Survey of Cognitive Radio VANET

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Abstract

Vehicular Ad hoc Networks (VANET) becomes more popular in industry, academia and government. However, Typical VANET is challenged by high speed mobility and insufficient spectrum resources over congested scenarios. To address those serious problems, some articles have introduced Cognitive Radio (CR) technology into VANET and formed CR-VANET. In this article, we propose an overview of CR-VANET by exploring different architectures and features. Moreover, we provide taxonomy of state-of-the-art papers in this emerging field and the key articles are well analyzed respectively. In addition, we illustrate both research and application frameworks of CR-VANET based on our works, and propose some open research issues for inspiring future work.

Keywords: Vehicular Ad-hoc Networks, Cognitive Radio, CR-VANET, Spectrum Sensing, Spectrum Allocation

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1. Introduction

As an essential part of Intelligent Transportation System (ITS), Wireless Access in Vehicular Environment (WAVE) becomes more popular in industry, academia and government, and is expected to be an emerging research field with great prospect. Consisting of GPS and ad-hoc networks technology, WAVE, which mainly includes V2V (Vehicular to Vehicular), V2I (Vehicular to Infrastructure) or V2P (Vehicular to Person), can provide variety of services, such as accessing WLAN or Internet, collecting real time transportation information and broadcasting safety messages, etc.

Applications in Vehicular Ad-Hoc Networks (VANET) can be typically classified to two sets [1]: the safety applications (such as collision alarm, road congestion information, etc.) and non-safety applications (Internet access, E-mails, entertainments, etc.). Obviously, emphasizing on fulfilling recreational demands, non-safety applications require high-quality channel to support big throughputs but compromise more delay for their lower priority. On the contrary, safety applications are sensitive to delay, while they may only consume less throughput and bandwidth. That is to say, a second or a millisecond or a microsecond delay may lead to unthinkable serious results.

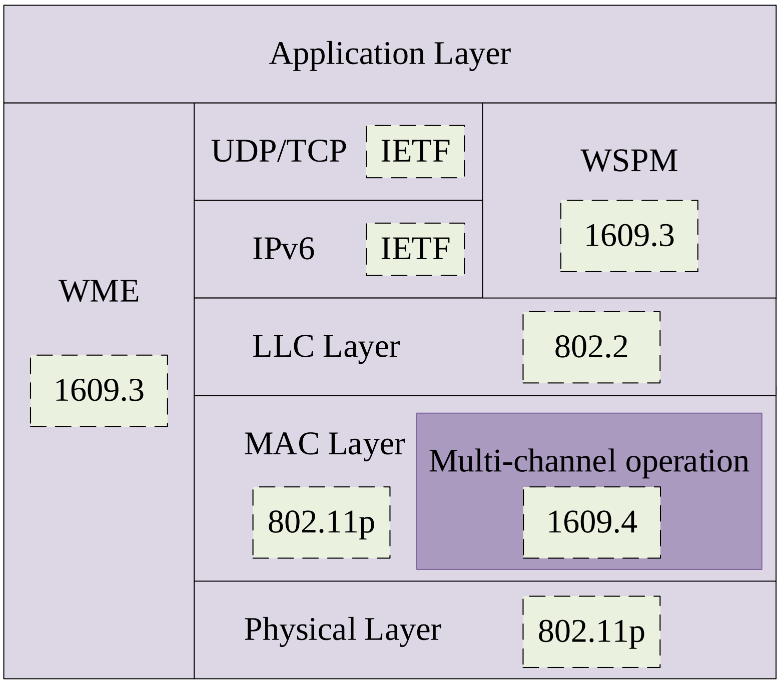

Fig. 1. Protocol Framework of VANET

IEEE 802.11p and IEEE 1609.x protocol family have been widely accepted standards for VANET. The basic protocol framework of VANET is shown in **Fig. 1**. 75 MHz between 5.850-5.925GHz are allocated for dedicated short-range communication (DSRC) by Federal Communications Commission (FCC) in 1999 [2], and inherited to IEEE 802.11p in 2004, which is the first standard to PHY and MAC layer of VANET [3]. Occupying in the 5.9 GHz band, 802.11p inherits many characteristics of 802.11a but revises some essential features to fit vehicular environment. For instance, the sub-channel bandwidth is cut from 20MHz in 802.11a to 10MHz in 802.11p to fight against the channel fading [4]; Enhanced Distributed Channel Allocation (EDCA) is instead of CSMA/CA in MAC protocol to realize priority allocation and minimize delay [5], etc. The upper layers of VANET are standardized by IEEE 1609 protocol family [1][6], in which 1609.4 focuses on multi-channel operation in MAC layer; 1609.3 deals with networking service, which contains issues of network layer and transport layer; 1609.2 addresses security services for applications and management messages. Particularly, 1609.3 defines a WAVE short message protocol (WSMP) dedicating to safety applications, while non-safety applications can transmit via IPV6 and TCP/UDP [6].

Though many valuable results have been addressed, two essential problems of VANET remain unsolved. One is that the high-speed feature and changeable topology of VANET lead to poor channel conditions (multipath fading, Doppler shift, delay, low throughputs, etc.) [8][9]; The other is that the 75MHz bandwidth fails to meet all users' requirements in high users density circumstance [10][11].

Concerning the two challenges, some researchers suggested providing more spectrum resources for VANET. However, it is hard to do because the available frequencies has almost been used up. To solving this dilemma, Cognitive Radio (CR) technology is introduced into VANET and formed CR-VANET [12][13]. Assisted by cognitive radio technology [14], cars in CR-VANET can temporarily employ the unused licensed bands to broaden their bandwidth without interfering licensed users. In many articles, the dedicated licensed band is TV band ranging 470-698MHz [15] or ISM and UNII-3 band ranging 5.725-5.855GHz [16]. Results show that CR-VANET can improve the throughput and support more users in high user density circumstance [12]. Though it remains to be an emerging research field, CR-VANET has already gained many achievements. In this paper, we will summarize state-of-the-art articles and analyze the key results among them.

The rest of this paper is structured as follows: In Section 2 the overview of CR-VANET is presented. In Section 3, important achievements of CR-VANET are summarized and analyzed in physical layer, MAC layer and routing layer, respectively, then a basic research framework of CR-VANET is illustrated. After that, an application framework of CR-VANET is proposed and some open research issues are discussed. Finally, Section 5 concludes the paper.

2. The Overview of CR-VANET

If the allocated 75MHz bandwidth is enough to be used, CR-VANET keeps cognitive mechanism in silence and makes no difference with typical VANET. Otherwise, cognitive radio technology is awoken and some vacant spectrum holes are detected and used to offer the additional capacity. Compared with traditional CR networks, secondary users are quickly moving cars in CR-VANET. This mobility feature influents spectrum sensing and allocation significantly [8][17]. **Table 1** shows the basic comparison of traditional cognitive radio, VANET and CR-VANET, respectively.

