Cognitive Vehicular Networks

SMART RADIOS FOR SMART VEHICLES

Marco Di Felice, Rahman Doost-Mohammady, Kaushik R. Chowdhury, and Luciano Bononi

The recent strides made in vehicular networks have enabled a new class of in-car entertainment systems and enhanced the ability of emergency responders using opportunistic spectrum usage enabled by cognitive radio (CR) technology. These CR-enabled vehicles (CRVs) have the ability to use additional spectrum opportunities outside the IEEE 802.11p-specified standard 5.9-GHz band. The aim of this article is to provide a taxonomy of the existing literature on this fast-emerging application area of CRV networks, highlight the key research that has already been undertaken, and point toward the open problems. We explore different architectures [i.e., completely decentralized as well as base station (BS) supported], the sensing schemes suited for highly mobile scenarios with emphasis on cooperation, and spectrum access methods that assure the availability of the required quality of service (QoS). Moreover, we describe the design of a new simulator tool that is able to merge information from real-world street maps with licensed user activity patterns, thereby resulting in a powerful platform for testing and analysis of protocols for CRVs. Finally, the article lists several open research challenges aimed at drawing the attention of the reader toward the important issues that need to be addressed to realize the vision of completely autonomous CRVs.

After a decade of research and investments in vehicular networks, the large-scale deployment of distributed systems based on inter-vehicular communication appears

Digital Object Identifier 10.1109/MVT.2012.2190177
Date of publication: 21 May 2012

1556-6072/12/$31.00©2012IEEE

as a concrete possibility in the next few years. As an example, in the United States and Europe, the bands at 5.85–5.925 GHz of the wireless spectrum have been reserved for both intervehicular and vehicle-to-roadside BS communication, whereas the transmitting operations in these bands have been regulated by the IEEE 802.11p and IEEE 1609.4 standards [16], [17]. At the same time, several applications for drivers' safety (e.g., adaptive cruise control systems) and traffic monitoring (e.g., traffic information and monitoring systems) have been already implemented and evaluated in realistic urban environments. One of the concerns, however, is the need for strict bandwidth and delay thresholds to support these vehicular applications, especially in the light of different quality of service (QoS) requests arriving from multiple sources, and in urban scenarios where the devices contending for the channel are significantly high [1]. The resulting problem of spectrum scarcity for IEEE 802.11p-based vehicular applications has been demonstrated in [2]. This growing spectrum-scarcity problem will likely become more acute, given the spurt in high-bandwidth multimedia applications (e.g., video streaming) for in-car entertainment, and for driver-support services, such as multimedia-enabled assistance.

The CR technology [3] is an enabling technology for opportunistic spectrum use, which directly benefits various forms of vehicular communication. In such a network, each CRV implements spectrum management functionalities to 1) detect spectrum opportunities over digital television (TV) frequency bands in the ultrahigh frequency (UHF) range, 2) decide the channel to use based on the QoS requests of the applications, 3) transmit on it, but without causing any harmful interference to the licensed owners of the spectrum. However, CRVs have many unique characteristics that involve additional considerations than merely placing a CR within a vehicle. As an example, unlike static CR systems, the spectrum availability perceived by each moving vehicle changes dynamically over time as a function not only of the activities of the licensed or primary users (PUs) but also based on the relative motion between them. Thus, spectrum measurements need to be undertaken over the general movement path of the vehicles, leading to a path-specific distribution, instead of focusing on the temporal axis alone. While this calculation is nontrivial, the CRV network can also leverage the constrained nature of motion, i.e., along linear and predecided paths corresponding to streets and freeways. At busy hours or in urban areas, spectrum information can be exchanged over multiple cooperating vehicles, leading to know more about the spectrum availability. This also allows the vehicles that follow to adapt their operations and undertake a proactive response, which is infeasible in both static or nonstationary scenarios with random motion.

SPECTRUM ALLOCATION IS PERFORMED TO MEET THE QOS REQUIREMENTS OF VEHICULAR APPLICATIONS, SUCH AS BANDWIDTH USAGE FOR NONSAFETY APPLICATIONS AND DELAY CONSTRAINTS FOR SAFETY-RELATED APPLICATIONS.

