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Cognitive radio network in vehicular ad hoc network (VANET): A survey

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Abstract: Cognitive radio network and vehicular ad hoc network (VANET) are recent emerging concepts in wireless networking. Cognitive radio network obtains knowledge of its operational geographical environment to manage sharing of spectrum between primary and secondary users, while VANET shares emergency safety messages among vehicles to ensure safety of users on the road. Cognitive radio network is employed in VANET to ensure the efficient use of spectrum, as well as to support VANET's deployment. Random increase and decrease of spectrum users, unpredictable nature of VANET, high mobility, varying interference, security, packet scheduling, and priority assignment are the challenges encountered in a typical cognitive VANET environment. This paper provides survey and critical analysis on different challenges of cognitive radio VANET, with discussion on the open issues, challenges, and performance metrics for different cognitive radio VANET applications.

Subjects: Algorithms & Complexity; Computer Science; Computer Science (General); Information & Communication Technology (ICT); Systems & Computer Architecture; Systems & Control Engineering; Technology; Transport & Vehicle Engineering

Keywords: cognitive radio network; vehicular ad hoc network (VANET); ad hoc networks; intelligent transportation system (ITS); inter-vehicle communication (IVC)

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PUBLIC INTEREST STATEMENT

Cognitive radio network and vehicular ad hoc network (VANET) are recent emerging concepts in wireless networking. Cognitive radio network obtains knowledge of its operational geographical environment to manage sharing of spectrum between primary and secondary users, while VANET shares emergency safety messages among vehicles to ensure safety of users on the road. Cognitive radio network is employed in VANET to ensure the efficient use of spectrum, as well as to support VANET's deployment. Random increase and decrease of spectrum users, unpredictable nature of VANET, high mobility, varying interference, security, packet scheduling, and priority assignment are the challenges encountered in a typical cognitive VANET environment. This paper provides survey and critical analysis on different challenges of cognitive radio VANET, with discussion on the open issues, challenges, and performance metrics for different cognitive radio VANET applications.

1. Introduction

Cognitive radio network emerged as the key solution to solve scarcity in spectrum. The primary idea of cognitive radio network is to allow usage of the licensed (primary) users and the unlicensed (secondary) users to share the same bandwidth without causing harmful interference. A cognitive radio device must intelligently detect the availability of spectrum and assign suitable users to occupy the spectrum bandwidth without causing interference to the authorized users (Gonzalez, Picone, & Colabrese, 2012). Cognitive radio (CR) technology is capable of making corresponding changes in certain operating parameters and adapt to its internal states by sensing its surrounding environment (Richard Yu, 2011). Cognitive radio was first proposed by Mitola and Maguire (1999) where a Radio Knowledge Representation Language with cognitive radio was proposed to actively manipulate protocol stack in order to adapt and satisfy user needs efficiently. This transforms radio nodes from being blind executors of predefined protocols into intelligent radio domain agents that actively deliver services with the realization of CR.

There are a few challenges in implementing efficient cognitive radio vehicular ad hoc network (VANET). Cognitive radio networks are motivated by studies such as Islam et al. (2008) and Datla, Wyglinski, and Minden (2009) which revealed that a large percentage of the licensed spectrum still experience lack of utilization. Issues such as common control channel, joint spectrum sensing, and cognitive implementation architecture are the open issues highlighted for cognitive radio network development work in Liang, Chen, Li, and Mähönen (2008).

On the other hand, VANET is an emerging technology which addresses issues which concern with car-to-car communication. VANET utilizes ad hoc multi-hop communication among cars with diverse mobility patterns. Vehicle-to-Infrastructure network which can also be referred to as Vehicle-to-Roadside network utilizes statically deployed Access Points or Base Stations to connect moving cars (Xu, Garrison, & Wang, 2011). The main purpose of VANET is to ensure safety on the roads. In addition to safety applications, VANET also allows users to enjoy comfort applications, such as web browsing and multimedia data downloading (Sou, Shieh, & Lee, 2011). Standards for VANET such as The Institute of Electrical and Electronics Engineers (IEEE) P1609 Wireless Access Vehicular Environment, Dedicated Short Range Communication, and IEEE 802.11p have been developed to accommodate to VANET's requirements (Wang et al., 2012).

With the growing demand for VANETs, cognitive radio network seems to be a promising solution to solve spectrum scarcity. The main challenges for cognitive radio network with VANET are to deal with high mobile nodes under dynamic channel conditions while providing fair spectrum share among nodes. In addition, varying and unpredictable nature of VANET, scheduling efficiency, security, priority assignment, and high nodes mobility are main challenges in ensuring a deployable VANET.

Framework such as Di Felice, Chowdhury, and Bononi's (2010) which allows spectrum sharing opportunities for Inter Vehicle Communication (IVC) with the use of cooperative sensing, spectrum allocation, and cooperation process is influential to promote robust primary user detection under fading conditions (Barrachina et al., 2012; Maslekar, Mouzna, Boussedjra, & Labiod, 2012).

The main contributions of this work are as follows: firstly, the overview of the advanced cognitive radio network and VANET is discussed. Secondly, the challenges and approaches toward designing cognitive radio VANET are explored. Thirdly, the open issues and research directions of cognitive radio VANET are discussed. Fourthly, the performance metrics for different cognitive radio VANET applications are analyzed.

The outline of the rest of the article is as follows. In Section 2, we discuss the overview of the current advancements of cognitive radio network and VANET. Section 3 focuses on the challenges and approaches in designing cognitive radio network in VANET. The open issues and research directions

of cognitive radio VANET are discussed in Section 4. The performance metrics for different applications is discussed in Section 5. Finally, Section 6 concludes the paper.

2. Overview of advanced cognitive radio network and VANET

In order to solve spectrum starvation in VANET, cognitive radio network is a promising solution toward achieving dynamically accessed available radio spectrum in an opportunistic manner. Motivated by the above observations, this section introduces the main issues and challenges dealt by cognitive radio network and VANET and the approaches toward addressing these challenges individually as discussed in the following sections.

Figure 1 lists the challenges in cognitive radio network which include beacons, spectrum sensing, geo-location database, medium access control (MAC), and implementation of reliable test beds. On the other hand, in VANET, we encounter issues such as network selection, cross-layer design, routing, security, and implementation of reliable simulators or test beds before the actual deployment of VANET. These issues and implementation of cognitive radio VANET are discussed in detailed in the below sections.

2.1. Cognitive radio network

The main concern in cognitive radio network is to identify available free spectrum. The current spectrum managements which detect and manage the usage of spectrum are discussed in this section. The coordination of operation in cognitive radio network is mainly governed by the level of security, cross-layer design, and MAC layer. The detailed approaches and challenges toward achieving overall spectrum efficiency are discussed in the following subsections.

2.1.1. Detecting availability of a channel

In this section, ways to detect availability of a channel in a cognitive radio network are discussed. There are generally three common methods to detect availability of a channel: beacons, spectrum sensing, and geo-location database. These methods are discussed in detailed below.

2.1.1.1. Beacons. Beacons are signals which are sent to different channels to identify the channel availability. In order to transmit beacons, a communication device must have adequate radio frequency output power to disseminate the beacons to their respective locations. The main drawback of using beacons is the increase of frequency resources and additional interference sources which decrease the efficiency of the spectrum.

However, usage of beacons allows sharing of information on the spectrum availability and thus in Lei and Chin (2008), synchronization with index and payload is proposed to form an energy-efficient structure for beacon signal transmission in cognitive radio system. In Derakhshani, Le-Ngoc, and Vu (2010), beacons are used to perform study on interference caused by secondary users due to misdetection and capacity outage of the primary users in cognitive radio network.

Figure 1. Overview of challenges in cognitive radio network and VANET.

2.1 Cognitive Radio Network
2.1.1   Detecting Availability of a Channel
2.1.1.1 Beacons *2.1.1.2 Spectrum Sensing* *2.1.1.3 Geo-Location Database*
2.1.2   Coordination of Operation in Cognitive Radio Network
2.1.2.1 Security *2.1.2.2 Cross Layer Design* *2.1.2.3 Medium Access Control (MAC)*
2.1.3 Simulation/Testbed Tools
2.2 VANET
2.2.2   Network Selection *2.2.3 Cross Layer Design* *2.2.4 Routing* *2.2.5 Security* *2.2.6 Simulators/Test beds*

The different applications of beacons are explored in Vinel, Belyaev, Egiazarian, and Koucheryavy (2012), where the video-based overtaking assistant is significantly improved by exploiting information from the beacons on the position, speed, and direction of all the vehicles to ensure early detection of oncoming traffic. This ensures a warning is sent to the driver whenever needed. A simple time-based threshold policy for collective protection of primary users where the coordination of primary and secondary users is proposed to enable sharing of available opportunities is discussed in Ngoga, Yao, and Popescu (2012). In order to ensure the transmission within the given collision constraint, an analytical framework for carrier sense multiple access (CSMA)-based coexistence mechanism is integrated and the suggested model is shown to allow characterization of individual secondary users under various back off settings.