Table 1. Basic Comparison of Traditional Cognitive Radio, VANET and CR-VANET

	CR network	**VANET**	**CR-VANET**
Range	~30km	Few kilometers	Few kilometers
Mobility Feature	Stationary	High mobility, can exceed 100km/h	High mobility, can exceed 100km/h

Topology	Centralized	Centralized(V2I) or Ad-hoc(V2V, V2P)	Centralized, ad-hoc, or integration of both
Propagation Environment	Line-of-sight(LOS) Slow time variation	Both LOS and NLOS (Non-Line-of-Sight) Rate of time variation depends on vehicle speed	Both LOS and NLOS Rate of time variation depends on vehicle speed
Performance Indicator	Network throughputs, Delay	Transmission capacity, Delay	Transmission capacity, Delay
Application	Internet access	ITS	ITS

Distinguished from different sensing holders and whether involving centric nodes or not, the architecture of CR-VANET can be classified as three cases shown in **Fig. 2**. In case (a), cars can only apply for spectrum from nearest centric node and wait for its authorization via a control channel. There are two kinds of centric nodes: one is geo-location databases which store vacant band information but never perform sensing [18][15], those vacant band information are updated by spectrum governors; the other is infrastructure Base Stations(BS) which has the ability of both spectrum sensing and allocation [19]. Case (b) illustrates a non-centric architecture of CR-VANET, in which all cars are equipped with cognitive radio devices to perform sensing task themselves. Their sensing results are shared and managed via public control channel among them. This architecture is usually used in V2V and V2P communication system [20][21][22]. Case (c) can be regarded as an integration of case (a) and (b), cars take charge of spectrum sensing like (b), while centric nodes participate in spectrum allocation and management. This architecture is widely involved in V2I communication system [23].

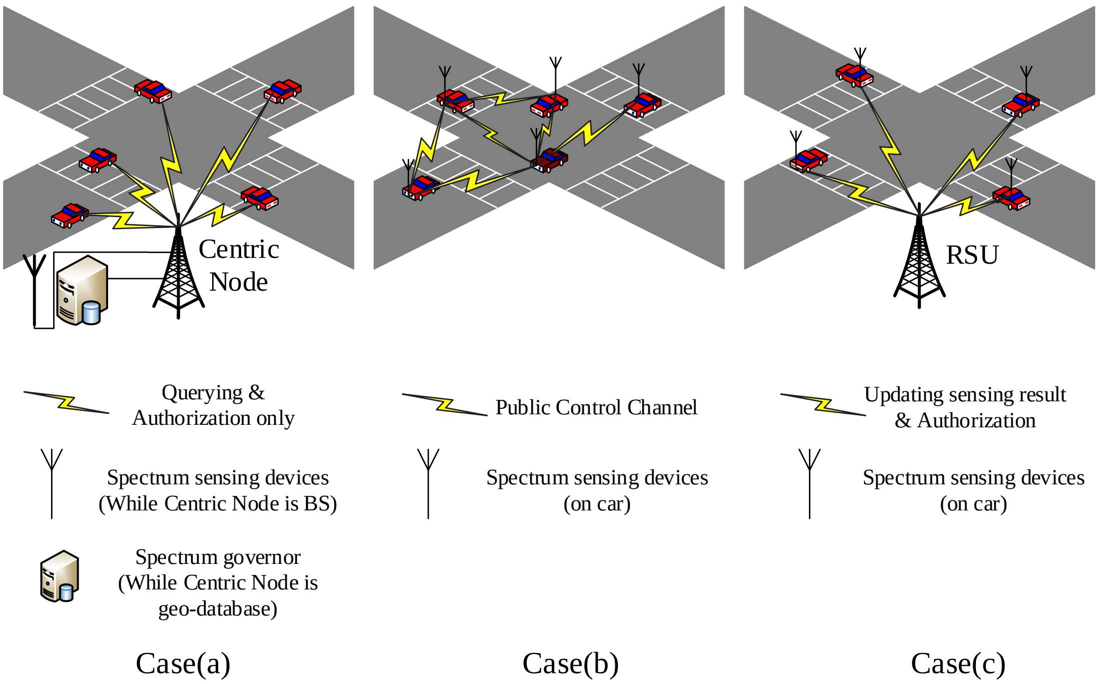

Fig. 2. Three Cases of CR-VANET Architecture

Similar to the traditional computer network, the hierarchy of CR-VANET can be organized as several layers. In Physical layer, CR-VANET inherits almost all VANET techniques such as orthogonal frequency division multiplexing (OFDM), and this layer seriously lacks of researchers' attentions. Data-link layer (mainly is MAC layer) concerns about the frame structure of CR-VANET, which is also the key layer of merging CR technology with VANET. Two prolific research fields in this layer are spectrum sensing and spectrum allocation in vehicular environment. Various sensing solutions, such like centralized sensing and cooperative sensing, are proposed to meet different circumstances [8][15][20][23]. Meanwhile, many researches also consider appropriate spectrum allocation schemes for inter-cell or intra-cell scenarios [24][25][26][27][28]. Appropriate router algorithms concerning with both cognitive mechanism and vehicular environment are expected in CR-VANET's router layer, where few papers focusing on this field [29][30][31][32]. Actually, since many influential issues(variant topology, spectrum sensing, etc) impact multiple layers [21][33], the aforementioned articles usually claim their achievements as a cross-layer design, though they mainly focus on techniques in a particular layer.

Another important issue in CR-VANET is choosing an indicator to evaluate network performance. Different articles choose different indicators depending on their purposes. In articles concerning about spectrum sensing, they usually use detection rate(detection accuracy, miss alarm probability or false alarm probability) or sensing delay as indicators [8][20]. While some articles talking about MAC or router schemes will choose network throughput or delivery rate to be indicators [29][30][31]. To our best knowledge, there is not still a widely accepted indicator in CR-VANET.

Though CR-VANET has attracted full attentions from academia, its standardization works and industries applications still ramain in perlimary states. However, both CR networks and VANET have been srandarized well, the IEEE 802.22 (for CR networks), IEEE 802.11p (for VANET) and IEEE 1609 (for VANET) are best examples of their standards efferts. The protocols comparison of traditional cognitive radio, VANET and CR-VANET are shown in **Table 2**. Since CR-VANET is still under academic research and lacks of dominant protocol designs in every layers, it seems too early to standarize CR-VANET without enough research and experiments. As for the industries, though practical VANET systems has already been a popular topic, CR-VANET is far from been considered. Some companies have annouced "VANET" applications, like the SYNC system developed by Ford and Microsoft, the IOS in car system by Apple, etc. But those applications are not typically VANET applications because they mainly focus on communication between a car and electronic devices in the car, not between cars on the road. The real VANET practical systems are usually launched by national projects. For example, the NOW (Network on Wheels) project [56] and ADASE (Advanced Driver Assistance Systems in Europe) project [57] in Europe; the VSC-A project [58] in US; the "Association of Electronic Technology for Automobile Traffic and Driving" project [59] in Japan, etc. With the trends of VANET becoming more practical, the standarization and practical implement of CR-VANET will also be encouraged and promoted.

Table 2. Protocol Comarison of Traditional Cognitive Radio, VANET and CR-VANET

	CR network	**VANET**	**CR-VANET**
PHY layer	IEEE 802.22[53]	IEEE 802.11p[1]	No dominant agreement based on 802.11p and involving cognitive mechanism.