We envisage CRV networks to fall under three broad classes shown in Figure 1. In the first example, such networks could be formed between vehicles only that rely on cooperation for increasing accuracy. The second class deals with periodic interactions between vehicles and roadside BSs, where the latter acts as a repository of data that is subsequently used by passing vehicles. Finally, a completely centralized network is possible, in which the BS autonomously decides the channels to be used by the CRVs, without relying on information from the vehicles. The following section describes the possible applications of CRV networks, which will undoubtedly result in higher levels of adoption and widespread use of this technology.

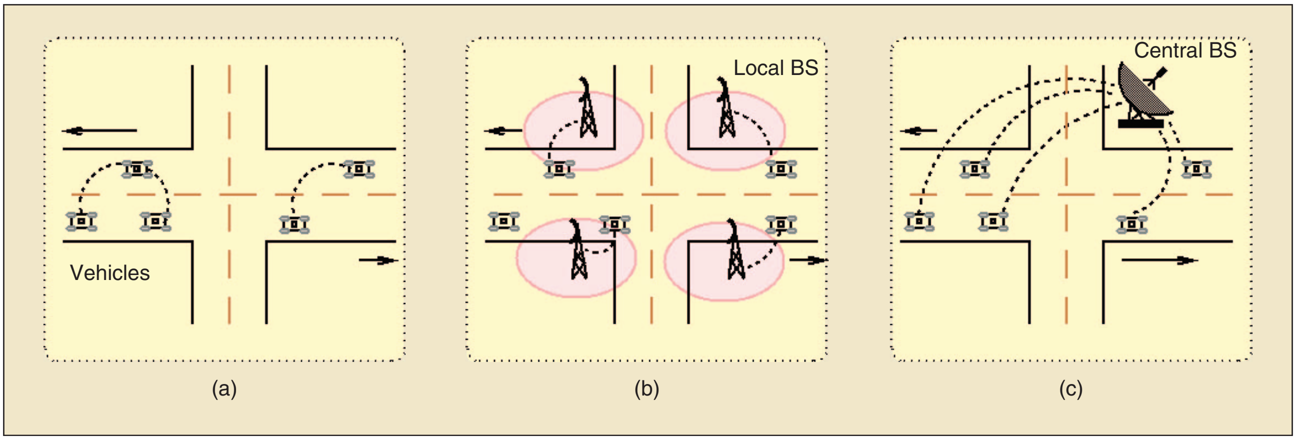

FIGURE 1 Three deployment architectures for CRV networks: (a) vehicle to vehicle only, (b) multiple local BSs, and (c) centralized BS-serving vehicles.

Applications of CRVs

The particular choice of transmission frequency, the bandwidth available for transmissions, and the interference caused in that range are important factors influencing the applications. In the following, we describe how CRVs will change existing and emerging vehicular applications.

- *Vehicle-to-Vehicle (V2V) Communication:* In high traffic areas, delays are caused by accidents, road blockages, and road repairs, and slow traffic can be avoided by communicating average velocity, acceleration, and brake status, all of which require periodic exchange of data with neighboring vehicles. These systems generally operate in the 5.9-GHz band. Practical systems created by Honda and Volkwagen-led consortium [4] have their transmission ranges limited to a few dozen meters, which also impacts the distance at which a corrective action is undertaken. There is, hence, a motivation to use lower frequencies in the sub-gigahertz range as the signal propagates much further, increasing the effectiveness of the response significantly.
- *Entertainment and Information Systems:* In-car streaming video entertainment options, as well as driver assistance through real-time feeds on traffic, weather, and visual inputs from external cameras are finding increasing commercial acceptance. These applications have strict bandwidth and QoS requirements. While recent work has approached both theoretical and practical aspects of multimedia delivery in vehicles [1], there are inherent scalability limitations of using fixed range or unlicensed bands alone, further motivating the use of CR technology.
- *Public Safety Communication:* The breakdown of the public safety communications infrastructure has occurred repeatedly in large-scale natural disasters, such as the recent hurricane Katrina, wherein public safety personnel has to resort to nonelectronic means of communication. CRVs will allow distributed spectrum access in the uncongested licensed frequencies, which is especially useful for mobile public safety personnel that operate in the field during such outages, and also those beyond the reach of the fixed infrastructure installations.

Characteristics and Features of CRVs

In this section, we describe the characteristic features of CRV networks that play a vital role in their design and also differentiate them from general-purpose CR networks.

