VEHICULAR NETWORKING IN THE TV WHITE SPACE

Challenges, Opportunities, and Media Access Control Layer Issues

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With the increase of wireless data traffic demand, supplementing dedicated short-range communications (DSRC) with additional spectral opportunities becomes very important. In many countries, due to the switchover from analog to digital television, a significant portion of the television (TV) band has been released for opportunistic cognitive access. Therefore, one possible solution to the spectrum scarcity problem in the DSRC band is to offload a portion of data traffic to the TV white space (TVWS) band. However, expansion of vehicular networks to the TVWS by means of cognitive radio technologies causes novel challenges such as random channel availability, strict protection of incumbent spectrum users, and dealing with interference among heterogeneous cognitive networks. In this article, we

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outline the challenges and opportunities involving TVWS access for vehicular networks, with an emphasis on media access control (MAC) layer issues. Numerical results of the DSRC system augmented with a TVWS cognitive module are also presented.

Supplementing the DSRC Band

Tens of megahertz of bandwidth in the 5.9-GHz band [which is also called the DSRC band by the U.S. Federal Communications Commission (FCC)] have been allocated to vehicular communications to support intelligent transportation systems.

However, many studies have shown that the DSRC band requires further spectral resources to accommodate either emerging safety-related applications like collision avoidance and safety warning, or nonsafety applications like remote vehicle diagnostic, file downloading, web browsing, and video streaming [1]. Meanwhile, due to the switchover from analog to digital television, many TV channels in the ultrahigh-frequency and very-high-frequency bands have been released for cognitive access in many countries, including the United States [2], the United Kingdom, Canada, and South Africa. These TV channels are referred to as the *TVWS channels*. Hence, a potential solution to the DSRC spectrum-scarcity problem is to offload a portion of data traffic from the DSRC band to the TVWS band. Specifically, many studies show that the TVWS-enabled vehicular network can not only deliver massive delay-tolerant packets from nonsafety applications like multimedia streaming [1], [3] but also improve the capability of vehicles to disseminate delay-sensitive packets from safety-related applications [1], [4].

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Due to unique propagation characteristics of the TVWS channels, TVWS-enabled vehicular networking is faced with the following novel challenges:

- *Protection of incumbent TVWS users*: To protect the incumbent service [or primary user (PU)], such as a TV broadcast, the FCC issued strict rules on transmission time and the power of secondary users (SUs) such as vehicles. Geolocation/database access and spectrum sensing are proposed to conform to these rules. However, [5] shows that none of these approaches can guarantee sufficient

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PU protection in vehicular networks, which calls for more reliable methods.

- *Interference from other secondary networks*: Since TVWS is an unlicensed band, most existing wireless networks are allowed to utilize it, which creates a novel coexistence challenge. Moreover, according to the FCC [2], TVWS devices are classified into three categories: fixed devices, portable devices operating in Mode I, and portable devices operating in Mode II. Fixed devices are allowed to use 4 W of transmission power, while portable devices (e.g., vehicular TVWS devices) can only use up to 100 mW transmission power, which results in an even worse coexistence environment for portable devices.
- *Spatiotemporal variations of TVWS channels*: Due to the FCC's rules on PU protection, the availability of TVWS channels can vary rapidly as vehicles move fast on roads. Vehicles must evacuate a channel immediately when the channel becomes unavailable, which calls for reliable detection of channel variations, and efficient mechanisms to break an existing link on the old channel and reestablish a new link on another available TVWS channel.
- *Dual-band operation requirements for vehicles*: Since both the DSRC and the TVWS bands are available, a novel challenge arises that vehicles must be able to disseminate communication between the two bands seamlessly. First, it's essential to study under what conditions vehicles should utilize one band or the other. Second, seamless migration mechanisms are required to realize the switchover. Finally, significant differences of the two bands on propagation properties make dual-band operations more difficult.
- *High mobility of vehicles*: High mobility of vehicles is already a main concern in DSRC vehicular networking. It becomes more challenging in TVWS-enabled vehicular networking because high mobility aggravates the spatiotemporal variations of TVWS channel availability, which poses more difficulties for PU protection, coexistence with other SU networks, and dual-band operations [6]. For example, vehicles may need to frequently send a channel availability request to TVWS databases due to their high mobility, which can cause congested uplinks to the databases. As a result, vehicles can fail to obtain the channel availability information (CAI) in time.