2.1.1.2. Spectrum sensing. The presence of available channels is detected in cognitive radio network with the use of spectrum sensing. If the channel is determined to be vacant and the constraints of the channel are satisfied, the secondary user occupies the respective available channel. One of the advantages of spectrum sensing in cognitive radio network is the independence of the framework quality which does not require the usage of database connection. However, the incapability of spectrum sensing to reduce false alarms due to interference reduces the efficiency of spectrum sensing.

There are two ways where spectrum sensing in cognitive radio networks could be performed: energy detection and feature detection. In Axell, Leus, Larsson, and Poor (2012) and Subhedar and Birajdar (2011), recent advances on spectrum sensing in CR such as constant false alarm rate detector, energy detection, feature detection, blind detection, multiband sensing, wideband spectrum sensing, compressive sensing, and cooperative spectrum sensing are some of the challenges and approaches discussed.

To minimize interference impact on the spectrum sensing cognitive radio networks, in Lo, Akyildiz, and Al-Dhelaan (2010), an Efficient Recovery Control Channel design is proposed to update a list of channels commonly available to neighbors. In the list of channels, each secondary user is able to efficiently establish new control channels among neighbors in response to primary user's activity changes. The proposed method is proven to be able to minimize the primary user interference.

With spectrum sensing, the presence of available channel could be detected even without the usage of database connection. A significant advantage of spectrum sensing allows spectrum sensing to be deployed in cognitive radio network. If the interference caused by devices could be resolved and the efficiency of spectrum sensing could be increased with better feature and algorithm to ease spectrum detection, spectrum sensing projects high potential to lead toward the integration of cognitive radio network.

2.1.1.3. Geo-location database. A geo-location database is necessary to determine the availability of the spectrum in their respective location to ensure operability of cognitive radio network. Once an initial access to the database is done, the available channel can be determined with the use of database enquiry. Rather than sensing spectrum or sending beacons, a database is established to respective locations to provide users an insight to the channel availability upon request. Small coverage area provides better spectrum efficiency in geo-location database framework.

In Denkovska, Latkoski, and Gavrilovska (2011), two existing approaches for television white spaces, FCC and electronic communications committee (ECC), are evaluated. It is shown that ECC is protection oriented, whereas FCC concentrates on extensive reusage of spectrum holes. Both approaches show that small coverage area of secondary networks gives significantly increased spectrum efficiency. Using geographical information, a routing protocol is also proposed in Kim and Krunz (2011). Distributed routing protocol is proposed where path selections and resource allocations are

determined by receivers on a per-packet and per-hop basis. The proposed framework efficiently adapts to spectrum dynamics and node mobility.

On the other hand, in Karimi (2011), a geo-location database with detailed calculations is performed to derive location-specific maximum permitted emission levels for white space devices (WSDs) operating in Digital Terrestrial Television bands.

Geo-location database highlights the necessity of reliable information in the database to ensure smooth operation of spectrum allocation in cognitive radio network. However, the setup of a database on a wide-scale basis requires effort and cost. Geo-location database marks a leap in the cognitive radio network if the usage of database is permissible.

2.1.2. Coordination of operation in cognitive radio network

In order to ensure smooth and efficient operation in cognitive radio network, general issues such as security, cross-layer design, and MAC should be standardized and optimized to ensure efficient cognitive radio network. These issues are discussed in detailed below.

2.1.2.1. Security. Cognitive radio network is still vulnerable to attacks due to its users' mobility and open communication framework. To reduce the possibility of attacks, a centralized security can be implemented to enhance the security level in cognitive radio network. This ensures the privacy of users is well protected. A range of security breaches and attacks are discussed in Tang, Yu, Huang, and Li (2012). In order to counter Spectrum Sensing Data Falsification attacks to cognitive radio mobile ad hoc networks, a novel bio-inspired consensus-based cooperative spectrum sensing scheme is presented.

An authentication scheme using identity (ID)-based cryptography with threshold secret sharing is also proposed. In Baldini et al. (2012), a range of threats, vulnerabilities, mitigations, and protection techniques to support the feasible deployment of software-defined radio and cognitive radio, and an overview of the security threats and related protection techniques for software-defined radio and cognitive radio (CR) technologies are identified. Several security requirements such as controlled access to resources, robustness, protection of confidentiality, protection of system integrity, protection of data integrity, compliance to regulatory framework, accountability, and verification of identities are determined as the basic security standards to be achieved before cognitive radio network can be implemented. Malicious attacks reduce the reliability of spectrum sharing in cognitive radio networks.

2.1.2.2. Cross-layer design. Different layers of communication cooperate within cognitive radio network to provide accessible spectrum detection and utilization. In order to ensure the functionality of cognitive radio network, in Chen and Wyglinski (2009), a novel spectrum allocation approach which optimizes each individual wireless device and its single-hop communication links with the use of partial operating parameter and environmental information from adjacent devices within the wireless network is proposed.

The framework shows the ability to minimize the bit error rate and Out-Of-Band interference while maximizing overall throughput with the use of a multi-objective fitness function. On the other hand, to provide quality video streaming, in Tom, Li, Asefi, and Shen (2012), video streaming is formed as a cross-layer design problem where a quality of experience (QoE)-oriented video streaming framework is used. The improvement in transport control protocol (TCP) is observed in Luo, Yu, Ji, and Leung (2010) where spectrum sensing, access decision, physical layer modulation, and coding scheme and data link layer frame size are considered in a cross-layer design approach in cognitive radio networks to maximize the TCP throughput. Cross-layer in cognitive radio network in general shows an increase in performance experienced by primary and secondary users if the information from different layers of communication is collaboratively utilized.

2.1.2.3. Medium access control. MAC is the key toward enabling the deployment of technologies for dynamic spectrum allocation. To improve the accuracy of spectrum sensing and further protect the primary users, in Zhang and Hang (2010), the cooperative sequential spectrum sensing at physical layer and packet scheduling at MAC layer over wireless dynamic spectrum access networks is proposed. The Markov chain model and queuing model are used to study the proposed protocol.

To address low throughput in data transmission, a closed form expression is derived to maximize allowable power for a cognitive radio transmission based on an interference model is proposed in Salameh, Krunz, and Younis (2009). By eliminating common control channel, a MAC scheme proposed in Kondareddy (2008) explores the employment of multi-hop routing to improve the perceived throughput. The need for a common control channel is eliminated for the entire network. This eliminated the control channel saturation problem and denial of service (DoS) attacks.

Collision avoidance (CSMA/CA) is modified in Liu, Hu, Xiao, and Liu (2010), in order to make the framework feasible for cognitive radio environment. The proposed CSMA/CA is designed as such to suit the application of IEEE802.22 which suffers from uncertain spectrum and frequency width.

2.1.3. Simulation/test bed tools

In order to test the functionality of the cognitive radio network under realistic environments, several test beds are currently being implemented. In Chen, Guo, and Qiu (2011), architecture for cognitive radio network test beds with functional architecture for cognitive radio network nodes is proposed. In Qiu et al. (2010), a real-time cognitive radio test bed with considerations on the design architecture, hardware platform, and key algorithms is built. Cognitive radio network is taken into consideration for smart grid applications as well. With consideration in ECMA-392 international standard, in Franklin et al. (2010), an ultra-high frequency band cognitive radio test bed is built based on ECMA-392 international standard which defines the MAC and physical (PHY) operation for television wide space (TVWS) communication between portable devices. The test bed is verified to be operated in line with the FCC rules. In the near future, advanced test beds with complete functionalities can be used to further develop and test cognitive radio networks under realistic environment.

2.2. VANET

The recent strides made in vehicular networks allow the advancement of VANET technology to provide linkage among vehicles for safety information sharing purposes. This decreases the probability of collisions. In this section, the various VANET architectures such as IEEE802.11p standard, network selection in VANET, cross-layer design, routing, security, simulators, and test beds are discussed.

2.2.1. Network selection

To support intelligent transportation system applications, VANET for exchange of safety information between users can be implemented using networks such as wireless fidelity, WiFi IEEE802.11p, wireless access in vehicular environments (WAVE), WAVE IEEE 1609, worldwide interoperability for microwave cccess, WiMAX IEEE802.16, bluetooth, infrared, and ZigBee to ensure dynamic mobility communications. IEEE802.11p defines the advancement of IEEE802.11. An overview of the standards proposed for IEEE 802.11p is presented in Jiang and Delgrossi (2008) and IEEE Std 1609.3-2010 (2010).

The standard proposed for IEEE802.11p discusses on layers 3 and 4 of the Open System Interconnection model which includes Internet Protocol, User Datagram Protocol, and TCP elements of the Internet model. Management and data services within WAVE devices are also highlighted in the draft. The implementation of IEEE802.11p under field operational test is made possible in Hernández-Jayo et al. (2012) which supports the deployment of VANET.

Further to this standard, the implementation of IEEE802.11p has been highly researched to provide better efficiency to VANETs applications as shown in Jiang, Alfadhl, and Chai (2011) where all resources on the road side units (RSUs) are scheduled as a whole and buses are used as moving

infrastructure points to reduce the burden on RSUs. Both, Variable-Length Contention Free Period for MAC and Time-To-Live values are used to guarantee data credibility on buses.