MAC layer	IEEE 802.22	IEEE 802.11p IEEE 1609.4	Combination of VANET and CR networks protocols, based on 802.11p and involving cognitive mechanism.
Routing layer	No dominant agreement	IEEE 1609.3 WAVE short message protocol (WSMP)	No dominant agreement

3. Existing Research Works of CR-VANET

In this part we provide taxonomy of state-of-the-art papers in CR-VANET and analyze some key articles. Distinguished from their research focuses, they can be classified into physical layer, MAC layer and router layer works.

3.1 Physical Layer Works of CR-VANET

Though few articles concerning about physical layer of CR-VANET, many questions are still unsolved. In physical layer, the works mainly focus on channel model, interference and capacity.

3.1.1 Channel Model of CR-VANET

Because of fast moving, the mobility feature of cars makes the channel model fading seriously, even in the simplest model the distance between communication devices will change quickly and randomly. However, in almost all papers investigated by us, the researchers evaluate their designs or protocols only on the basis of the Rayleigh or Nakagami-m fading channel model. Hence, the future researchers on CR-VANET must treat their vehicle mobility model more carefully. Generally, the random Poisson Point Process [54] in different dimensions can be chosen. The Markov mobility model is also a good choice for grid-like roads [55], while in some unique scenarios, the researchers have to use the special mathematical model.

3.1.2 Interference in CR-VANET

There are two important interference issues should be noticed in CR-VANET: the interference from other networks and the interference to primary user in CR-VANET. The first interference issue has been studied in VANET field and CR field, respectively. However, researchers of VANET seldom treated spectrum as changeable resources, and researchers of CR only involved static users. The second issue is typically a research topic of cognitive radio, however, the achievements in cognitive radio research treat secondary users as static points rather than moveable points. So dedicated interference researches considering both the dynamic spectrum and the mobility feature of CR-VANET is an interesting research topic in future.

3.1.3 Transmission Capacity of CR-VANET

Transmission capacity, which is also called network throughput, is one of the most essential question in physical layer of CR-VANET. There are many forms of the equations of transmission capacity based on different researches [34][35][36]. Generally, a simple equation representing one hop transmission capacity T can be expressed as below:

$$T(\varepsilon) = \lambda(\varepsilon)(1-\varepsilon)R \qquad \varepsilon \in (0,1) \tag{1}$$

where R represents data rates, which is usually normalized to 1 in many articles; λ is the density of the nodes with successfully data transmission; And ε represents outage probability, which is always determined by the signal to interference and noise ratio (SINR). Obviously, both λ and T are the function of ε. Hence, it can be concluded from (1) that one hop transmission capacity is decided by node density, outage probability and data rates. When more hops are considered, the mean of every hop's transmission capacity may be regarded as transmission capacity of the pathway.

3.2 MAC Layer Research of CR-VANET

Researches of CR-VANET MAC layer mainly focus on spectrum sensing and allocation, as shown in **Fig. 3**. According to their sensing architecture, spectrum sensing schemes in CR-VANET can be classified into centralized sensing, distributed sensing and integrated sensing. However, spectrum allocation schemes in CR-VANET are classified by their functions: the inter-cell allocation or intra-cell allocation. A cell in CR-VANET is a two dimension (2D) area with several cars. There must be one road side unit (RSU) in centralized architecture or one primary car in distributed architecture dealing with intra-cell spectrum allocation and management, which is usually called center node or cluster header. Meanwhile, in a network consists of many cells, it is common that some congest cells are lacking of spectrum while their adjacent cells may remain some frequency idle. Consequently, it is also important to find appropriate inter-cell spectrum allocation schemes for CR-VANET.

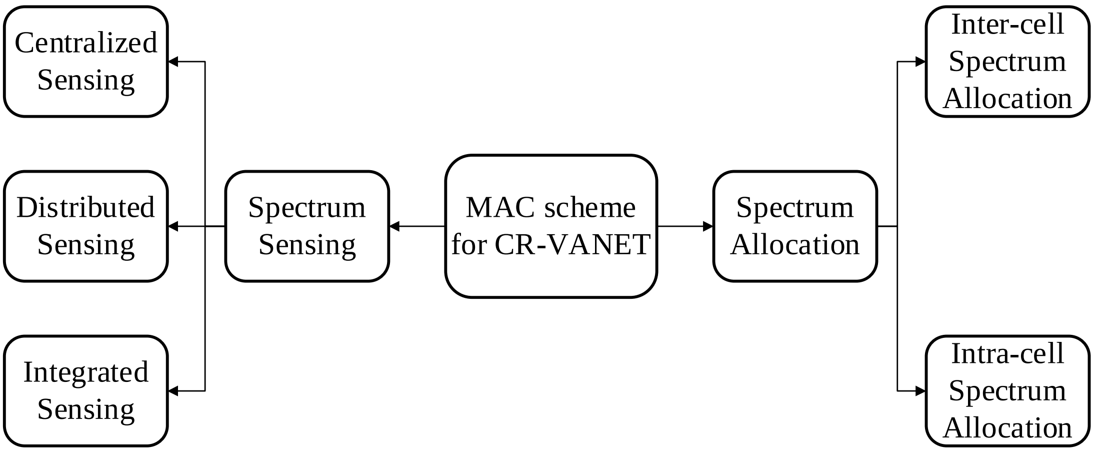

Fig. 3. The Spectrum Sensing and Allocation Works on CR-VANET

3.2.1 Spectrum Sensing Works on CR-VANET

Compared with traditional cognitive radio networks, the spectrum sensing task in CR-VANET almost makes no any difference. Nevertheless, considering the poor channel condition in vehicular environment, it is necessary to choose or create some ideal sensing techniques weakening the impact of mobility. Here some major ways of spectrum sensing in CR networks are presented and discussed whether they can be used in vehicular environment or not.

To be noticed, the spectrum sensing issue is always a cross layer issue. Spectrum sensing not only relates to MAC layer designs, but also involves many physical layer techniques such as signal detections. The reason we discuss spectrum sensing in MAC layer section is that most works of spectrum sensing in CR-VANET focus on different MAC layer protocols rather than new signal sensing techniques. Consequently, in CR-VANET researches, physical layer techniques of spectrum sensing are usually almost the same as those techniques in CR networks.

(1) Spectrum sensing methods in CR-VANET

Since spectrum sensing has been fully studied in CR systems, few articles focus on the new sensing methods. In [37], Yucek et al. introduce some common methods of spectrum sensing, like matched filter, energy detector, cyclo-stationary sensing, waveform-based sensing etc. Theoretically, all methods mentioned above can be implemented in CR-VANET, but the mobility feature of vehicular environment would limit their performance to different extents.

Different spectrum sensing architecture (Centralized sensing or distributed sensing) also demands different sensing methods. For example, marched filter is always adopted in centralized sensing architecture, because Centric Nodes (CN) can afford complex devices and higher accuracy sensing can compensate for the case with lower density sensing units. Meanwhile, energy detector can be supported by distributed sensing architecture for its simplicity and cooperative sensing technique will offset its inferior accuracy. So choosing desirable sensing methods is a process of compromise and trade-off. In addition, related works concerning spectrum sensing, to our best knowledge, usually based on static ad hoc network (traditional cognitive radio network). Future research need to pay more attention on the impact of secondary users' mobility [21].