Vehicular Networking in the TVWS Band

Vehicular channel access in TVWS is subject to protection of incumbent users, e.g., digital TVs and microphones [2]. In the following section, we discuss the following MAC issues:

- obtaining the CAI
- coexistence with other heterogeneous networks
- operations in both the TVWS band and the DSRC band
- efficient channel selection schemes.

TVWS CAI

To protect the PU of the TVWS band, the FCC requires that all TV band devices (TVBDs) must obtain the CAI first and utilize the channels only if they are not being used by incumbent users. In [2], two methods are proposed for TVBDs to obtain the CAI, namely, database access and spectrum sensing. In the first method, a TVBD first determines its location and sends a CAI request to its closest TVWS database. After receiving the request, the database replies to the TVBD with the CAI near the TVBD's location. In the second method, TVBDs obtain the CAI independently through local spectrum sensing. Many spectrum-sensing technologies have been developed, such as energy detection, compressed sensing, waveform-based sensing, and pattern recognition–based sensing. Since the database access method is believed to be more accurate, it is regulated as a mandatory technology for all TVBDs by the FCC, while spectrum sensing is regulated as an optional technology [2].

One problem with the database access method is the determination of the channel over which TVBDs send the CAI requests before they know the available TVWS channels. A straightforward solution is to allocate a dedicated out-of-band control channel for the CAI queries. However, to the best of our knowledge, no regulations have been published to allocate such a channel. In addition, the FCC requires that portable TVBDs must request the CAI for every movement of 100 m, which can cause severe traffic congestion and delayed response at the database due to the high mobility of the vehicles. To solve this issue, a method is proposed in [7] to reduce the query load of the databases using a speed-aware vehicle grouping scheme. Another potential solution is that vehicles download all CAI based on their predetermined routes from a single database. However, this requires additional data storage space in the vehicles. Moreover, neither the database access nor the spectrum sensing method alone can meet the FCC's regulations on incumbent user protection in a vehicular environment [5]. Therefore, mixed technologies with both TVWS database access and spectrum-sensing functionality should be explored to satisfy the regulations on PU protection.

Coexistence with Heterogeneous Networks

Due to the unlicensed nature of the TVWS, various networks will coexist and interfere with each other in this band, which creates a novel spectrum-sharing issue.

This issue is more pronounced than the coexistence of Wi-Fi, ZigBee, and Bluetooth networks in the 2.4-GHz industrial, scientific, and medical radio band due to superior propagation properties in the 54–698-MHz range and the regulations on incumbent user protection. Also, the FCC allows fixed TVBDs to use up to 4 W transmitting power while limiting the transmitting power of portable TVBDs to 100 mW. The power asymmetry policy creates an even worse coexistence environment for vehicular networks. Although the IEEE 802.19.1 standard [16] has been published to facilitate the coexistence of heterogeneous networks in the TVWS, as shown in Figure 1, the framework highly relies on additional coexistence entities, including coexistence managers, coexistence enablers, and coexistence information servers. Considering the huge cost of building the coexistence infrastructure, it may take a long time to fully implement the coexistence framework, even if a sufficient budget were provided. Hence, more practical coexistence solutions for vehicular networks need to be developed.

Two IEEE standards dedicated to TVWS access have been published, namely, IEEE 802.22 [17] for high-power cellular networks, and IEEE 802.11af [18] for low-power ad hoc networks. Therefore, as shown in Figure 1, we particularly consider the coexistence of vehicular

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networks with these two networks. Since the transmission power level of IEEE 802.11af devices is similar to that of vehicular devices, it is important to guarantee fair spectrum sharing between the two networks. As an example, the coexistence problem between portable cognitive emergency wireless networks (PCENs) is addressed in [8], in which a stochastic–geometric model is used to characterize the potential reduction of the effective service area caused by adjacent homogeneous PCENs. There, the relationship between the PCEN service area and TVWS-related system parameters is studied analytically. However, the method does not apply to the coexistence of vehicular networks and IEEE 802.11af networks due to the high mobility of the vehicles and the heterogeneous properties of the two networks. In addition, other coexistence methods can be explored, such as power control, dynamic channel selection, listen-before-talk, time-division multiple