- *Integration with Spectrum Databases*: Recent U.S. Federal Communications Commission (FCC) rulings foresee the creation of spectrum databases that specify two modes of device operation [5]. Mode II devices have geolocation and database access to maintain a continuously updated spectrum occupancy list, while Mode I devices periodically query Mode II devices for spectrum updates. In the context of CRVs, each vehicle must hence have a dedicated out-of-band radio interface to directly query the database (for Mode II), or multiple roadside BSs must be placed, akin to mile markers, that feed this information to an onboard radio operating in Mode I.
- *Application Scenario*: The strict requirement that Mode I devices must receive updates every 60 s influences the placement and density of roadside BSs. This impacts the investment in the supporting infrastructure that CRV networks require to strictly follow the FCC rules, and this will vary based on specific areas of a given city and on the traffic experienced during the busy hours.
- *Impact of Mobility*: The FCC ruling also specifies a sensing-only mode, in which a CR device relies on local sensing results, once it is rigorously certified [5]. In a CRV, a vehicle may collect multiple sensing samples at different locations, but inside the same PU activity region. Since the collected samples might exhibit different degrees of correlation based on the characteristics of the environment (e.g., presence of buildings) and the speed of the vehicle, merging these data points correctly is important [6]. Thus, spectrum management in CRVs cannot be performed without considering traffic conditions and vehicular speed.
- *Application Scenario*: The impact of mobility on spectrum management will directly influence correctness of the sensing information. In a region with tall skyscrapers, such as Boston downtown area where we conducted several studies, the mobility resulted in several nonintuitive results [7]. In some cases, low mobility was better, as more samples per unit area were collected. Yet, in other cases, high mobility allowed the vehicle to move away from a shadow region quickly, giving improved sensing performance.
- *Role of Cooperation*: In CRV networks relying on sensing-only mode, cooperation among vehicles can be leveraged through their predictable mobility pattern to perform enhanced spectrum sensing and decision. Here, a vehicle is aware of the spectrum resources available on its path in advance, i.e., before arriving in the area of interest by leveraging the spectrum information provided by other vehicles. However, the set of cooperating neighbors may dynamically change as an effect of the varying topology, thus impacting the performance of the cooperation scheme over time.
- *Application Scenario*: Cooperation will not only result in many safety-related V2V communications but also serve to predict the spectrum usage ahead. The ability to chart out spectrum (apart from the route alone, which is now commonplace) will enable the choice of specific applications, yet serve to discount others that will experience disruptions. Moreover, future route-determining software could also factor this

locally obtained information to identify the regions where the user may have the best travel experience, going beyond the shortest distance alone.

- *Presence of a Common Control Channel (CCC)*: In CRV networks, a CCC is already provided in the 5.9-GHz band through the IEEE 802.11p protocol, which addresses some of the concerns present in general CR networks. However, there is still a possibility that the CCC in the 5.9-GHz band becomes easily saturated in congested scenarios (e.g., peak hours of traffic) as indicated in [2]. Hence, control messaging must be minimized in CRV networks, or additional control channels (CHs) must be identified.
- *Application Scenario*: In the event of a sudden disaster, the rapidly occurring peak traffic rate may overwhelm existing communication resources, and primary responders might be unable to maintain connectivity to each other and the control room. By limiting self-generated control information, the overall impact of a sudden rise of channel usage may be minimized.

Classification of Existing Schemes for CRVs

Research on CRV networks has mainly focused on spectrum sensing and spectrum access. The classification of existing schemes is shown in Figure 2.

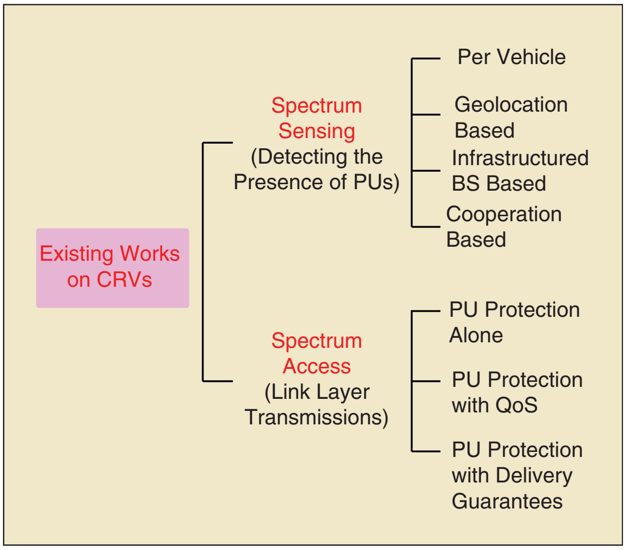

FIGURE 2 The classification of existing works on CRVs.