The transmission of acknowledgments for successfully received access categorized broadcast data frames allowed the transmitter to know whether the data frames are successfully received. With this information, the necessity to perform retransmission is evaluated. These are implemented in Enhanced Distributed Channel Access (Barradi, Hafid, & Gallardo, 2010). Arbitration Inter Frame Space Number parameter associated with different access categories is also implemented based on strict policies for access based on the suggested framework.

In order to increase the contention level and decrease information dissemination delay, a geo-casting packet transmission technique for IEEE802.11p is proposed to transmit safety messages in a VANET (Javed & Khan, 2011). The impact of urban characteristics, RSU deployment conditions, and communication settings on the quality of IEEE 802.11p is presented based on an extensive field testing campaign in Gozalvez, Sepulcre, and Bauza (2012). Results show that the streets' layout, urban environment, traffic density, presence of heavy vehicles, trees, and terrain elevation should be considered when configuring urban RSUs.

A design and analysis study is conducted on providing Internet access for VANET by combining Proxy Mobile IPv6 (PMIPv6) and ETSI TC ITS Geo-Networking (GN) protocols in Sandonis, Calderon, Soto, and Bernardos (2012). Detailed performance evaluations which include the performance metric of packet delivery ratio, delay, handover, and overhead are analyzed. The performance metric shows that the design of PMIPv6 and ETSI TC ITS Geo-Networking (GN) protocols is feasible for employment. In IEEE802.11p, the PHY and MAC layer based on existing IEEE802.11 standards are improved for vehicular applications. The performance of EEE802.11a-, IEEE802.11b-, and IEEE802.11 g-based VANETs is evaluated in Shen, Zou, and Liu (2009). Results showed that within certain distance, IEEE802.11a- and g-based VANET are able to achieve better stability good put, while IEEE802.11b-based VANET is better suited for long-distance communication. On the other hand, a novel adaptation of PMIPv6 for multi-hop VANET scenarios is introduced in Asefi, C′espedes, Shen, and Mark (2011) to ensure efficient network mobility management. This shows the importance of network selection in VANET toward determining the transmission efficiency.

2.2.2. Cross-layer design
The paradigm of cross-layer design in VANET has been proposed as an alternative solution toward achieving better efficiency in VANET. Cross-layer design utilizes information sharing among different layers to achieve robust protocols. In Jarupan and Ekici (2011), the architecture of cross-layer designs has been discussed as an alternative method to allow information to be shared across layer boundaries in order to create robust and efficient protocols. Several open research problems for, e.g., striking the balance between modularity and cross-layer design, system stability, realistic physical layer and mobility modeling, and standardization of cross-layer designs are listed.

In order to recover broken links in multicasting VANET, in Chang, Liang, Lai, and Wang (2012), a cross-layer uni-cast-type multi-hops local repair approach is proposed to increase the network throughput. Results show better successful repair rate, control message overhead, packet delivery ratio, and network good put. A cross-layer design which jointly optimizes routing and MAC functions is proposed in Jarupan (2009) to discover stable and delay efficient routes for highly dynamic communication networks. Various packet traffic statistics which are collected by the MAC layer from different locations in the networks are used to determine small end-to-end delay routes.

2.2.3. Routing
The process of selecting path in VANET is crucial to determine the reliability of information dissemination. In Fonseca and Vaz~ao (2012), various existing position-based routing protocols and its applicability to different environments are studied. The studies are characterized into vehicular network environment, topology-based protocols, and position-based protocols. One of the routing

methodologies suggested in Oliveira et al. (2012) involves information being obtained from mobility models. This information is used in practical routing algorithms to improve path duration. For high-vehicles density area, the packets are routed over the oldest links created by vehicles which are moving in the same direction. For small-vehicles density area, routings are accomplished according to the most recent links created by vehicles moving both directions. A geographic stateless routing combined with node location and digital map can also be used to provide high packet ratio with comparable latency to other geographic routing schemes (Xiang, Liu, Liu, Sun, & Wang, 2012).

A routing protocol where data gathered through passive mechanisms to calculate the reliability scores for each street edge to select the most reliable route can be considered for design of VANET routing (Bernsen & Manivannan, 2012). Routing performance in a one-way-multi-lane scenario can be enhanced by having each candidate to self determine its own priority using node degree, expected transmission count, and link lifetime (Wang & Lin, 2012). Packet delivery ratio and throughput can be increased if the individual routes through a reliable, stable, and durable routing path.

To increase delivery probability and reduced the delivery delay, a vehicle delay tolerant network routing protocol can be designed to make routing decisions based on geographical data and by combining the multiple-copy and single-copy (Soares, Rodrigues, & Farahmand, 2011). To securely and efficiently accomplish route optimization procedures in VANET, a Batch Binding Update Scheme can be used (Yeh, Yang, Chang, & Tsai, 2012). To facilitate video frame distortion and streaming start-up delay, an application-centric routing framework for real-time video transmission over urban multi-hop VANET can be employed (Asefi, Mark, & Shen, 2011). Queuing can be made based on mobility model, spatial traffic distribution, and probability of connectivity for sparse and dense VANET scenarios. Most routing algorithms used only one network path at a time. A multi-path routing can be considered to enable multi-alternative paths in VANETs.

2.2.4. Security

Since VANET involves information sharing among unknown users on the road, security becomes a main concern in ensuring safety in VANET. Thus, in Hu, Chen, and Li (2012), ring signature technique is used to perform an efficient multi-level conditional privacy preservation authentication protocol in VANET. This method offers conditional privacy preservation authentication with multi-level counter measure. However, ring signature technique increases the communication overhead directly proportional to the number of ring members. Therefore, a SMART protocol which employs data aggregation tool with message fragmentation to achieve efficient bandwidth usage is suggested in Nair, Soh, Chilamkurti, and Park (2012).

The data are first broken down and analyzed to ensure unnecessary data are eliminated. Data analyzed are stored in every node to create a well-organized data structure. In order to solve the inefficient deployment and potential RSU emulation attacks, a study has been conducted to study the impact of the inter-road side unit interference on beacon broadcasting (Ganan et al., 2012). It is shown that the broadcast performance drops when a vehicle is in range of four RSUs that are hidden from one another.

This proves the incapability of current IEEE 1609.4 medium access technique to cope with the interference caused by overlapping RSUs. This could be solved by identifying road side units emulation attack (REA) attackers and excluding them from the network. In general, security in VANET is still vulnerable to malicious attacks. To become a real technology that guarantees public safety, issues such as authentication and key management, privacy, secure positioning, and threat model are to be explored.

2.2.5. Simulators/test beds for VANET

VANET simulators are fundamentally different from mobile ad hoc network (MANET) simulators. In VANET, roadside obstacles, traffic flow models, trip models, varying vehicular speed and mobility, traffic conditions, tc. are the main considerations in designing VANET framework. Simulators for

VANET are still undergoing further development and in Francisco, Toh, Cano, Calafate, and Manzoni (2009), various simulators are compared and analyzed for research purposes.

Mobility generators such as simulation of urban mobility (SUMO), MOVE, CityMob, FreeSim, Street Random Waypoint, Netstream, VanetMobiSim, Network Simulator - 2 (ns-2), global mobile information system simulator (GloMoSim), Java in Simulation Time/Scalable Wireless Adhoc, and Sensor Nodes are found to have good software features and traffic model support. However, all networks simulators described above do not specifically address VANET scenarios and requirements. In terms of VANET simulators, Traffic and Network Simulation Environment, GrooveNet, Estinet Network Simulator, and Emulator and Realistic Simulator for VANET are widely accepted and commonly used to support VANET research.

On the other hand, test beds for VANET applications are currently being developed extensively to suit the needs of research and development. In Amoroso, Marfia, Roccetti, and Pau (2012a), preliminary results that assess the feasibility of VANET system taken from real experiments performed on Los Angeles freeways and roads in August 2011 are analyzed, whereas in Amoroso, Marfia, Roccetti, and Pau (2012b), preliminary results provided from a set of experiments on a vehicular highway accident warning system are used for verification purposes. A vehicular test bed called University of California at Los Angeles Campus Vehicular Testbed (UCLA C-VeT) campus test bed developed to validate the models and protocols before being deployed in a large scale proves to be useful for framework verification (Gerla, Weng, Giordano, & Pau, 2012).

The concept uses two case studies carried out in the UCLA open vehicular test bed which validates the model by experimenting through emulation or simulation and performed parallel experiments to compare different network configurations under the same mobility and external interferences. It is suggested that the spectrum sensing performance with cognitive radio is to be implemented in the near future. A design framework which considers roadside infrastructure as well as emergency vehicle warning system which utilizes the IVC to signal other vehicles about the route information is suggested in Buchenscheit, Schaub, Kargl, and Weber (2009). The prototype has been tested under a real environment with emergency vehicles and traffic light. VANET simulators and test beds provide a good simulation and testing environment for VANET deployment.