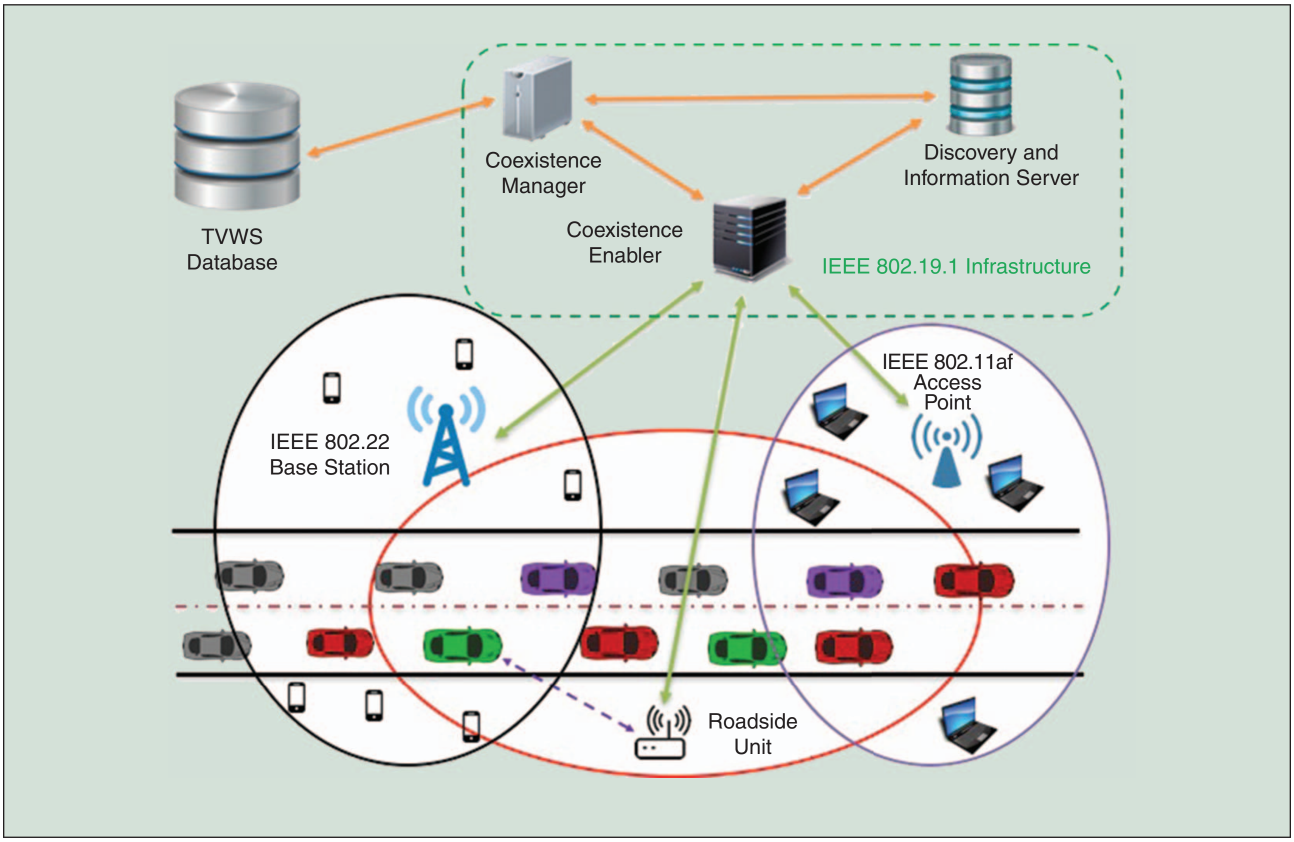

FIGURE 1 A diagram of the coexistence of multiple TVWS secondary networks.