Spectrum Sensing

This key component of CRV networks ensures that the spectrum availability is correctly detected, which is a challenge in highly mobile scenarios. We identified four different sensing techniques that have been proposed in the literature of CRV networks. A comparative description of the characteristics of each sensing technique is shown in Table 1.

Per-Vehicle Sensing Techniques

In this approach, CRVs sense the TV band by using any traditional sensing technique proposed in the literature of CR systems, i.e., energy detector, matching filter, or cyclostationary techniques [3]. Since each CRV performs spectrum sensing and decision autonomously, the implementation complexities and the network support are minimal. At the same time, there are several concerns on the accuracy provided by per-vehicle sensing techniques. While the thresholds imposed by IEEE 802.22 standard on the CR receiver sensitivity are very low (i.e., -116 dBm for TV bands), the sensing output in the presence of obstructed environments and high mobility might be easily biased by propagation phenomena such as fading or shadowing effects.

Geolocation-Based Techniques

Recent FCC directives [5] suggested the utilization of geolocation database as an alternative or complementary technique to sensing-only schemes. Geolocation database can provide information about the bands, including the exact types of PUs and their locations and specific protection requirements. As a result, CRVs do not need to sense for the presence of PUs and can adjust their transmitting parameters not to interfere with the licensed users. This solution is suitable for CRVs, since each vehicle might be likely equipped with self-localization systems (e.g., global positioning system device). Moreover, the digital maps

TABLE 1 *The comparison among different sensing techniques for CRVs.*

Technique	*Reference*	*Pros*	*Cons*
Per vehicle	[3]	Low implementation complexity, no network support required	Low PU protection in the presence of fading
Geolocation based	[8], [9]	High PU receivers protection	Implementation and update costs, coverage is an issue
Infrastructured BSF based	[10]	Higher accuracy than per-vehicle, BS can provide a long-term history of the channel (memory effect)	Fixed infrastructure needed, overhead for V2I communication might be an issue
Cooperation based	[7], [11]	More robust to fading effects than per vehicle, no infrastructure required, possibility to know channel conditions in advance	Performance dependent on traffic density and cooperation parameters (e.g., frequency of updates)

RECENT FCC DIRECTIVES SUGGESTED THE UTILIZATION OF GEOLOCATION DATABASE AS AN ALTERNATIVE OR COMPLEMENTARY TECHNIQUE TO SENSING-ONLY SCHEMES.

might be easily integrated with PU information provided by a spectrum allocation database (e.g., the TV query [8] service in the United States). However, there are important concerns on the implementation of geolocation techniques, i.e., the costs for building the database, the coverage area of the service, the requirements for the CR vehicles. For this purpose, some recent works [9] investigate the possibility to use geolocation information in conjunction with sensing (cooperative or not) techniques. One advantage of this joint technique is that CRVs might still be able to access the licensed TV spectrum in regions where the database information are incomplete or missing.

Infrastructured BS Based

A new type of cooperative sensing approach is described in [10]. Here, the network uses a stationary BS that provides coordination instructions to the passing vehicles, which can take then undertake the final sensing results locally. The BS continuously gathers information of the PU occupancy at its location through energy detection, which is a fast but coarse result, and leaves fine-grained sensing (e.g., feature detection) to the CRVs. The advantage of this method is that any change in government policy of new regulatory standards as well as PU parameters can be easily loaded at the BS for further adapting the operation.

Cooperative Techniques Between Any Neighboring Vehicles

A problem with a centralized fusion center or BS is pointed out in [11], where we argue that each vehicle may have a different view of the spectrum usage, based on its location. Instead, they propose a belief propagation method that requires each CRV to periodically send out its respective belief of the presence of a PU. Each vehicle combines these belief vectors with its own to generate a new belief. This is then passed on, and after several iterations, the network is envisaged to enter into a steady state. Several issues need to be further explored in this work, such as the speed of convergence in the network, the practical and theoretical bounds of belief techniques, and the extent of belief propagation with respect to vehicle velocity.