(2) Spectrum sensing architecture in CR-VANET

Sensing technology in CR-VANET can be classified as 3 architectures: centralized, distributed and integrated sensing architecture.

A. Centralized sensing architecture

The essential part of this architecture is the Centric Nodes (CN) restoring vacant band information or sensing results. When a car applies to nearest CN for spectrum resources, CN checks its database and authorizes the car to occupy one vacant band. There are two kinds of CN: the widely implemented one in US and UK is called geo-databases [38][39][15], which are purely databases without sensing function; the other is usually called base stations which can perform spectrum sensing [19]. Results shows that geo-databases can achieve higher utilization of TV white spectrum resources than sensing-only techniques [40], so most centralized sensing architecture is based on gro-databases' solution, though it lacks of spectrum sensing. The advantage of centralized sensing architecture is that cars are free of the sensing task, and more complex sensing methods such as marched filter can be implemented to improve sensing accuracy. However, some inevitable drawback still remains.

Firstly, the whole system relies on the accuracy location of cars, which can be obtained by GPS or cellular system. In [8], H. Kremo et al. have proved that the position information is not accuracy enough, and they need a specific high-quality channel for position transmitting, which increases the complexity. Secondly, centralized architecture needs a control channel supporting interaction between CN and cars. While in some extreme case, there is no spectrum resource to build it. The last weakness, which also counts most, is delay. Both querying database and authorization require time. Meanwhile high density of cars can cause unbearable query number to database, which results in delay too. As a time variant networks, such serious delay is intolerable.

B. Distributed sensing architecture

In distributed sensing architecture, each car firstly does the spectrum sensing itself [41]. As aforementioned, the accuracy of this method is not good. To address this issue, cooperative sensing techniques is adopted in almost all articles. Hence, it is also called cooperative sensing architecture. In cooperative sensing scheme, all cars can exchange their sensing results through one or some public control channels, which is static or allocated by some primary cars [33]. Combining many cars' results, it is possible to achieve enough sensing accuracy through particular algorithms. Compared with centralized sensing architecture, distributed one requires simpler devices (databases or base stations vs on-car sensing devices) but provides almost same accuracy through cooperative sensing technique. Moreover, cooperative sensing can build public control channels using sensed spectrum resources rather than occupying VANET channels.

In [8], the author discusses the utilization of time diversity technology in cooperative sensing. The literature firstly assumes a shortest sensing interval without interrupting PU, this interval is divided into several time slots and during every slot cars have enough time to sense and transmit at least one frame. This assumption may hold on when the car is equipped with the fast sensing methods such as energy detector. Since cars can sense several times during a sensing interval, time diversity mechanism requires one car perform sensing in every slot but remain transmitting data in same channel until the whole interval passed. At the beginning of the next interval, those sensing results gathered from the last interval can be used to choose a new channel for transmission. This inspiring technique allows cars in low density environment can still perform cooperative sensing by themselves.

As a derivation of cooperative sensing, Li et al introduce the belief propagation technology in [20], each car periodically builds a belief vector representing the probability of PU's presence and broadcasts it respectively. After that, each car combines other cars' belief vectors and its own sensing results to generate a new belief vector, then broadcast the new one. This cyclical process stops when it falls into steady state. Results show that cooperative sensing accuracy is enhanced through belief propagation. However, this paper remains in primary states and the converging time of such cyclical process needs more studies.

C. Integrated Sensing Architecture

Inspired by [42], Di Felice et al. presents a integrated sensing structure combining cooperative sensing and database lookup technology [23]. In this architecture, cars are classified into 3 sets, Model I cars communicate with databases directly, Model II cars leverages Model I cars to query databases, while Sensing-only cars can only sense TV white spectrum themselves. By determining optimal ratio of 3 kinds of cars, the goal of this article is to guarantee maximum protection of licensed users while minimizing the overhead for white space detection of TV spectrum. **Table 3** shows the comparison of three spectrum sensing architectures.

Table 3. Comparison of Three Spectrum Sensing Architecture

Architecture	Reference	Pros	Cons
Centralized	[15][19][38][39]	Using more accurate sensing methods, Combining with geo-database to improve accuracy	Need dedicate control channel, Delay issue
Distributed	[20][33][41]	Using cheap sensing device to achieve enough accuracy, Don't need dedicate control channel	Network complexity is higher(mobile ad hoc network)
Integrated	[23][42]	Highest accuracy achieved by combination of above two sensing ways	Most complex network and high devices costs

3.2.2 Spectrum Allocation in CR-VANET

Once the spectrum holes are known, correctly allocating and appropriately using the spectrum has a multifold impact. Although spectrum allocation schemes for cognitive radio have been studied for years, those results cannot be directly applied to CR-VANET because secondary users are common supposed stationary in those works while they (cars) are quickly move in vehicular environment. So the spectrum allocation is more challenging and complex in CR-VANET. In this section we introduce some methods which can be classified as inter-cell spectrum allocation and intra-cell spectrum allocation.

(1) Inter-cell spectrum allocation

In the traffic jams cognitive cell, the transmission of a large amount of collision avoidance and auxiliary driving information will lead to a sharp increase in demand of spectrum resources. However, in the adjacent cell, the traffic load may be light and the spectrum may be residual. So the real-time and efficient spectrum methods for inter-cell spectrum allocation are studied in [24][25][26].

A. Non-cooperative game theory

Game theory is widely utilized as an efficient tool for analyzing the spectrum allocation problem in wireless networks. The non-cooperative game theory has been studied in [24] for inter-cell resource allocation. A method to assign the sub-channels and power to the uplink users is proposed to minimize the transmission power. In [25], Nash Bargaining solution (NBS) is studied in the scenario of power, rate, and sub-channel allocation for single-cell OFDMA systems to obtain a fair and efficient performance.

B. Cooperative bargaining solution

As we are known, the cooperative bargaining solutions have seldom been used to the inter-cell resource allocation especially in cognitive radio networks. In [26], two alternative bargaining solutions, such as Generalized Nash Bargaining Solution (GNBS) and Generalized Raiffa-Kalai-Smorodinsky Bargaining Solution (GRKSBS), are proposed to model the inter-cell allocation problem. For asymmetric cells with different bandwidth requirements, these solutions are generalized with bargaining powers to achieve trade-off between the weighted fairness and overall achievable rate. Furthermore, a practical two-cell allocation algorithm is proposed for three cases with different traffic loads. **Table 4** shows the comparison of inter-cell spectrum allocation techniques for CR-VAENT.

Table 4. Comparison of Spectrum Allocation Techniques for CR-VANET

Technique	Reference	Pros	Cons
Non-cooperative game theory	[24],[25]	Minimize transmission power of the cognitive users	The scheme is only suitable for two load states
Cooperative bargaining solution	[26]	Achieve trade-off between the weighted fairness and overall rate, and the QoS support of safety application is considered	The allocation scheme is more complexity

(2) Intra-cell spectrum allocation

When the intra-cell road side unit or cluster head obtains the sensed states of all shared-use spectra, the appropriate decision on spectrum allocation management is needed. Due to the dynamic spectrum sharing of CR, spectrum allocation in CR-VANET becomes more complicated. The time-varying, location-dependent spectrum availability and Quality of Service (QoS) support of safety service should be considered.