3. Designing cognitive radio in VANET: challenges and approaches

VANET deployment faces bandwidth allocations challenges due to the random number of users in the application. As such, the implementation of cognitive radio network technology in VANET has been explored to further enhance the spectrum distribution model in VANET. Recent works on cognitive radio network in VANET as shown in Figure 2 are discussed in this section.

3.1. Cognitive radio with VANET—A general idea (IEEE standards)

VANET is a special class of MANET, with nodes in VANET generally representing highly mobile vehicles. Cognitive radio network on the other hand is a method which addresses the spectrum scarcity in the network. While mobile nodes move in a random manner in VANET, spectrums are being utilized in a high density environment. A general idea of how to incorporate cognitive radio network with VANET is discussed in this section. A large amount of spectral congestion due to high vehicle density might affect the performance of the network. Therefore, in Kirsch and O'Connor (2011), a

Figure 2. Current advancements of cognitive radio with VANET.
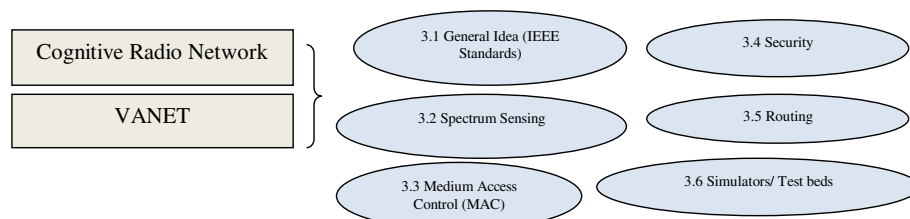
cognitive radio system is proposed to spatially and temporarily add additional radio channels to VANET when there is a high vehicle density. This framework allows high priority safety messages and secondary VANET applications to be transmitted successfully without much delay and with increased performance. A distributed channel coordination scheme that exploits the data transmission rate and the range of various frequencies is proposed for vehicle-to-vehicle communication (Tsukamoto, Matsuoka, Altintas, Tsuru, & Oie, 2009). A channel utilization model which utilizes each channel changes temporally and spatially for both primary and secondary usage is also developed. Even under temporal and spatial changes, the proposed scheme is able to utilize the unused frequency reliably.

Cognitive network principles are used to increase spectrum allocated to the control channel of WAVE protocols (Fawaz, Ghandour, Olleik, & Artai, 2010). The proposed system employs data sent by the cars to road side units to forward the aggregated data to a processing unit which created the data contention locations and generated spectrum scheduled to be dispatched to the passing cars. Advanced wireless architectures and its applications on vehicle networks are addressed in cognitive radio by seeking better spectrum reuse via Peer-to-Peer (P2P), ad hoc, and multi-hop solutions (Gerla & Kleinrock, 2011).

Negative impacts of cognitive radio technology in vehicular networks include the consequences of users not detecting a primary (licensed) user and thus causing interference to the user and the modulation techniques based on system signal to interference and noise ratios are discussed in Nyanhete, Mzyece, and Djouani (2011). To improve the performance of cognitive radio technology in vehicular networks, in Kakkasageri and Manvi (2011), a model which uses cognitive agent concept for realizing intelligent information dissemination is proposed.

In order to minimize channel allocation time and management overhead, the limited bandwidth allocated to a region is divided into prefixed overlapping spatial clusters, whereas the channel in each cluster is divided into time slots in Tomar and Verma (2011). These time slots are allocated to vehicles according to the priority of request and the availability of the channel. The contention delay experienced by cars can be monitored on a control channel (Ghandour, Fawaz, & Artail, 2011). If the contention delay exceeds a delay threshold, the RSU increases the spectrum allocation to the control channel using cognitive network, whereas if the contention delay is measured below delay threshold, the measured values are used as reference input for the controller. Dedicated protocols and frequency resources show the potential of cognitive radio network in VANET.

3.2. Spectrum sensing in cognitive radio VANET

Cognitive radio network spectrum sensing in VANET is capable of effectively detecting other transmissions, and identifying their current transmission data, and location for efficient spectrum allocation to take place. In Xiao Yu Wang and Pin-Han Ho (2010), a novel framework of coordinated spectrum sensing in cognitive radio-enhanced vehicular ad hoc networks (CR-VANETs) is introduced. The proposed sensing coordination framework uses spectrum sensing architectures, stand-alone, and cooperative sensing to achieve better sensing accuracy, efficiency, and fairness. The spatial correlation can be utilized using message passing among neighboring vehicles in order to perform collaborative spectrum sensing (Li & Irick, 2010). This is achieved using belief propagation (BP) which is applied to perform distributed observation and exploit the redundancies in both space and time.

In VANET, differing densities of primary users are common. In Pu Wang, Jun Fang, Ning Han, and Hongbin Li (2010), the channels between the primary user, cognitive user, and the variance of the noise seen at the cognitive user are used to develop a generalized likelihood ratio test to detect the presence/absence of the primary user, with the assumption that no prior knowledge of the primary user's signaling scheme. Since speed of detection is important and detection based on small number of samples is beneficial for vehicular applications, the proposed method is advantageous for VANET applications. Wavelet transform and wavelet packets can also be used in cognitive radio applications with vehicular communication for spectrum sensing and adaptive multicarrier transmission in

order to solve channel impairments, especially in high relative velocity communication peers (Maurizio & Vlad, 2011).

A cognitive vehicle-to-vehicle framework which leverages the cooperation among vehicles in order for the vehicles to be aware of the spectrum conditions on future positions along its path is proposed in Di Felice et al. (2010). A collaborative sensing and decision algorithm can be designed to enable vehicles to share spectrum information and to know the spectrum availability in advance along their motion paths to increase sensing accuracy (Felice, Chowdhur, & Bononi, 2011). To improve spatial reuse and avoid interference in vehicular networks, a cognitive channel hopping (CCH) protocol is proposed to select channels based on channel quality measurements in order to significantly improve the network performance (Choi, Im, Lee, & Gerla, XXXX).

A framework with three components: opportunistic access to shared use channels, reservation of exclusive use channel, and cluster size control, is developed for a channel access management framework for cluster-based communication among vehicular nodes in Niyato, Hossain, and Wang (2011). This framework is developed to maximize the utility of the vehicular nodes in the cluster, to minimize the cost of reserving exclusive use channel, and to meet the QoS requirements of data transmission and the constraint on probability of collision with licensed users. To address the opportunistic channel access and joint exclusive use channel reservation plus cluster size control, two constrained Markov decision process (CMDP) formulations are used.

A database-assisted sensing using parameters such as vehicular density, base station radio coverage, and the trade-offs between local and database-assisted sensing analysis is proposed in Doost-Mohammady and Chowdhury (2012) to minimize the cost of operation and limiting the resulting errors in spectrum detection. A spectrum sensing using energy detection over Gamma-shadowed Nakagami-mcomposite fading channel can be used to overcome small- and large-scaled fading (Rasheed & Rajatheva, 2011).

Throughput can be used as the performance metrics for spectrum sensing. Throughput maximization problem in cognitive VANET is investigated in Pan, Li, and Fang (2012). Using the features of cooperative communications and the availability of licensed spectrum, the link is classified into cooperative links and general links. Depending on the available bands, extended link-band pairs are developed to form a three-dimensional cooperative conflict graph. The performance of link scheduling with appropriately selected transmission mode is better than purely relying on one transmission mode. In general, a central database can be used with spectrum sensing to further enhance the performance of cognitive radio networks in VANET.

3.3. Medium access control (MAC) protocols for cognitive radio VANET

Medium access control addresses channel control mechanisms in cognitive radio VANET. A multi-channel MAC design which supports concurrent transmissions by allocating the channel with every beacon interval may not be feasible in a fast-fading VANET environment. A MAC design based on opportunistic spectrum access that selects channel at every individual transmission cannot provide fair share of spectrum among devices.

Therefore, in Chung, Yoo, and Kim (2009), a cognitive MAC for VANET which employs both, long-term and short-term spectrum access, provides fair share and exploits multi-user diversity while achieving high throughput. A MAC for WAVE is proposed in Shah, Habibi, and Ahmad (2012) to improve the channel utilization and reliability of safety messages by adopting EDCA and cognitive radio concept. The quality of channel can be accessed prior to transmission by employing dynamic channel allocation and negotiation algorithm using an efficient multichannel QoS cognitive MAC (MQOG) (Ajaltouni, 2012). To achieve significant increase in channel reliability, throughput, and delay while simultaneously addressing quality of service, an efficient MAC protocol for cognitive radio VANET should be implemented.

3.4. Security in Cognitive Radio VANET

VANET provides access for random users to communicate and share safety information on the road. Cognitive radio network provides efficient spectrum sharing among vehicle users. Therefore, security in cognitive radio network VANET is the key toward making cognitive radio network in VANET a reality. In Muraleedharan and Osadciw (2009), information disseminated using distributed sensor technology is implemented as part of the cognitive security protocol for VANET. This protocol ensures reliability and optimality of the protocol by employing a distributed sensor technology while prioritizing prevention of data aging, efficient quality of service (QoS), and robustness against denial of service (DoS) attacks.