Cooperative Techniques Between Selected Neighboring Vehicles

The problem of choosing the extent of cooperation in a vehicular environment based on specific concerns of correlated readings, and a priori spectrum availability detection at future anticipated locations, is addressed in [7]. The road is divided into short segments, allowing a vehicle in the current segment to gather spectrum information up to h segments ahead from vehicles in front. Thus, when the vehicle determines its own spectrum to use for the next portions of the road, it broadcasts its choices, thereby allowing subsequent vehicles to also adjust their own parameters. A correlation-aware weighted average is used at each vehicle to combine the results of the local sensing activity with the information coming from other CRVs.

Spectrum Access

Once the sensing results are known, correctly choosing the spectrum and the appropriate method of using it has a multifold impact, which is the focus of this section.

Licensed/PU Protection Alone

In this approach, the CRVs decide the spectrum to use with the goal of minimizing the harmful interference to PUs, but without taking into account the specific QoS requirements of the vehicular applications. A range of metrics for spectrum selection by CRVs, such as spectrum with the highest 1) data rate, 2) product of rate and channel utilization, and 3) product of rate and expected vacant channel duration are defined in [12] and evaluated through a simulation study.

Spectrum Access with QoS Support

In this approach, spectrum allocation is performed to meet the QoS requirements of vehicular applications, such as bandwidth usage for nonsafety applications and delay constraints for safety-related applications. To this purpose, a three-pronged approach is proposed in [13] for clustered vehicles, involving selection and access of shared channels, exclusive-use channels, and cluster size control under the dual constraints of meeting the QoS specifications and PU protection. The shared channels belong to the licensed bands used for intercluster communication, and it may not be always available for use by the CRVs. Conversely, the exclusive-use channels are typically reserved portions of the spectrum, such as short-range transmission frequencies specified in the IEEE 802.11p standard, and used for intracluster networking. The cluster size, the bandwidth allocation for each CRVs, and the spectrum allocation for each cluster are decided through an optimization framework implemented by the BSs and are based on the constrained Markov decision process (CMDP) model.

Spectrum Access with Delivery Guarantees Only

When a complete QoS provision is unavailable or not required, issuing guarantees for data delivery will assist in reliable transmission of public safety information. This is indeed a problem in classical IEEE 802.11p-based networks that have well-defined CCH and service channel (SCH) durations of 50 ms each. Safety message delays should be less than 200 ms for adequate response time of the drivers and, coupled with the need for message repetition, the window of 50 ms appears inadequate [2]. Hence, we propose a feedback-loop method where local BSs assist vehicles in securing additional spectrum. The CRVs periodically provide feedback to the BSs about the spectrum usage, allowing the incremental addition of new spectrum to the network pool to the extent that channel contention is below a predecided threshold.

Open Research Issues

In the following, we discuss some important research issues relative to the impact of the vehicular mobility, security aspects, and the evaluation methodology for CRV networks.

Impact of Vehicular Mobility on Spectrum Management

Mobility has both positive and negative implications for CRV networks. On the one hand, the Doppler spread caused by mobility might result in inaccurate detection of occupied frequencies, which may cause harmful interference to the PUs. On the other hand, a moving CRV can collect signal samples at different locations along its path, thus increasing the spatiotemporal diversity of the samples, and reduce the risk of incorrect decision caused by shadowing effects. In [6], we investigate the performance of spectrum sensing with mobile CR sensors through a theoretical study, and they show that the accuracy of sensing increases with vehicle speed due to the increased spatiotemporal diversity. Also, they demonstrate the existence of an interesting tradeoff between sensing scheduling and cooperation among nodes. When CRV nodes are moving at high speed, it is more efficient to sense multiple times that wait for predetermined intervals between two sensing instants, since the observations are likely not correlated. In the converse case, when CRVs are moving slowly, it is better to cooperate with other nodes than sensing the channel with high frequency. However, this work does not take into account the planned paths and the constrained nature of the movement caused by the road topology. For instance, the collaborative spectrum framework described in [7] allows a vehicle to gather information about spectrum opportunities over an enlarged area that includes the current location and also past and future locations. Our sample experiments undertaken with a universal software radio peripheral device placed on top of a moving vehicle in [7] also demonstrate that sensing accuracy is a function of both specific locations and speed. These results are summarized in Figure 3 for three locations: A has moderately spaced buildings of medium height, B has a bridge location with