A. Spectrum allocation with PU protection alone

In [43], without taking into account the specific QoS requirements of the vehicular applications, the CR-VANET decides the spectrum to use with the goal of minimizing the harmful interference to primary users. In this paper a rang of metrics for spectrum selection by CR-VANET are defined and evaluated through a simulation study, such as spectrum with the highest data rate, product of rate and channel utilization, and product of rate and expected vacant channel duration.

B. Spectrum allocation with QoS support

For this respect, spectrum allocation is used to meet the QoS requirements of vehicular application, such as delay constraints for safety application and bandwidth for service application. To maximize the throughput of secondary users by using the technique of Lyapunov optimization, in [27], Urgaonkar R. et al. exploit a Markov random walk model of secondary users and proposes an opportunistic scheduling policy for secondary networks. With the assumption that the channel availability statistics information are known for vehicles, in [44], Giordano et al. investigates the optimal channel access in CR-VANET to maximize the utility of vehicles under certain QoS constraints. In [28], a framework with three components is proposed to meet the QoS. The problem of optimal channel access management is formulated as a constrained Markov decision process (CMDP).Once the cluster head obtains the sensed states of all shared-use channels, the decision on channel access can be made. Next, this decision as well as the information of exclusive-use channel is sent to the cluster member during the handshaking period. Then the cluster member transmits data using the shared-use channel or the exclusive-use channel. This data transmission period is divided into two parts, transmission from cluster member to cluster head and transmission from cluster head to destination.

3.2.3 MAC Protocol in CR-VANET

CR-VANET has the characteristics of high mobility and rapid dynamic topology, and the latency and reliability for the traffic safety and non-safety services are different. Therefore, designing a suitable MAC protocol for CR-VANET turns to be a challengeable task. According to our research, there is still no dominant design of CR-VANET MAC protocol.

However, in order to give a general view of CR-VANET's MAC layer, we summarize some essential articles and present a preliminary design of CR-VANET MAC protocol. With the characteristic of VANET system, the design of slot structure of CR-VANET system is generally shown in **Fig. 4**.

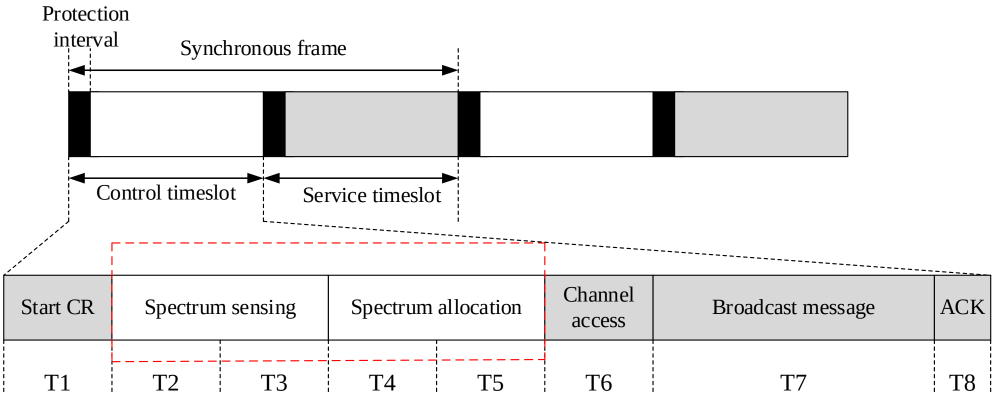

Fig. 4. Slot Structure of CR-VANTE

3.3 Routing Schemes in CR-VANET

Routing in CR-VANET faces unique challenges, compared with conventional mobile ad hoc networks (MANETs). In MANETs, the routing protocols are expected to adapt to node mobility and channel dynamics [45][46] . While in CR-VANET, in spite of that, routes should be more quickly modified according to the activity of primary users and frequency in the spectrum pool. There have been several routing protocols for CR networks [47][48][45] etc. However, they do not consider mobility at vehicular speeds. In most of these protocols, the route is established during the route discovery phase and it can be changed when messages are dropped or new PU activity is detected. Such an approach suffers significant performance degradation when spectrum availability or node locations change faster than the rate of route updates. Several routing protocols for vehicular ad hoc networks have been proposed [49][50]. However, most of them have focused on short-range car-to-car ad hoc communications to aid intelligent transportation systems (ITS) in urban areas. The distance between two nodes is much shorter than transmission range. Moreover, none of them considered the opportunistic spectrum access unlicensed ISM band to acquire more capacity. At present, the research on routing protocols for CR-VANET are really rare.

(1) Prediction-based cognitive topology control routing

In [29], the author proposes a distributed prediction-based cognitive topology control (PCTC) scheme to introduce the cognition capability to routing in CR-VANET. PCTC is a middle-ware-like cross-layer module residing. It uses cognitive link availability prediction, which is aware of the interference to primary users and predicts the available duration of links. Based on the link prediction, PCTC captures the dynamic changes of the topology and constructs an efficient and reliable topology, which is aimed at mitigating rerouting frequency and improving end-to-end network performance such as throughput and delay.

(2) Spectrum-aware beacon-less geographical routing

A spectrum-aware beacon-less geographical (SABE) routing protocol for CR-VANET is proposed in [30]. The main idea of SABE is that the routing decision as well as the resource allocation strategy is made by receivers on a per-packet and per-hop basis, so that the proposed protocol can efficiently adapt to spectrum dynamic. A source CRV broadcasts a forward request packet, and includes in its available resources and location. Receivers calculate a link weight with consideration of their available resources and locations. In the proposed protocol, CR-VANET jointly selects relay nodes, channels, and transmission power constraints. This selection process is carefully executed so that ongoing communications between primary users and other CR-VANET are not disrupted. Once the relay nodes are selected, they continue to relay more messages as long as they stay in a predefined forwarding area. By doing so, the overhead for selecting relay nodes can be substantially reduced.

(3) Cognitive multicast using OFDM sub-carriers and network coding

Cognitive multicast (CoCast) is a cognitive multicast routing protocol inspired by on-demand multicast routing protocol [31]. CoCast attempts to provide adequate throughput performance by selecting and using idle ISM channels. After discovering the channels, nodes collaborate to form a multicast tree using an ad hoc on-demand distance vector (AODV). In the original CoCast, it is assumed that the channels are orthogonal. In [32], this assumption is relaxed by allowing channels to overlap, as done in IEEE802.11a/g, in which OFDM is used to mitigate Adjacent Channel Interference (ACI) effect and narrowband interference, and the network coding is used to reduce duplicate packet reception and relax the need of packet retransmission.

Based on above studies, we can know that routing in CR-VANET should have some unique characteristics such as PU interference awareness, Link-availability prediction and adaptive ability etc. The authors introduce the routing metrics in light of the overhead for selecting nodes, end-to-end delay, and rerouting frequency. For instance, the simultaneous transmit and receive (STAR) capacity in [30] enables a transceiver to transmit and receive over different channels simultaneously. Thus, the CR-VANET can opportunistically exploit multiple spectrum holes using only a single transceiver radio. However, in [29], the system has two radios (one for receiving and the other for transmitting), so the overhead will be higher than [30]. The comparative description of the characteristics of each routing protocol is shown in **Table 5**.