VANET in general is vulnerable to DoS attacks. Jamming attacks interfere with legitimate wireless communications and degrade the overall quality of service (QoS) of network. A jammer transmits only when valid radio activity is signaled from its radio hardware to detect a particular class of jamming attack (Hamieh, Ben-Othman, & Mokda, 2009). The presence of jamming has been successfully detected using the proposed model. Security in cognitive radio VANET is still scarce and thus, the potential of further advancement in order to have a standardized security framework to ensure the reliability of the deployment of cognitive radio network in VANET should be developed.

3.5. Routing in cognitive radio VANET

In cognitive radio VANET, by employing different allocations of spectrum in the network, safety messages are routed across the network to reach other designated vehicles. The problem of routing in cognitive radio network which revolves around the identification and maintenance of the optimal path from source to destination using the available common channel is addressed in Barve and Kulkarni (2012).

The characteristics features limiting factors of the existing routing protocols are also investigated in Kim, Oh, Gerla, and Lee (2011), where the geographical location and sensed channel information are used to perform cognitive routing, yielding in a drastic improvement in throughput. The proposed protocol used unlicensed band and operates in an ad hoc, multi-hop mode which is different from the conventional cognitive radio strategies. In Liu, Ren, Xue, and Chen (, 2012), an expected path duration-maximized routing (EPDM-R) algorithm is developed in cognitive radio VANET (CR-VANET) where the expected link duration for each link is calculated.

Consequently, the maximum bottleneck algorithm is used to solve for the route that achieves the longest expected path duration. The proposed algorithm is shown to have larger average path duration than the Dijkstra-based schemes. A cross-layer channel assignment and routing algorithm which addresses the interference avoidance issues in cognitive radio network and maximizes the throughput by making use of the adjacent hop interference information are proposed in Zhan, Ren, Zhang, and Li (2012). In the above-mentioned techniques, routing in cognitive radio VANET commonly deals with achieving less delay and high throughput in communication. Further research on routing topologies to suit the deployment of cognitive radio VANET holds a great potential for further research investigation.

3.6. Simulators/test beds for cognitive radio VANET

To perform realistic experiments with the use of a few real vehicular resources in order to test new strategies and performances of VANET protocols, a test bed is proposed in Marfia et al. (2011). VANET protocols are tested as a function of different frequencies and interface switching delays in order to deal with scarcity of spectrum in dynamic environments. A set of preliminary results based on a highway accident warning system and a cognitive network using Microsoft Software Radio (SORA) technology is also presented. Test beds for VANET application hold a promising field for further research. Meanwhile, for cognitive radio VANET research purposes, simulators for VANET as discussed in section 2.2.5 can be used to perform simulations on cognitive radio VANET to address the open issues and research directions of cognitive radio VANET.

4. Designing cognitive radio network in VANET: open issues and research directions

In Steenkiste, Sicker, Minden, and Raychaudhuri (2009), several open issues and features of cognitive radio networks such as spectrum sensing, policies specifying how the radio can operate, and physical limitations of radio operation, databases configuration, radio self-configuration, adaptive algorithms, and security issues are addressed as part of the future directions of cognitive radio network.

Several characteristics and features of cognitive radio VANET are also discussed in Di Felice, Doost-Mohammady, Chowdhury, and Bononi (2012). These characteristics and features include integration with spectrum databases, impact of mobility, roles of cooperation, and presence of a common control channel. Challenges with vehicular communication based on IEEE 802.11 such as vehicular speed, distance, handover and mobility management, and unique multi-hop inter-vehicular communication are specified in Saeed, Naemat, Aris, Mat Khamis, and Awang (2010). Further research work, open issues, and research directions are discussed in this section where insights on the possible research directions are identified. Figure 3 shows the summary of the open issues and directions of cognitive radio VANET. The open issues and research directions are discussed in detailed in the following sections.

4.1. Coordination between licensed networks users and unlicensed users

One of the main issues in establishing cognitive radio network among VANET vehicles is to guarantee a smooth coordination among licensed network users. Secondary users in cognitive radio network in VANET should not interrupt the utilization of licensed networks users (primary users). To ensure efficient operation among cognitive users, a licensee can employ cognitive radio network internally within its own network. This method increases the efficiency of radio networks usage. On the other hand, the secondary users can utilize multiple licensed services by proper scheduling. Mutual interference can be avoided with efficient coordination.

4.2. Duration of spectrum opportunities

Random switching of spectrum affects the performance of a communication. Therefore, a vehicle user should be able to choose the spectrum which guarantees the best connectivity within the longest time frame. A database can be established in each cluster to maintain the current information of each spectrum. With database application, before the allocation of spectrum to vehicles can be established, the database provides insight into the best, nearest, and longest duration of spectrum opportunities for secondary users to evaluate and select the best spectrum to establish connection. This guarantees spectrum utilization as well as the duration of spectrum availability and efficient communication connection.

4.3. Random movements of vehicles

Vehicles in VANET move in a random manner. Therefore, the possibility of a vehicle to stay put in the same location is minimal. The duration of spectrum usage is generally short and thus, spectrum switching occurs frequently. This random movement of VANET vehicles increases the challenges of implementing cognitive radio network with VANET. VANET users must be able to detect the best available spectrum and establish a quick connection before the vehicle moves out from the cluster. The vehicle should also be able to detect and make connections with the next spectrum before the vehicle moves out from the cluster. The handover process that takes place should not imply a huge

Figure 3. Open issues and research directions.

Open Issues and Research Directions
4.1 *Coordination between Licensed Networks Users and Unlicensed Users*
4.2 *Duration of Spectrum Opportunities*
4.3 *Random Movements of Vehicles*
4.4 *Multiple Points of Observation*
4.5 *Interference*
4.6 *Delay*
4.7 *Security*

effect on the communication links. The handover scheme in VANET holds a promising research possibility to ensure the viability of the implementation of cognitive radio network in VANET.

4.4. Multiple points of observation

Cognitive radio network (Kaur, 2014) offers multiple point spectrum observation for VANET users. Due to the ever-changing environment, the information obtained from each spectrum cannot be guaranteed as clusters are located near each other and the possibility of interference is relatively high. These uncertain outdoor factors cause false alarms in VANET where conditions such as available spectrums are not detected and non-idle spectrums are selected due to false data retrieved. Cognitive radio network in VANET is severely affected if the wrong dissemination of information is circulated. To avoid false alarms in multiple points of spectrum observation, a framework that ensures the reliability of data dissemination on each spectrum should be designed to ensure the efficiency and feasibility of cognitive radio network in VANET. A proper selection mechanism based on parameters which reflect the conditions of the current cognitive radio network conditions as well as the current VANET users locations should be integrated.

4.5. Interference

With primary and secondary users, interference between cognitive radio networks is the main issues to be faced. One of the solutions proposed in Kim and Gerla (2012) suggests a cognitive multi-channel, multi-radio multi-cast protocol known as CoCast. CoCast is developed to overcome interference issues between Wi-Fi users as well as inter-vehicle users. Two additional features such as parallel frame transmission over orthogonal frequency division multiplexing (OFDM) sub-channels and network coding are used to exploit spectral diversity and sub-channel frames, respectively. Results show that the external interference effectively reduces in a multicast scenario, especially in a channel environment where channels overlap in frequency. With vehicles in VANET moving in a random manner and multiple points of spectrum observation (Lim, Chang, Alias, & Loo, 2015; Lim, Chang, & Yusoff, 2016), interference is an avoidable issue and thus, a proper framework as discussed in Zhao, Zhu, Chen, Zhu, and Li (2013) and Jia, Lu, and Wang (2014) should be designed to ensure secondary users can transmit under minimal interference environment without disturbing the physical process of adjustment in primary users.

4.6. Delay

VANET is initially developed to ensure safety messages can be sent across vehicles in VANET to minimize collisions and promote safety on the road. These safety messages must be transmitted without further delay. Any overdue safety messages losses its functionalities. Under cognitive radio network, spectrum sharing and spectrum allocation should be deployed under specified delay constraints. These delay constraints become stringent, especially in VANET applications. Therefore, a suitable framework should be employed to ensure delay in cognitive radio VANET is minimal. Parameters such as geo-location of VANET vehicles can be employed to ensure if the locations of VANET vehicles are identified under cognitive radio network framework and thus, proper spectrum allocation can be made to minimize transmission delay.

4.7. Security

In cognitive radio VANET, vehicles connect to an available spectrum and communicate from one vehicle to another vehicle randomly. This framework leads toward the vulnerability of the primary and secondary users to succumb to different malicious attacks (Mohammed & Al-Daraiseh, 2014). Attacks such as DoS and jamming should be identified before transmission begins to ensure safety of users are not violated. The detection and prevention of attacks in cognitive radio VANET should be properly designed to ensure the feasibility of cognitive radio VANET deployment in a real-time framework.

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5. Performance metrics

In this section, some of the performance metrics used to evaluate cognitive radio VANET are discussed. In Section 5.1, the common performance metrics are discussed. In section 5.2, with the use of Table 1, the performance metrics are listed according to their applications.

