteristics and performance of C2C (Car to Car) communication in urban environments. In the proposed model, it is assumed that the intervals of CCH and SCHs are equal and all the moving cars have information to transmit (only during SCH) in packets of 500 *bytes*. Subsequently, the model is simulated in a city scenario with an area of l*km* x l*km* and 100 blocks. The simulation results reveal that IEEE 802.11p technology is adequate as long as the number of cars remains small (< 100 cars in the simulation area). As the number of cars increases, (500, normal traffic flow), the number of contention cases also increases. With dense traffic flow (>1000 cars), the results are drastically degraded, even with the use of the EDCA mechanism. However, the simulation scenario does not consider the road safety applications during CCH, which are more critical and important in VANETs. Furthermore, the assumption that all the moving cars have information to transmit during SCH may not be suited to the realistic VANETs environments.

The IEEE 1609 WAVE and IEEE 802.11p trial standards are evaluated in [15] under three distinct simulation scenarios. The first one is a flat open air environment with a number of static vehicles. The second is an urban one, corresponding to a region within Washington D.C., a digital form of the corresponding road network, while the third scenario corresponds to a roughly linear segment of a long highway, with a number of Road Side Units (RSUs) placed at varying intervals to generate traffic towards the passing vehicles. Thereafter, three results are derived from the simulations: (i) control channel traffic, which can be successfully received even at a distance of 2.5*km* in an open air scenario; (ii) the inter-RSU distance should fall in the range of 1000*m*-1500*m*; (iii) the delay on the control channel becomes longer than 100*ms* only when the total of the traffic offered approaches 1000 packets per second, which is too high for safety critical applications. Hence it is indicated in this paper that both WAVE and 802.11p appear to form a solid foundation for vehicular communication applications.

In [16], the authors evaluate IEEE 802.11p by considering collision probability, throughput and delay, by means of simulations and analysis. The simulation results show that the average value of end-to-end delay for AC3 is 1*s* for 300 nodes with a total offered traffic of 3000 packets per second, which is much higher than the maximum delay of 100*ms* for safety critical applications. However, the simulation scenario is not suitable for the realistic application, because it is not necessary that each node broadcasts 10 messages per second. Hence the real traffic for AC3 could be much lower than the scenario presented in this paper.

In [17], 802.11p and WiMAX technologies are compared in a high way scenario. Two scenarios to study the impacts of the source data rate and vehicle speed on 802.11p/WiMAX, are proposed. Subsequently, the coverage, average throughput, and end-to-end delay are evaluated for different vehicle speeds, traffic data rates, and network deployments. Finally, based on the simulation results, it is concluded that WiMAX offers large radio coverage and high data rates and that 802.11p is better suited to low traffic loads, where it offers very short latencies, even at high vehicle speeds. However, the simulation scenario presented in this paper only considers one vehicle; hence, the access collisions among the vehicles are not considered.

C. *Test-based evaluation*

In [18], the authors present an IEEE 802.11p full-stack prototype implementation of data exchange among and between vehicles and the roadway infrastructures. Three scenarios are considered in this work: hard-brake, accident, and tolling services. The performance of the proposed prototype is tested under realistic urban and suburban driving conditions. The results derived from the test show that communication is possible with a low Frame Error Rate (FER) or Bit Error Rate (BER) at approximately 400*m* with 22*dBm* EIRP (Equivalent Isotropically Radiated Power). It is also indicated in this paper that communication is possible at higher distances, approximately 1000*m* with the same EIRP of 22*dBm*. In addition, the best place for the location of antenna is also tested; the roof location is identified as the best place.

The authors in [19] carried out an infrastructure-to-vehicle trial using an IEEE 802.11p prototype on a real highway-the A12 in Tyrol, Austria. This paper presents the results of the evaluation of the average downstream performance of the PHY. It is indicated that shadowing effects, mainly caused by trucks, lead to a strongly fluctuating performance of the link quality, especially for settings with long packet lengths and high vehicle speeds. The maximum achievable range obtained in this paper is approximately 700*m* where the frame-success-ratio is continuously larger than 0.25. The maximum data volume that can be transmitted when a vehicle driven by a roadside unit, is achieved at low data rates of 6 and 9*Mbit/s*.