Table 5. Comparison among Different Routing Protocols

Technique	Reference	Pros	Cons
PCTC	[29]	More efficient and reliable topology than other; low rerouting frequency and delay.	PCTC requires local connectivity knowledge result in large message overhead.
SABE	[30]	The overhead for selecting relay nodes is substantially reduced.	The robustness of proposed algorithm should be improved.
CoCast	[31][32]	More robust to ACI and frequency selective fading; avoid external interference effectively especially in the channels overlap in frequency.	Two radios are needed, so the overhead for communication might be an issue.

3.4 Research Framework of CR-VANET

By exploring different features of different layers, a research framework of CR-VANET is proposed, as shown in **Fig. 5**. From **Fig. 5**, some serious problems caused by vehicular environment, like multipath fading, Doppler shift and short link maintaining time, will not only influent physical layer but challenge each layer of CR-VANET. The dynamic spectrum involved by cognitive radio shall also be considered in whole network design. The essential parts of CR-VANET research are recommended as 1)improving link maintenance and reliability in physical layer, 2)establishing appropriate MAC schemes, 3)designing low-delay routing protocol in router layer and 4)creating various applications in upper layers. The delay and transmission capacity of CR-VANET are main indicators of one research's performance.

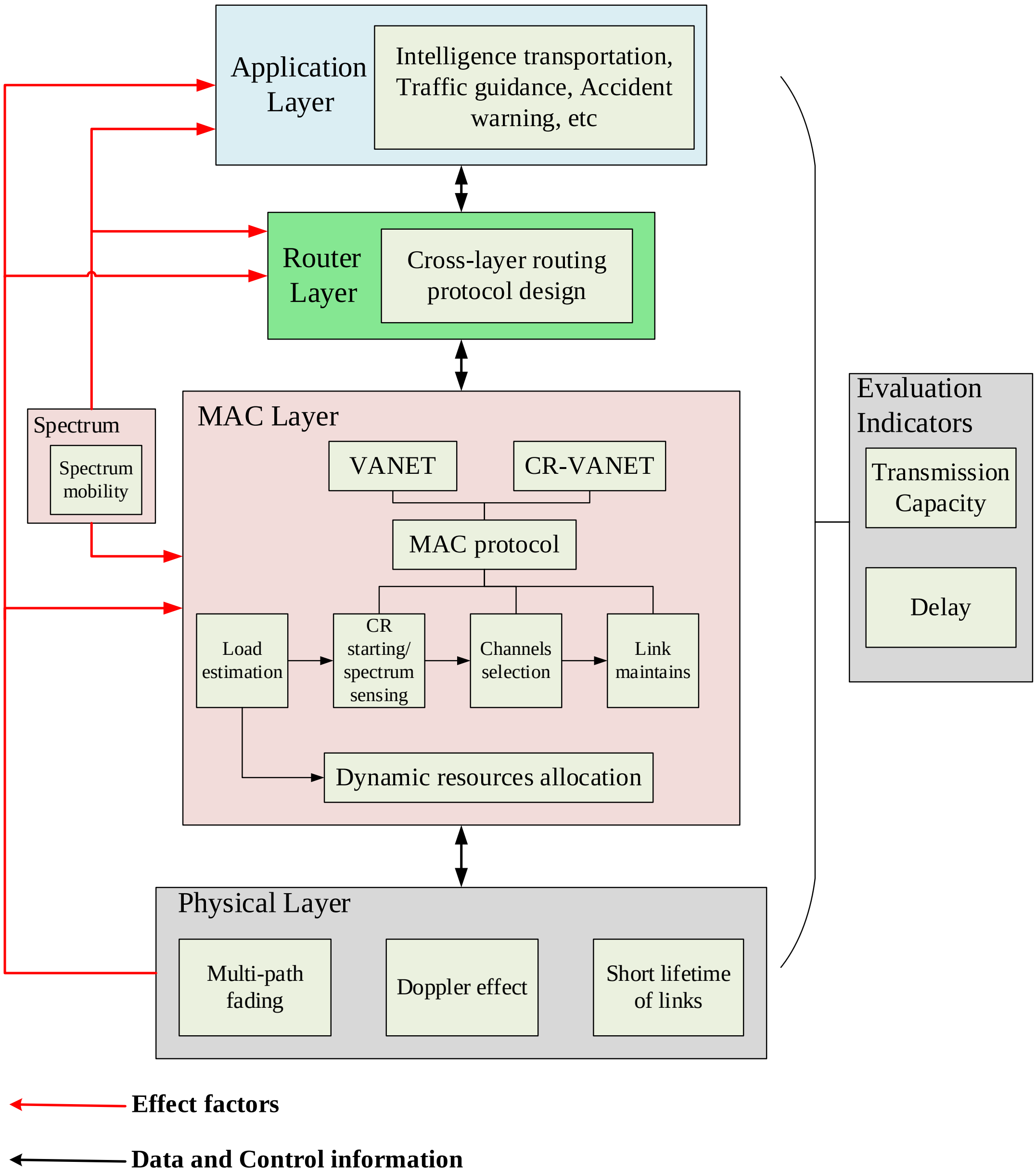

Fig. 5. Research Framework of CR-VANET

3.5 Proposed System and Simulation Results of CR-VANET

3.5.1 The Proposed CR-VANET Architecture

In order to evaluate the performance of the CR-VANET, we investigate a centralized CR-VANET architecture composed of three entities, i.e., the vehicle equipped with CR (CRV), the road side unit (RSU) based on CR (CR-RSU) and local information processing unit (LIPU) [60]. In general, we suppose the whole network can be divided into different cognitive subsystems each with several cognitive cells (CCs). As shown in **Fig. 6**, the system works as follows: Firstly, the CRVs take the task of local load estimation and spectrum sensing, and then periodically report related results to the corresponding CR- RSU. Then, the CR-RSU is responsible for data fusion and resource allocation in a single cognitive cell. Finally, LIPU will calculate and predict the network load metric of the subsystem and then decide when to trigger the adaptive cognitive spectrum sensing (ACSS) mechanism. In addition, LIPU is also in charge of inter-cell resource allocation with cooperative game theory and maintaining the cognitive spectrum pool.