5.1. List of performance metrics

(a) *Throughput* - Throughput is used to measure the average packet transmitted per second.

(b) *End-to-End Delay* - End-to-end delay is used to measure the time it takes to get a packet transmitted from the source to the destination node.

(c) *Transmission Overhead* - Transmission overhead measures the excess time/excess data as compared to the normal packet transmission.

(d) *Number of Messages per Node* - Number of messages per node measures the number of messages a node received/sent.

(e) *Minimum Number of Hops* - Minimum number of hops measures the minimum number of routers/devices a packet goes through before reaching its destination node.

(f) *Beacon Interval* - Beacon interval measures the total time required for a beacon to get transmitted.

(g) *Beacons per second* - Beacons per second measure the number of beacons sent/broadcasted over a period of time in seconds.

(h) *Density Estimation* - Density estimation measures/predicts/estimates the node density of a certain area defined by user.

(i) *Forwards per Route* - Forwards per route measure the number of forwarded packet per path/route.

(j) *Warning Notification Time* - Warning notification time measures the time it takes to notify or warn a user.

(k) *Path Duration* - Path duration measures the amount of time it takes to send/route a packet.

(l) *Packet Success Rate* - Packet success rate measures the percentage of a successfully transmitted packet for every attempt the packet is transmitted.

(m) *Spectrum/Bandwidth Utilization* - Spectrum or bandwidth utilization measures the percentage of spectrum/bandwidth used by the user on average.

(n) *Computational Time* - Computational time measures the complexity of the scheme used.

Table 1. Performance metrics	
Applications	**Performance metrics**
Cognitive Radio	
Beacons	a, b, c, d, e, f, g, h, i
Spectrum Sensing	a, b, c, h, m, n, o, p, r
Geo-Location Database	h, k, n, p
Cross-Layer Design	a, b, c, l, n
MAC	a, b, c, d, e, f, g, h, I, j, k, l, m, n, o, p, q, r
Test Beds	a, b, c, d, e, f, g, h, I, j, k, l, m, n, o, p, q, r
VANET	
Network Selection	a, b, c, d, e, f, g, h, I, j, k, l, m, n, o, p
Cross-Layer Design	a, b, c, l, n
Routing	a, b, c, d, e, h, I, k, l, n, p, q
Security	a, b, c, j, l, n, p, q, r
Simulators/Test beds	a, b, c, d, e, f, g, h, I, j, k, l, m, n, o, p, q, r

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(o) *Transmitted/Received Power* - Transmitted power measures the amount of power used to send a packet from source to destination node, whereas received power measures the amount of power when the packet reaches its destination node.

(p) *Probability of Detection* - Probability of detection measures the probability of a user getting detected.

(q) *Recover Time* - Recovery time measures the time it takes to recover a system.

(r) *False Alarm Probability* - False alarm probability measures the probability of getting false warnings or alarms.

5.2. Performance metrics and its applications

In this section, the performance metrics are listed according to its applications. In Table 1, the applications are divided into cognitive radio and VANET. The sub-applications are listed below. Table 1 is listed according to Figure 1 as discussed in the previous sections.

6. Conclusion

As described in this paper, despite the fact that considerable amount research work has been carried out in cognitive radio VANET, many practical problems still exist, which are yet to be solved. Several highlighted problems such as coordination between licensed and unlicensed users, duration of spectrum opportunities, multiple points of observation, interference, delay, and security are the main concerns in cognitive radio VANET. In addition, the current cognitive radio VANET uses mainly static networking parameters, even though cognitive radio network VANET is not static, and constantly exposed to ever-changing nature, fluctuating interference, high mobility, improper scheduling, and security breach. The lack of adaptivity and optimization of the current cognitive radio VANET makes cognitive radio VANET less efficient in terms of communication. Currently, cognitive radio VANET still has many loose ends which prevent the proper deployment of the framework. In order to ensure the applicability of cognitive radio VANET, proper framework which addresses the issues discussed in this paper should be developed. We are currently developing an integrated model which targets the deployment of a proper database. The database proposed uses parameters such as the locations of VANET vehicles, power model, and signal-to-noise ratio to address the issue of spectrum allocation in cognitive radio VANET. The proposed integrated model focuses on a make-before-break concept to ensure delay does not limit the transmission quality during a spectrum handover.

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References
Ajaltouni, H. E. (2012). *An efficient QoS MAC for IEEE802.11p over cognitive multichannel vehicular networks* (thesis). University of Ottawa.

Amoroso, A., Marfia, G., Roccetti, M., & Pau, G. (2012a). To live and drive in L. A.: Measurements from a real intervehicular accident alert test (pp. 328–332). Conference on wireless communications and networking, Paris.

Amoroso, A., Marfia, G., Roccetti, M., & Pau, G. (2012b). *Creative testbeds for VANET research: A new methodology* (pp. 477–481). Conference on consumer communications and networking, Las Vegas.

Asefi, M., C'espedes, S., Shen, X., & Mark, J. W. (2011). *A seamless quality-driven multi-hop data delivery scheme for video streaming in urban VANET scenarios* (pp. 1–5). Conference on communications, Kyoto.

Asefi, M., Mark, J. W., & Shen, X. (2011). *An application-centric inter-vehicle routing protocol for video streaming over multi-hop urban VANETs* (pp. 1–5). Conference on communications, Kyoto.

Axell, E., Leus, G., Larsson, E. G., & Poor, H. (2012). Spectrum sensing for cognitive radio : State-of-the-art and recent advances, IEEE Signal Processing Magazine, *29*, 101–116. http://dx.doi.org/10.1109/MSP.2012.2183771

Baldini, G., Sturman, T., Biswas, A. R., Leschhorn, R., G'odor, G., & Street, M. (2012). Security aspects in software defined radio and cognitive radio networks: A survey and a way ahead. *IEEE Communications, Surveys & Tutorials, 14,* 355–379.

Barrachina, J., Garrido, P., Fogue, M., Martinez, F. J., Cano, J. C., Calafate, C. T., & Manzoni, P. (2012). VEACON: A vehicular accident ontology designed to improve safety on the roads. *Journal of Network and Computer Applications, 35,* 1891–1900.
http://dx.doi.org/10.1016/j.jnca.2012.07.013

Barradi, M., Hafid, A. S., Gallardo, J. R. (2010). *Establishing strict priorities in IEEE 802.11p WAVE vehicular networks* (pp. 1–6) Conference on IEEE global telecommunications, Miami.

Barve, S. S., & Kulkarni, P. (2012). A performance based routing classification in cognitive radio networks. *International Journal of Computer Applications, 44,* 11–21.
http://dx.doi.org/10.5120/6370-8762

Bernsen, J., & Manivannan, D. (2012). RIVER: A reliable inter-vehicular routing protocol for vehicular ad hoc networks. *Computer Networks, 56,* 3795–3807.
http://dx.doi.org/10.1016/j.comnet.2012.08.017

Buchenscheit, A., Schaub, F., Kargl, F., & Weber, M. (2009). *A VANET-based emergency vehicle warning system* (pp. 1–8). Conference on vehicular networking, Tokyo.

Chang, B. J., Liang, Y. H., Lai, J. T., & Wang, J. W. (2012). *Cross-layer-based real-time local repair for multicasting in distributed vehicular ad hoc networks* (pp. 1–6). Conference on world telecommunications congress, Beijing.

Chen, S., & Wyglinski, A. M. (2009). Efficient spectrum utilization via cross-layer optimization in distributed cognitive radio networks. *Computer Communications, 32,* 1931–1943.
http://dx.doi.org/10.1016/j.comcom.2009.05.016

Chen, Z., Guo, N., & Qiu, R. C. (2011). *Building a cognitive radio network testbed* (pp. 91–96). In Proceedings of IEEE southeastcon, Nashville.

Choi, B. S. C., Im, H., Lee, K. C., & Gerla, M. (XXXX). CCH: Cognitive channel hopping in vehicular ad hoc networks, Conference on vehicular technology, *201,* 1–5.

Chung, S., Yoo, J., Kim, C. (2009). *A cognitive MAC for VANET based on the WAVE systems* (pp. 41–46). Conference on advanced communication technology, Phoenix Park.

Datla, D., Wyglinski, A. M., & Minden, G. J. (2009). A spectrum surveying framework for dynamic spectrum access networks. *IEEE Transactions on Vehicular Technology, 58,* 4158–4168.
http://dx.doi.org/10.1109/TVT.2009.2021601

Denkovska, M., Latkoski, P., & Gavrilovska, L. (2011). *Geolocation database approach for secondary spectrum usage of TVWS* (pp. 369–372). Conference on 19th telecommunications forum, Las vegas.

Derakhshani, M., Le-Ngoc, T., Vu, M. (2010). *Interference and outage analysis in a cognitive radio network with beacon* (pp. 261–264). Conference on 25th biennial symposium on communications, Stockholm.

Di Felice, M., Chowdhur, K. R., & Bononi, L. (2010). *Analyzing the potential of cooperative cognitive radio technology on inter-vehicle communication* (pp. 1–6). Conference on wireless days, Venice.