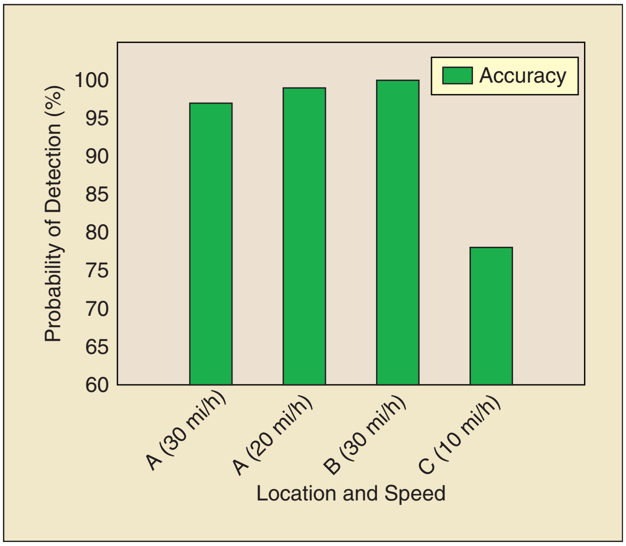

FIGURE 3 The spectrum sensing accuracy at three different locations of Boston: (A) moderately spaced structures, (B) open area, and (C) congested downtown.

open expanse on either side, and C is a busy downtown street in Boston.

Despite these preliminary results, there are still many unanswered questions on the impact of vehicular mobility on sensing performance, which are summarized as follows: What is the optimal technique to balance cooperation and spectrum scheduling for a moving CRV? How can the predictable mobility of vehicles be exploited to increase spectrum awareness? What is the impact of mobility parameters (e.g., speed and direction) on sensing performance?

Security Aspects of CRV Networks

Cooperation among vehicles improves the spectrum sensing accuracy. At the same time, it also poses several concerns from the point of view of trust and security [14]. CR radios may develop genuine hardware faults or turn on malicious being compromised, i.e., the users can falsify sensing reports such as the presence of a PU to guarantee the exclusive access on a channel. Existing schemes proposed for CR networks address the problem by assigning different weights to each node based on its trust and combine local decisions based on the weight of each node [14]. The situation is significantly more involved in mobile environments such as CRV networks, where the neighbor set might change over time. In other words, identifying a malicious vehicle that sends false-sensing reports while moving might require fast detection and correction, when compared with the static case. Additionally, the implementation of collaborative spectrum sensing in CRVs poses privacy concerns to end users. For instance, a potential attacker might track the identity and movements of a driver by eavesdropping the periodic spectrum information broadcast by the vehicle. In conclusion, the research questions related to security in CRV networks involve: How can