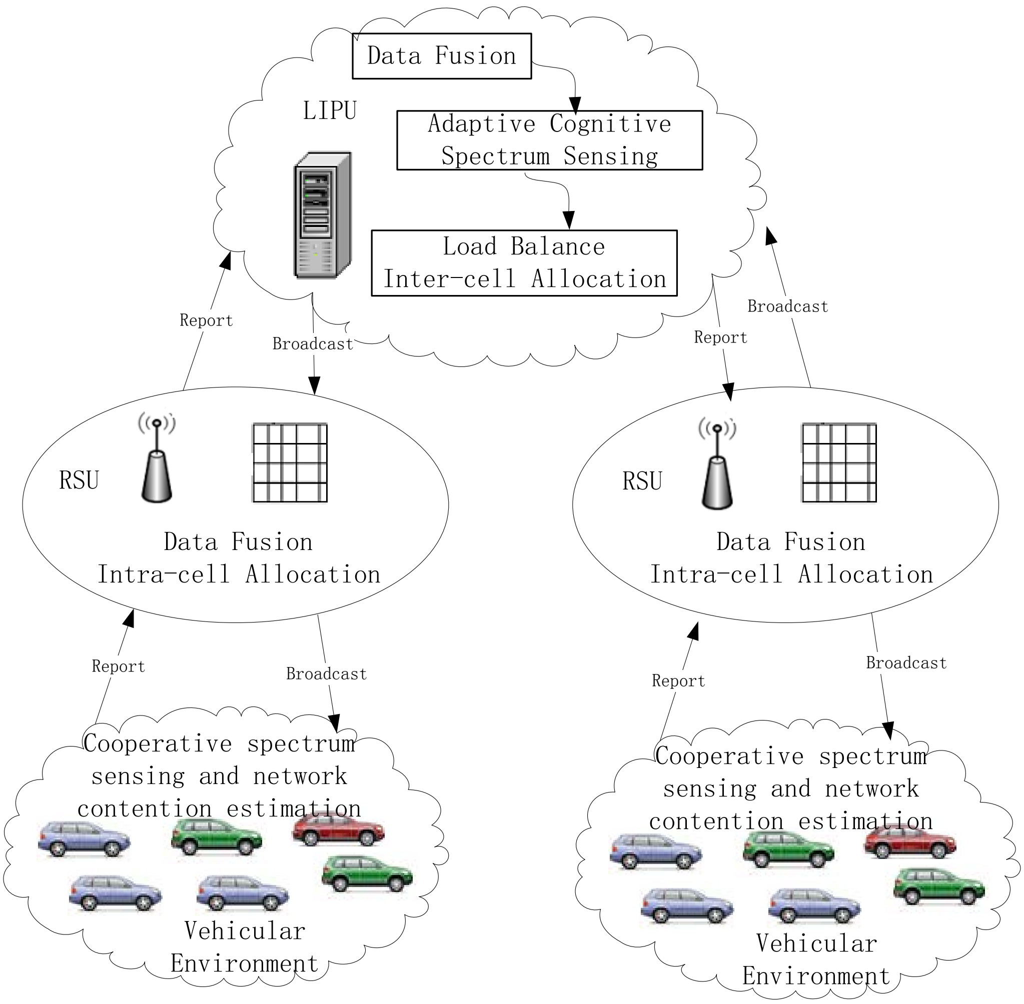

Fig. 6. Framework of the Proposed CR-VANET

3.5.2 Simulation Results for CR-VANET

We consider the following scenario where the initial static spectrum bandwidth is 10MHz, and 50 CR vehicles are distributed randomly in a cognitive cell with width of 500m. Once the cognitive radio starts, additional bandwidth will be detected and used to extend the communication spectrum pool and improve the QoS of vehicular applications. The bandwidth of the cognitive spectrum is set as 100MHz and 200MHz. The probability of PU access to arbitrary spectrum is modeled as a uniform distribution between 0.8 and 1. Assume only safety service is supported in this scenario, and set the delay thresholds as 100ms. With the simulator NS2, the transmitting packet rate is set as100packets/s, and the payload of each packet is 1024 bytes. The channel contention is varied by the number of CRVs requesting for service which is increasing by the speed of 6 pairs/min.

Fig. 7 to **Fig. 9** shows the delay, packet loss rate and throughput performance between CR-VANET (labeled with ACSS) and traditional VANET, respectively. It can be observed from **Fig. 7** and **Fig. 8** that VANET with CR function can greatly reduce the transmission delay, especially on the heavy contention status. Moreover, the wider cognitive pool is, the more additional spectrum can be sensed to extend the communication bandwidth and improve the QoS of safety applications. In **Fig. 9**, it is obvious that the throughput of CR-VANST scheme can be improved to some extent, when the network load status is heavy. However, the whole throughput will be decreasing when more and more vehicles are competing for the limited additional spectrum. Thus, the CR-VANET can make great effect and get better throughput performance than traditional VANET.

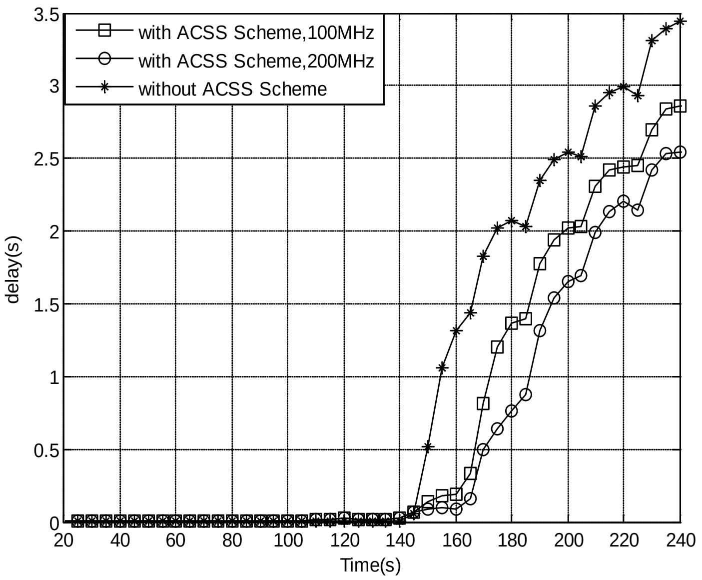

Fig. 7. Transmission Delay between CR-VANET and Traditional VANET

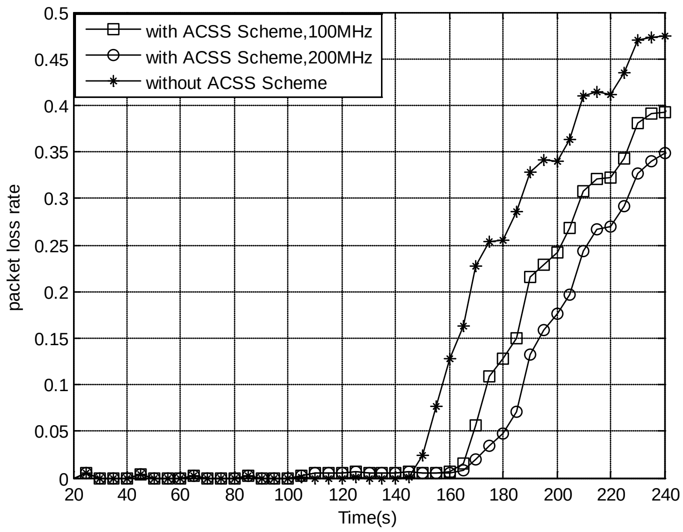

Fig. 8. Packet Loss Rate between CC-VANET and Traditional VANET

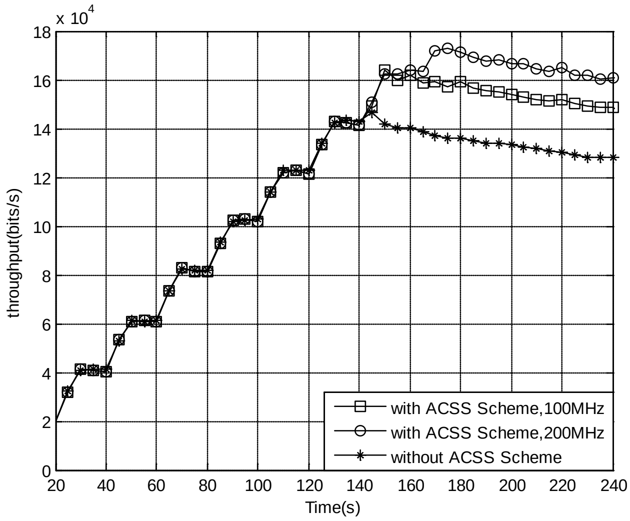

Fig. 9. Throughput between CC-VANET and Traditional VANET

4. Application Framework of CR-VANET & Open Research Issues

CR-VANET has been researched for years and gained many achievements as aforementioned. In this part, application framework of CR-VANET is firstly discussed. Then, some open research issues are suggested.