Di Felice, M., Doost-Mohammady, R., Chowdhury, K. R., & Bononi, L. (2012). Smart radios for smart vehicles: Cognitive vehicular networks. *IEEE Vehicular Technology Magazine, 7,* 26–33.
http://dx.doi.org/10.1109/MVT.2012.2190177

Doost-Mohammady, R., Chowdhury, K. R. (2012). *Design of spectrum database assisted cognitive radio vehicular networks.* Conference on cognitive radio oriented wireless networks, Sydney.

Fawaz, K., Ghandour, A., Olleik, M., & Artai, H. (2010). *Improving reliability of safety applications in vehicle ad hoc networks through the implementation of a cognitive network.* (798–805). Conference on telecommunications, Singapore.

Felice, M. D., Chowdhur, K. R., & Bononi, L. (2011). *Cooperative spectrum management in cognitive vehicular ad hoc networks* (pp. 47–54). Conference on vehicular networking, St. Petersburg.

Fonseca, A., & Vaz~ao, T. (2012). Applicability of position-based routing for VANET in highways and urban environment, *Journal of Network and Computer Applications, 36,* 961–973.

Francisco, J. M., Toh, C. K., Cano, J. C., Calafate, C. T., & Manzoni, P. (2009). A survey and comparative study of simulators for vehicular ad hoc networks (VANETs). *Wireless Communications and Mobile Computing, 11,* 813–828.

Franklin, A. A., Pak, J., Jung, H., Kim, S., You, S., Um, J., … Kim, C.(2010). *Cognitive radio test-bed based on ECMA-392 international standard* (pp. 1026–1030). Conference on 7th international symposium on wireless communications systems, York.

Ganan, C., Loo, J., Ghosh, A., Esparza, O., Rene1, S., Munoz, J. L. (2012). *Analysis of inter-RSU beaconing interference in VANETs.* Conference on international workshop on multiple access communications, Ireland.

Gerla, M., & Kleinrock, L. (2011). Vehicular networks and the future of the mobile internet. *Computer Networks, 55,* 457–469.
http://dx.doi.org/10.1016/j.comnet.2010.10.015

Gerla, M., Weng, J. T., Giordano, E., & Pau, G. (2012). Vehicular testbeds - model validation before large scale deployment. *Journal of Communications, 7,* 451–457.

Ghandour, A. J., Fawaz, K., & Artail, H. (2011). *Data delivery guarantees in congested vehicular ad hoc networks using cognitive networks* (pp. 871–876). Conference on wireless communications and mobile computing, Doha.

Gonzalez, A. L., Picone, M., & Colabrese, S. (2012). *Cognitive radio and applications.* Rome: Sapienza University Di Roma.

Gozalvez, J., Sepulcre, M., & Bauza, R. (2012). IEEE 802.11p vehicle to infrastructure communications in urban environments. *IEEE Communications Magazine, 50,* 176–183. http://dx.doi.org/10.1109/MCOM.2012.6194400

Hamieh, A., Ben-Othman, J., & Mokda, L. (2009). *Detection of radio interference attacks in VANET* (pp. 5077–5081). Proceedings of the 28th IEEE conference on global telecommunications, Honolulu.

Hernández-Jayo, U., Sainz, N., Iglesias, I., Elejoste, M. P., Jiménez, D., & Zumalde, I. (2012). *IEEE802.11p field operational test implementation and driver assistance services for enhanced driver safety* (pp. 305–310). Conference on consumers communications and networking, Las vegas.

Hu, X., Chen, Z., & Li, F. (2012). Efficient and multi-level privacy-preserving communication protocol for VANET. *Computers and Electrical Engineering, 38,* 573–581.

IEEE Std 1609.3-2010. (2010). *IEEE standard for wireless access in vehicular environments (WAVE) - networking services* (pp. 1–144). Revision of IEEE standard 1609.3-2007.

Islam, M. H., Koh, C. L., Oh, S. W., Qing, X., Lai, Y. Y., Wang, C., … Toh, W. (2008). *Spectrum survey in Singapore: Occupancy measurements and analyses* (pp. 1–7). 3rd International Conference on cognitive radio oriented wireless networks and communications, Luxemborg.

Jarupan, B. (2009). *Cross-layer design for location and delay aware communication in vehicular networks.* The Ohio State university thesis, Columbus.

Jarupan, B., & Ekici, E. (2011). A survey of cross-layer design for VANETs. *Ad Hoc Networks, 9,* 966–983.
http://dx.doi.org/10.1016/j.adhoc.2010.11.007

Javed, M. A., & Khan, J. Y. (2011). *A geocasting technique in an IEEE802.11p based vehicular ad hoc network for road traffic management* (pp. 1–6). Conference on Australasian telecommunication networks and applications, Melbourne.

Jia, D., Lu, K., & Wang, J. (2014). A disturbance-adaptive design for vanet-enabled vehicle platoon. *IEEE Transactions on Vehicular Technology, 63*, 527–539. http://dx.doi.org/10.1109/TVT.2013.2280721

Jiang, D., & Delgrossi, L. (2008). *IEEE 802.11p: Towards an international standard for wireless access in vehicular environments* (pp. 2036–2040). Conference on IEEE vehicular technology, Singapore.

Jiang, T., Alfadhl, Y., & Chai, K. K. (2011). *Efficient dynamic scheduling scheme between vehicles and roadside units based on IEEE 802.11p/WAVE communication standard* (pp. 120–125).Conference on ITS telecommunications, St. Petersburg.

Kakkasageri, M. S., & Manvi, S. S. (2011). Intelligent infromation dissemination in vehicular ad hoc networks. *International Journal of Ad hoc, Sensor and Ubiquitous Computing, 2*, 112–123. http://dx.doi.org/10.5121/ijasuc

Karimi, H. R. (2011). *Geolocation databases for white space devices in the UHF TV bands: Specification of maximum permitted emission levels* (pp. 443–454). Conference on new frontiers in dynamic spectrum access networks, Aachen.

Kaur, S. (2014). Intelligent in wireless networks with cognitive radio networks. *IETE Technical Review, 30*, 6–11.

Kim, W., & Gerla, M. (2012). Cognitive multicast with partially overlapped channels in vehicular ad hoc networks. *Ad hoc networks,11*, 2016–2025.

Kim, J., Krunz, M. (2011). *Spectrum-aware beaconless geographical routing protocol for mobile cognitive radio networks* (pp. 1–5). Conference on IEEE global telecommunications, Istanbul.

Kim, W., Oh, S. Y., Gerla, M., & Lee, K. C. (2011). *CoRoute: A new cognitive anypath vehicular routing protocol* (pp. 766–711). Conference on wireless communications and mobile computing, Istanbul.

Kirsch, N. J., O'Connor, B. M. (2011). *Improving the performance of vehicular networks in high traffic density conditions with cognitive radios* (pp. 552–556). Conference on IEEE intelligent vehicle symposium, Baden.

Kondareddy, Y. R. (2008). *MAC and routing protocols for multi-hop cognitive radio networks*. Auburn university thesis, Auburn.

Lei, Z., & Chin, F. (2008). A reliable and power efficient beacon structure for cognitive radio systems. *IEEE Transactions on Broadcasting, 54*, 182–187.

Li, H., & Irick, D. K. (2010). *Collaborative spectrum sensing in cognitive radio vehicular ad hoc networks: Belief propagation on highway* (pp. 1–5). Conference On vehicular technology, Taipei.

Liang, Y. C., Chen, K. C., Li, G. Y., & Mähönen, P. (2008). Cognitive radio networking and communications: an overview. *IEEE Transactions on Vehicular Technology, 60*, 3386–3407.

Lim, J. M. Y., Chang, Y. C., Alias, M. Y., & Loo, J. (2015, June). Joint optimization and threshold structure dynamic programming with enhanced priority scheme for adaptive VANET MAC. *Wireless Networks,* 1–17.

Lim, J. M. Y, Chang, Y. C., & Yusoff, M. (2016, March 27–28). *A Novel Optimization Scheme for Human-Computer Cognitive VANET Interaction with Information System Integration*. 5th International Conference on Human Computing, Education and Information Management System, Sydney.

Liu, Y., Hu, S., Xiao, Y., & Liu, X. (2010). *CSMA/CA-based MAC protocol in cognitive radio network* (pp. 163–167). Conference on 3rd IET wireless, mobile and multimedia networks, China.

Liu, J., Ren, P., Xue, S., & Chen, H. (2012). *Expected path duration maximized routing algorithm in Cr-Vanets* (pp. 723–727). Conference on communications in China: wireless networking and applications, China.

Lo, B. F., Akyildiz, I. F., & Al-Dhelaan, A. M. (2010). Efficient recovery control channel design in cognitive radio ad hoc networks. *IEEE Transactions on Vehicular Technology, 59*, 4513–4526. http://dx.doi.org/10.1109/TVT.2010.2073725

Luo, C, Yu, F. R., Ji, H., & Leung, V. C. M. (2010). Cross-layer design for TCP performance improvement in cognitive radio networks. *Vehicular Technology, IEEE Transactions, 59*, 2485–2495.