In [20], the reliability of 802.11p is analysed using real-world application data traffic, collected from three vehicles communicating with each other under both an open field traffic environment and a freeway traffic environment on a highway in the US. The reliability is analysed based on the metrics of the packet delivery ratio and the distribution of consecutive packet drops. The experimental data indicates that 802.11p provides an adequate degree of communication reliability under both traffic environments, and that the packet drops do not occur in bursts, even in the harsh freeway traffic environment. However, this scenario only considers three vehicles and the reliability of 802.11p under a high data traffic environment is not evaluated.

IV. Enhancements of 802.11p MAC

In the former section, the evaluations of 802.11p are presented. In this section, the focus falls only on the 802.11p MAC protocol and the exiting enhancements of the said protocol are presented and discussed. In [21], it is indicated that the MAC parameters for the original IEEE 802.11p MAC protocol can lead to undesired throughput performance because the backoff window sizes are not adaptive to the dynamics in the numbers of vehicles attempting to communicate. Thereafter, in this paper, two algorithms are proposed to address this problem. The first is named the Centralized Enhancement Algorithm (CEA) in which the exact information about the number of concurrent transmitting vehicles is used to calculate the optimal window size. However, the exact number of concurrent transmitting vehicles is difficult to obtain in the real network. Subsequently, the authors propose a Distributed Enhancement Algorithm (DEA) which estimates the number of concurrent transmitting vehicles and adapts the window size. The simulation results indicate that the proposed DEA can improve the throughput of the network from 7% to 79% for different networks. However, the estimation of the number of concurrent transmitting vehicles is not very accurate and hence the gain of throughput is not stable for different networks.

In [22], the authors propose a Vehicular Channel Access Scheme (VCAS) to optimise the channel throughput. In VCAS, all OBUs (On Board Units) have to listen to CCH for receiving WAVE announcement frames, which carry WSA (WAVE Service Advertisement) information and are broadcast by RSU during CCH intervals. Thereafter, a number of OBUs with similar transmission rates are grouped into one SCH by using the transmission distance threshold carried by the WSA frame. The group sizes of channels are controlled in order to fulfil the fairness requirement. In order to flexibly compromise in the tradeoff between throughput and fairness, a marginal utility model is proposed. Simulation results demonstrate that the proposed VCAS with marginal utility provides a flexible method to handle versatile vehicular scenarios. However, VCAS requires that RSU has two or more transceivers, which might not be suited to certain environments.

In [23], the authors propose an improved channel access scheme to allow a station to stay on a service channel for as long as it requires before returning to the control channel. The main idea of this algorithm is to cut off CCH to extend SCH and hence to improve the service channel utilisation. However, in vehicular networks the safety messages, which are transmitted during CCH, enjoy a higher priority; hence the CCH interval must be guaranteed. In addition, only one user is only considered in this paper and the effects incurred by changing channel intervals to its neighbours, are not analysed and presented.

A Detection-Based MAC protocol is presented in [24], in which RTS /CTS (Request To Send/Clear To Send) is used to detect network congestion through message exchange and to predict the number of competing nodes. Subsequently, the nodes dynamically adapt the contention window size based on the network status detection and the prediction of the competing nodes. The proposed Detection-Based MAC outperforms both IEEE 802.11 Base Access and RTS/CTS in total throughput by 50.4% and 62.6% higher, respectively; and the collision rate by 48.8% and 10.6% less, respectively. Besides, it is proved that Detection-Based MAC has the least standard deviation of delay. However, it is not explained clearly in this paper how the nodes guarantee that the predicted number of competing nodes is accurate.

In [25] the Coupon Collector's Problem [26] in the IEEE 802.11p MAC is presented. It is indicated that much time for collecting all vehicle information is needed owing to the randomness of the channel access in the IEEE 802.11p MAC and the unreliable nature of the safety beacon broadcast. Therefore, the authors propose a solution approach to the Coupon Collector's Problem which suppresses the WAVE nodes that succeeded in the previous attempt from contending for the channel for the next few safety beacon intervals. However in this algorithm, the application level feedback is used and transmitted in order to let the successful nodes know that they have succeeded, which consequently increases the network traffic. Furthermore, the safety beacon is time critical; hence the suppression of the safety beacon may not be suited to the vehicular networks.