4.1 Application Framework of CR-VANET

Intelligent transportation system is a huge system applied to the entire traffic management system. Application framework of CR-VANET is composed of three parts: information transmission network (ITN), ground transportation applications (GTA) and other information and application platform (INP). Information transmission network provides technical support for V2V and V2I communications, and connects to the internet or mobile communication networks to realize the information interaction between vehicle networks with different departments and services platform. Now, we take the traffic accidents and traffic jams as example to explain the behavior of CR-VANET, and give its applications in traffic safety.

(1) Application prospects 1: accident and collision warning

As shown in Section 1, when vehicles crashed, the safety messages should be broadcasted quickly by CR-VANET system.

Case1: If the network has enough spectrum resources, then CR-VANET

- ➢ Broadcasts safety messages to surrounding cars with high efficiency and low delay.
- ➢ Broadcasts warning information to remote vehicles and suggests them navigate other paths in time.
- ➢ Reports information to the traffic manage center who will promptly dispatch the corresponding staff to deal with related matters.

Case2: If the vehicle network congests, the more spectra are needed, and then CR-VANET starts cognitive mechanism to explore spectrum holes. After that, CR-VANET completes those processes in case 1 with the updated spectrum resources.

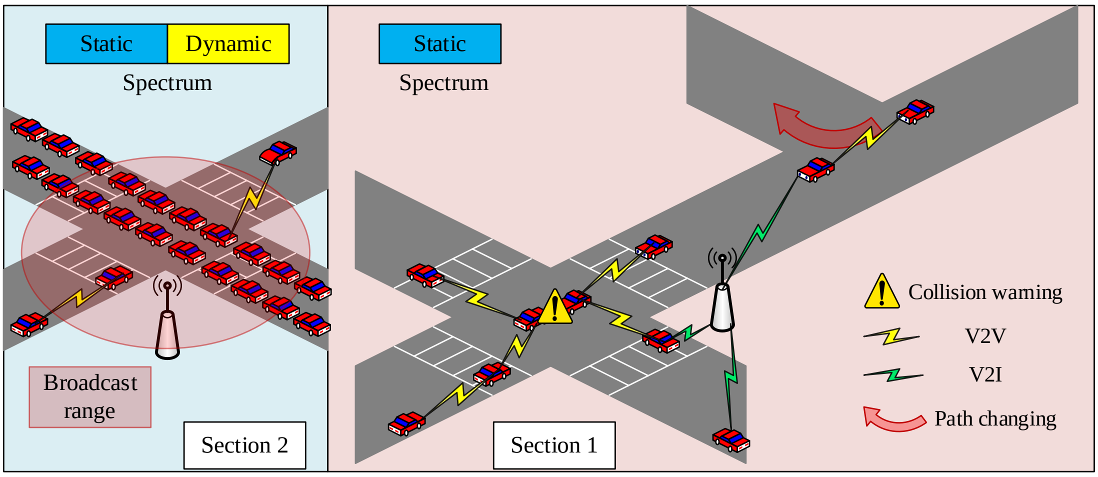

Fig. 10. Application Framework of CR-VANET

(2) Application prospects 2: traffic congestion and guidance

When congestion occurs on Section 2 as shown in **Fig. 10**. CR-VANET needs more spectrum resources to support all cars' demands. At this time, CR-VANET starts cognitive mechanism immediately to sense more vacant bands. After that, CR-VANET

- ➢ Broadcasts the information of congestion to the vehicles in their peripheral area and suggest them avoid congestion.
- ➢ Reports information to traffic management center.
- ➢ Transmits congestion information by all possible kinds of platforms to public, such as live maps, SMS, etc.

Meanwhile, considering the priority of security services, the system uses resource allocation techniques to optimize spectrum scheduling and management. The design of CR-VANET application framework is still in preliminary level and more works should be done in future.

4.2 Open research issues

As aforementioned in section 3, improving network performance through physical layer technology would achieve little. However, some article have proved cooperative communication technology can realize higher channel reliability [51][52], introducing cooperative communication into CR-VANET may leads an innovation in physical layer. Another potential breakpoint in this field is deducing the transmission capacity for CR-VANET, this work will provide a more universal indicator presenting network capacity of CR-VANET.

Establishing appropriate MAC schemes, especially desirable sensing schemes for vehicle environment is a hot topic in CR-VANET research. Some essential problems are still unsolved such as: To what extend does mobility parameters (high speed, changeable topology, etc.) impact on sensing accuracy? What is the optimal scheme balances all trade-offs in CR-VANET's MAC design? All those issues shall be paid more attentions in future research.

Various trade-offs exist in spectrum sensing process as we discussed in 3.2.1 section. In fact, classical cooperative sensing structure can be regarded as "spatial diversity", because it collects sensing results of cars in different positions to get an accurate result. If this "special diversity" combines with "time diversity" mentioned in [8], the sensing results may be more accurate. However, implementing both diversity techniques leads to more delay, how to balance accuracy and delay would be an interesting issue.

Although dynamical resource allocation according to the number and needs of inter-cell users are discussed in some resource allocation algorithms for CR-VANET, the model is only suitable for two adjacent cognitive cells. Hence, work for more cells is needed in the future. Furthermore, considering the complexity, a flexible and effective algorithm to satisfy the real-time requirements of the VANET is also expected.

Cross layer design is another issue to be addressed. Combining some factors of PHY layers such as multi-path fading, Doppler effects, wireless interference, high-quality channels are selected for cross-layer routing to increase its robustness. As we all known, network throughput depends on not only the resource allocation and access algorithm, but also the outage probability of the communication between vehicles. Consequently, network capacity with the outage probability need to be deduced. Additionally, there are still some open questions needed to be further discussed, such as problems of the exposed and hidden terminal, security transmission, private information protection, big data mining for traffic, and so on.

5. Conclusion

In this article, an overview of CR-VANET was presented, the state-of-the-art articles in this field were classified and some key achievements were analyzed respectively. Both the research and application frameworks of CR-VANET were illustrated. In addition, some open research issues were proposed and discussed which might be a good reference for other researchers.

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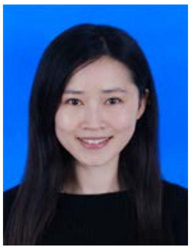

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