Marfia, G., Roccetti, M., Amoroso, A., Gerla, M., Pau, G., & Lim, J. H. (2011). *Cognitive cars: Constructing a cognitive playground for VANET research testbeds*. Proceedings of the 4th International Conference on Cognitive Radio and Advanced Spectrum Management, Spain.

Maslekar, N., Mouzna, J., Boussedjra, M., & Labiod, H. (2012). CATS: An adaptive traffic signal system based on car-to-car communication, *Journal of Network and Computer Applications, 36*, 1308–1315.

Maurizio, M., & Vlad, P. (2011). Cognitive radio communications for vehicular technology – wavelet applications. *Vehicular Technologies: Increasing connectivity, 13*, 223–238.

Mitola, J., & Maguire, G. Q. (1999). Cognitive radio: making software radios more personal. *IEEE Personal Communications, 6*, 13–18. http://dx.doi.org/10.1109/98.788210

Mohammed, M. A., & Al-Daraiseh, A. A. (2014). Toward secure vehicular ad hoc network: a survey. *IETE Technical Review, 29*, 80–89.

Muraleedharan, R., & Osadciw, L. A. (2009). *Cognitive security protocol for sensor based VANET using swarm intelligence* (pp. 288–290). Conference on signals, systems and computers, Pacific Grove.

Nair, R., Soh, B., Chilamkurti, N., & Park, J. J. J. H. (2012). Structure-free message aggregation and routing in traffic information system (SMART). *Journal of Network and Computer Applications, 36*, 974–980.

Ngoga, S. R., Yao, Y., & Popescu, A. (2012). *Beacon-enabled cognitive access for dynamic spectrum access* (pp. 49–56). Conference on next generation internet, Karlskrona.

Niyato, D., Hossain, E., & Wang, P. (2011). Optimal channel access management with qos support for cognitive vehicular networks. *IEEE Transactions on Mobile Computing, 10*, 573–591. http://dx.doi.org/10.1109/TMC.2010.191

Nyanhete, E. R., Mzyece, M., & Djouani, K. (2011). *Operation and performance of cognitive radios in vehicular environments*. Conference on SATNAC, Tshwane.

Oliveira, R., Luís, M., Furtado, A., Bernardo, L., Dinis, R., & Pinto, P. (2012). Improving path duration in high mobility vehicular ad hoc networks. *Ad hoc Networks, 11*, 89–103.

Pan, M., Li, P., & Fang, Y. (2012). Cooperative communication aware link scheduling for cognitive vehicular networks. *IEEE Journal on Selected Areas in Communications, 30*, 760–768. http://dx.doi.org/10.1109/JSAC.2012.120510

Pu Wang, P., Jun Fang, J., Ning Han, N., & Hongbin Li, H. (2010). Multiantenna-assisted spectrum sensing for cognitive radio. *IEEE Transactions on Vehicular Technology, 59*, 1791–1800. http://dx.doi.org/10.1109/TVT.2009.2037912

Qiu, R. C., Chen, Z., Guo, N., Son, Y., Zhang, P., Li, H., & Lai, L. (2010). *Towards a real-time cognitive radio network testbed: architecture, hardware platform, and application to smart grid* (pp. 1–6). Conference on IEEE workshop on networking technologies for software defined radio networks, Boston.

Rasheed, H., & Rajatheva, N. (2011). Spectrum sensing for cognitive vehicular networks over composite fading. *International Journal of Vehicular Technology,* 1–9. http://dx.doi.org/10.1155/2011/630467

Richard Yu, F. (2011). *Cognitive radio mobile ad hoc networks.* Berlin: Springer.

Saeed, R. A., Naemat, A. B. H., Aris, A. B., Mat Khamis, I., & Awang, M. K. B. (2010). Evaluation of the IEEE 802.11p-based TDMA MAC method for road side-to-vehicle communications. *International Journal of Network and Mobile Technologies, 1*, 81–87.

Salameh, H. B., Krunz, M., & Younis, O. (2009). MAC protocol for opportunistic cognitive radio networks with soft guarantees. *IEEE Transactions on Mobile Computing, 8*, 1339–1352. http://dx.doi.org/10.1109/TMC.2009.19

Sandonis, V., Calderon, M., Soto, I., & Bernardos, C. J. (2012). Design and performance evaluation of a PMIPv6 solution for geonetworking-based VANETs, *Ad hoc Networks, 11*, 2069–2082

Shah, N., Habibi, D., & Ahmad, I. (2012). *Multichannel cognitive medium access control protocol for VANET.* (pp. 222–233). Conference in vehicular technology, New York, NY.

Shen, Y., Zou, Q., & Liu, Z. (2009). *Performance evaluation of IEEE802.11-based adhoc wireless networks in vehicular environments* (pp. 1–4). Conference on wireless communications, networking and mobile computing, Beijing.

Soares, V. N. G. J., Rodrigues, J. J. P. C., & Farahmand, F. (2011). GeoSpray: A geographic routing protocol for vehicular delay-tolerant networks. *Information Fusion, 15*, 102–113.

Sou, S. I., Shieh, W. C., & Lee, Y. (2011). *A video frame exchange protocol with selfishness detection mechanism under sparse infrastructure-based deployment in VANET* (pp. 498–504). Conference on wireless and mobile computing, networking and communications, Wuhan.

Steenkiste, P., Sicker, D., Minden, G., & Raychaudhuri, D. (2009). *Future directions in cognitive radio network research* (pp. 1–37). NSF workshop report.

Subhedar, M., & Birajdar, G. (2011). Spectrum Sensing Techniques in Cognitive Radio Networks: A Survey. *International Journal of Next-Generation Networks, 3*, 37–51. http://dx.doi.org/10.5121/ijngn

Tang, H., Yu, F. R., Huang, M., & Li, Z. (2012). Distributed consensus-based security mechanisms in cognitive radio mobile ad hoc networks. *IET Communications, 6*, 974–983. http://dx.doi.org/10.1049/iet-com.2010.0553

Tom, H. L., Li, S., Asefi, M., & Shen, X. (2012). Quality of experience oriented, video streaming in challenged wireless networks: Analysis, protocol design and case study. *IEEE Communications Society, 7*, 9–12.

Tomar, R. S., & Verma, S. (2011). RSU assisted channel allocation in VANETs, *International Journal of Contemporary Research in Engineering and technology, 1*, 25–36.

Tsukamoto, K., Matsuoka, S., Altintas, O., Tsuru, M., & Oie, Y. (2009). Distributed channel coordination in cognitive wireless vehicle-to-vehicle communications (pp. 59–64). Conference on the institute of electronics, information and communication engineers (IEICE), Tokyo.

Vinel, A., Belyaev, E., Egiazarian, Karen., & Koucheryavy, Y. (2012). An overtaking assistance system based on joint beaconing and real-time video transmission. *IEEE Transactions on Vehicular Technology, 61*, 2319–2329. http://dx.doi.org/10.1109/TVT.2012.2192301

Wang, S. S., & Lin, Y. S. (2012). PassCAR: A passive clustering aided routing protocol for vehicular ad hoc networks, *Computer Communications, 36*, 170–179.

Wang, X. Y., & Ho, P. H. (2010). A novel sensing coordination framework for CR-VANETs. *IEEE Transactions on Vehicular Technology, 59*, 1936–1948. http://dx.doi.org/10.1109/TVT.2009.2037641

Wang, R., Rezende, C., Ramos, H. S., Pazzi, R. W., Boukerche, A., & Loureiro, A. A. F. (2012). *LIAITHON: A location-aware multipath video streaming scheme for urban vehicular networks* (pp. 436–441). conference on ieee symposium on computers and communications, Cappadocia.

Xiang, Y., Liu, Z., Liu, R., Sun, W., & Wang, W. (2012). GeoSVR: A map-based stateless VANET routing. *Ad hoc Networks, 11*, 2125–2135.

Xu, K., Garrison, B. T., Wang, K. C. (2011). *Throughput modeling for multi-rate IEEE 802.11 vehicle-to-infrastructure networks with asymmetric traffic* (pp. 299–306). In Proceedings of the 14th ACM international conference on modeling, analysis and simulation of wireless and mobile systems, New York, NY.

Yeh, L. Y., Yang, C. C., Chang, J. G., & Tsai, Y. L. (2012). A secure and efficient batch binding update scheme for route optimization of nested network mobility (NEMO) in VANETs, *Journal of Network and Computer Applications, 36*, 284–292.

Zhan, M., Ren, P., Zhang, C., & Li, F. (2012). *Throughput-optimized cross-layer routing for cognitive radio networks. Conference on communications in China: wireless networking and applications,* 821–826.

Zhang, X., & Hang, S. (2010). CREAM-MAC: Cognitive radio-enabled multi-channel MAC protocol over dynamic spectrum access network. *IEEE Journal of Selected Topic on Signal Processing, 5*, 110–123.

Zhao, Q., Zhu, Y., Chen, C., Zhu, H., & Li, B. (2013). When 3G meets VANET: 3G-assisted data delivery in VANETs. *IEEE Sensors Journal, 10*, 3573–3584.