In [27] a Self-organizing Time Division Multiple Access (STDMA) for real-time data traffic between vehicles is proposed. In STDMA the time is divided into frames as in a TDMA system and all vehicles strive for a common frame start. These frames, which are one second long in this paper, are further divided into slots, which typically correspond to the duration of one packet. Subsequently, each vehicle selects proper slots after four different phases: *initialization*, *network entry*, *first frame*, and *continuous operation*. STDMA attempts to ensure that each vehicle can access the channel regardless of the number of competing nodes. It is demonstrated via simulation that STDMA performs better than CSMA under the periodic vehicle to vehicle broadcasting scenario. Thereafter, CSMA and STDMA in [28] are compared for broadcasting periodic position messages in a realistic highway scenario. The scalability in terms of the number of vehicles that the VANET can support using metrics, such as channel access delay, probability of concurrent transmissions and interference distance, is investigated. It is concluded in [28] that the main difference between the MAC methods CSMA and STDMA occurs where concurrent transmissions take place in space- in CSMA it is randomly distributed whereas in STDMA it is scheduled using the side information from the position messages. Therefore, when the network load in a VANET increases, STDMA becomes more and more attractive compared to CSMA. STDMA may also provide increased reliability due to reduced interference for nodes situated closest to the current transmitters. STDMA provides fairness, predictable channel access delay, and good scalability since all channel requests turn into channel access, which are scheduled far apart in space. However, as indicated in [9] with respect to high vehicular mobility, this renders makes MAC coordination very difficult; hence the performance of STDMA needs further evaluation, especially with regards to the coordination issue.

A solicitation-based IEEE 802.11p operation mode called *WBSS User Initiation Mode* (W-UIM) is proposed in [29] to avoid packet collisions by using a polling scheme, where the WBSS means the WAVE Mode Basic Service Set (WBSS). In W-UIM, a WBSS user solicits data frames destined for itself in an opportunistic manner, by requesting the transmissions of the frames from a WBSS provider by a WAVE-poll frame. Throughput analysis proposed in this paper reveals that W-UIM achieves a stable saturated WBSS throughput which is higher than IEEE 802.11 irrespective of the number of contending and moving-away WBSS users. However, the analysis is only based on a theoretical calculation and is not verified by simulation or realistic experiment. Furthermore, the analysis method is not presented completely and clearly.

V. Present situations and future research directions of 802.11p MAC

In the previous two sections, the evaluations of 802.11p and the enhancements of 802.11p MAC are presented and discussed. In this section, the present situations of 802.11p MAC are summarized and presented based on the previous discussions. And then, the future research directions of 802.11p MAC are identified.

A. *Present situations of 802.11p MAC*

In this section, the present situations of the 802.11p MAC are discussed together with some important metrics, which are indicated as follows:

1. Throughput: Three analytical models have been proposed to analyse the throughput of 802.11p in [10], [11], and [12] respectively. All three of these models are based on Markov Chains. In order to improve the performance of 802.11p in terms of throughput, some enhanced MAC protocols, such as CEA and DEA in [21], the VCAS in [22] and the Detection-Based MAC in [24], have been proposed. VCAS requires that RSU possesses two or more transceivers. DEA and Detection-Based MAC use a similar concept: that the contention window size be adapted according to the network status. The main difference between these two algorithms lies in how to detect the network status. However, the status of the network obtained by these two algorithms has not been very accurate so far.

2. Scheduling: In [13] the effect of time allocations on CCH and SCH in IEEE 802.11p is investigated; the tradeoff between the numbers of users on CCH and SCH is described. In [23] an algorithm is proposed to improve the channel access scheme by adapting the intervals of CCH and SCH. However, the proposed algorithm in [23] cuts off CCH to extend SCH; hence it only improves the service channel utilisation without considering the control channel utilisation.