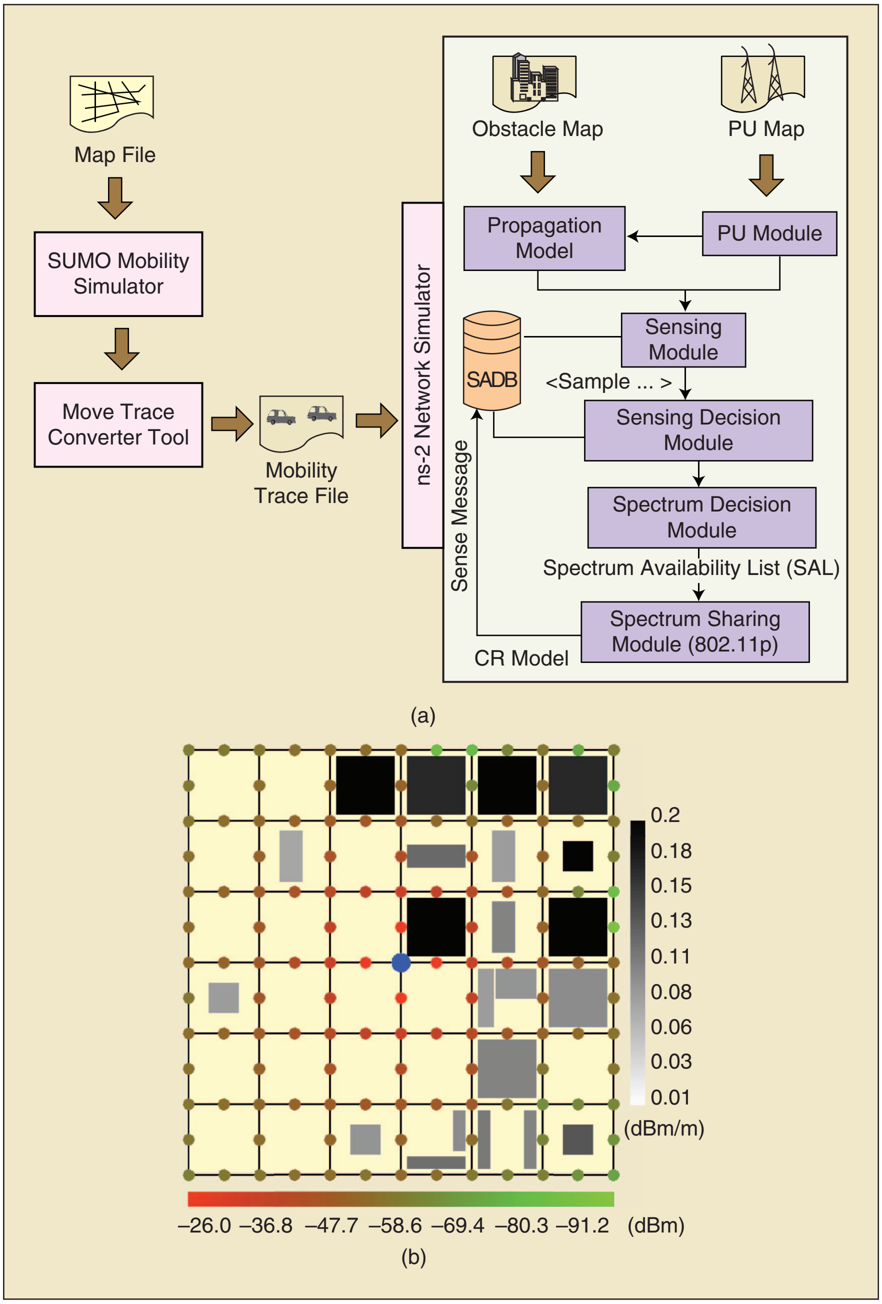

FIGURE 4 (a) The architecture of the ns-2 CRAHN tool for CRVs. (b) A screenshot of the simulator.

the system detect the presence of malicious CRVs that broadcast fake sensing reports while moving? How can the privacy of cooperating vehicles be protected?

Modeling and Simulation of CRV networks

Although several mobility generators and network simulations are available for vehicular networks, no general-purpose simulator for CRV networks has been developed. Our proposed simulator in [7] is a first step in this direction, building on the ns-2 cognitive radio ad hoc networks (CRAHN) environment [15], which in turn extends the ns-2 simulator with additional models for the simulation of CR networks. The ns-2 CRAHN model includes 1) a trace-driven model of PU activity, 2) a model of the cognitive functions undertaken by each CR, which includes spectrum sensing, spectrum mobility, and spectrum decision modules, and a 3) cross-layer information repository that allows users to implement spectrum-aware policies at network and transport layers. Our extensions for CRV networks involve creating specific street scenarios complete with intersections, roadside buildings with appropriate height selections through OpenStreetMap, and then generating movement traces for individual vehicles within this scenario through the mobility generator simulation of urban mobility (SUMO). The architecture of our simulation tool is shown in Figure 4(a). The additional propagation models that are part of our simulator tool use the building heights and other topological features to calculate fading effects at each mobility trace location. The graphical representation of the simulator result is shown in Figure 4(b), with the grid lines denoting streets and the (blue) circle in the middle denoting the location of the PU. The rectangular blocks denote attenuation regions based on the vertical black/white scale. This is a direct result of buildings present in the cells. The received power scale is shown along the horizontal plane, and varying intensity points on the grid cause errors in signal detection. The development of an accurate simulation platform continues to be an open research challenge, with additional features of spectrum database access, interaction with roadside BSs, and realistic spectrum management models yet to be implemented.

Conclusions

In this article, we have discussed the current state-of-the-art research on CRV networks. While we envisage that this technology will help to realize high-bandwidth multimedia applications, the research on CRV networks is still at a preliminary stage. The spectrum management functions proposed for general-purpose CR networks will need to be revisited by taking into account the characteristics of the vehicular environment, such as the role of the mobility, and the cooperation possibilities. The lack of realistic test beds and of simulation tools is a serious limitation, and effort needs to be invested in building such evaluation platforms that can provide realistic insights on the performance of CRV networks before the potential for this technology can be fully realized.

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