3. Collisions: In [14], the relation between the traffic flow and the contentions is analysed, it is demonstrated that the number of contention cases increase if traffic flow increases. In [20], it is indicated that 802.11p provides an adequate degree of communication reliability, and that the packet drops do not occur in bursts. It is proven that the Detection-Based MAC proposed in [24] can reduce the collision rate by adapting the contention window size based on the network status detection and the prediction of the competing nodes. In [25], a solution approach to the Coupon Collector's problem is proposed in order to reduce the collisions by suppressing some nodes contending. A solicitation-based IEEE 802.11p operation mode called W-UIM is proposed in [29] in order to avoid packet collisions by using a polling scheme.

4. Latency: In [15], it is concluded that only when the total amount of traffic offered approaches 1000 packets per second, does the delay on the control channel become longer than 100*ms*, which is too high for safety critical applications. In [16], it is indicated that the average value of end-to-end delay for AC3 is 1*s* for 300 nodes, with a total of offered traffic of 3000 packets per second, which is much higher than the maximum delay of 100*ms* for safety critical applications. In [17], 802.11p and WIMAX technologies are compared in a high way scenario and it is concluded that 802.11p is better suited to low traffic loads, where it offers very short latencies even at high vehicle speed.

5. Communication range: In [18], the results derived from the test indicate that communication is possible with low FER or BER at approximately 400*m* with 22*dBm* EIRP. It is also indicated that communication is possible at approximately 1000*m* with the same EIRP of 22*dBm*. In [19], the maximum achievable range is derived from a realistic experiment, which is approximately 700*m* where the frame-success-ratio is continuously larger than 0.25. In [15], it is proven that control channel traffic can be successfully received even at a distance of 2.5*km* in an open air scenario.

B. *Future research directions of 802.11p MAC*

VANETs possess certain characteristics due to the high speed mobility of the vehicle, for example, rapid changes of topology, potentially large-scale, veritable network density and so forth [30]. These characteristics indicate important implications for the design of MAC protocol in VANETs. Based on the characteristics of VANETs and the present situation of the 802.11p MAC protocol, the suggested future research directions of 802.11p MAC are furnished as follows:

1. Throughput improvement: In VANETs many safety messages need to be broadcast among vehicles periodically, while communication between vehicle and RSU is also needed in order to realise intelligent transport control. Hence, high throughput is required in VANETs. Due to the characteristics of VANETs, the network density and the topology of VANETs are not stable. Hence, an intelligent MAC protocol is needed

that can dynamically adapt its parameters based on the network status in order to improve the network throughput. In [21] and [24], certain algorithms have been proposed and further research is needed to improve the network detection algorithms.

2. Scheduling optimisation: The idea of adapting the intervals of CCH and SCH has been proposed in [13] and [23]. The algorithm proposed in [23] can improve the channel utilisation when there are a greater number of services messages and fewer control messages. Due to the variable network density in VANETs, a scheduling optimisation algorithm is needed to adapt the intervals of CCH and SCH, depending on the network status. In addition, the network detection algorithms could also be adapted to detect the network status.

3. Traffic control: It is stated in [14] that the number of contention cases increase if traffic flow increases. Contention incurs collisions, in other words, the number of collisions increases if the traffic flow increases. Hence, traffic control is the key to solve the collision problem in VANETs. Latency is very critical in VANETs due to the short time needed by a critical safety application. It is evident, when comparing the results of [15] and [16], that high traffic leads to longer periods of latency. Hence, traffic control is also the key to reducing latency in VANETs. Consequently, traffic control technology is needed to reduce collisions as well as latency in VANETs.

VI. Conclusions

In this paper, a survey of IEEE 802.11p MAC protocol in vehicular environments is presented. The 802.11p standard has attracted much attention as part of the WAVE protocol in VANETs. The 802.11p MAC protocol is very challenging due to the characteristics of VANETs. In this work, the existing evaluations of 802.11p are first presented and classified and the enhancements of 802.11p MAC are subsequently presented and discussed. Furthermore, the present situations of 802.11p MAC are concluded based on the above-mentioned existing evaluations and enhancements. Finally, three suggested research directions: (i) throughput improvement, (ii) scheduling optimization and (iii) traffic control, are proposed.

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