CONSIDERING THE HUGE COST OF BUILDING THE COEXISTENCE INFRASTRUCTURE, IT MAY TAKE A LONG TIME TO FULLY IMPLEMENT THE COEXISTENCE FRAMEWORK, EVEN IF A SUFFICIENT BUDGET WERE PROVIDED.

access, clustering-based methods, and game theoretical methods [6].

The power asymmetry policy of the FCC creates a challenging spectrum-sharing environment for portable networks when coexisting with high-power IEEE 802.22 networks. Specifically, the transmissions of fixed 802.22 devices can easily starve vehicular transmissions due to the large power difference. Even worse, it is almost impossible to request explicit coordination between the two networks because it requires significant changes to the existing 802.22 standard. Given these difficulties, a proactive coexistence framework is proposed in [9] to facilitate the spectrum sharing between a vehicular network and an 802.22 network. In this coexistence framework, vehicular devices use the existing 802.22 upstream scheduling information, which is periodically broadcast by the 802.22 base station, and adjust their own transmissions such that they can reuse the 802.22 upstream time slots without causing harmful interference to the 802.22 upstream transmissions.

Dual-Band Operations

In the considered framework, vehicles can use both the DSRC band and the TVWS band. This dual-band operation problem is similar to the multiband operation problem addressed in the IEEE 802.11ad [19] standard, where millimeter-wave devices can use both the 2.4-GHz band and the 60-GHz band. However, the DSRC/TVWS dual-band operation is more difficult because vehicles have different access priorities over the two bands, and mutual interference among vehicles is worse due to the aforementioned propagation properties of signals in the TVWS.

The dual-band operation requirement causes a novel spectrum handoff (or migration) problem, i.e., how a session on a DSRC channel can be migrated to a TVWS channel seamlessly. Similar to the control channel in the DSRC band, a DSRC service channel can be used as a dedicated TVWS control channel. Then, all spectrum handoff-related control messages can be exchanged on this TVWS control channel. More importantly, the TVWS control channel can also be used both to send CAI requests to the TVWS spectrum database and to coordinate access of the TVWS among adjacent vehicles. However, reserving the TVWS control channel requires significant change to the legacy IEEE 1609.4 standard [20] which can be infeasible. Another challenge of enabling dual-band operations is to determine the conditions under which a communication session should be migrated from the DSRC band to TVWS. More specifically, determination of the migration conditions requires evaluating and comparing channel quality in the DSRC band and TVWS, which is still an open research issue. Moreover, the design of efficient dual-band operation protocols is further complicated by vehicle mobility, different access priorities, and mutual interference between TVWS networks.

Channel Selection Schemes

Channel selection is a fundamental problem in multichannel wireless networks. For example, the DSRC band is composed of one control channel and six service channels, and the IEEE 1609.4 standard has been published to enable multichannel operations in vehicular networks. Similar to the DSRC band, the TVWS band also consists of tens of channels [2]. Compared with the channel selection problem in the DSRC band, the TVWS channel selection problem is more difficult because of the aforementioned challenges, such as the regulations on incumbent user protection. The channel selection problem becomes more challenging when TVWS and DSRC channels are jointly selected. Therefore, more advanced channel selection schemes must be developed to overcome these difficulties.

In [10], a centralized throughput-efficient channel selection method is proposed for TVWS-enabled vehicular networks. First, the availability of a TVWS channel is modeled as the return time of incumbent users, which is a random variable with known statistics. Then, the channel allocation problem is formulated considering the protection of incumbent users. Since the problem is proved to be nondeterministic polynomial-time hard, two approximation algorithms are developed, both with provable performance guarantees. In addition, the channel selection problem in TVWS-enabled vehicular networks is formulated as a matching problem in [11] by considering both throughput of the vehicular network and quality-of-service requirements of individual vehicles. Then, an algorithm is devised to solve the matching problem, which is proved to be stable and vehicle optimal. However, several open research issues still remain. One of them is accurate modeling of DSRC and TVWS channel quality. Conventional channel evaluation metrics like packet error rate and packet collision probabilities are not appropriate due to the random availability of the TVWS channels. In addition, development of distributed channel selection algorithms with both provable performance guarantees and low complexity is also a largely open issue.

Numerical Results

The IEEE wireless access in vehicular environment (WAVE) standard family is one of the main industrial efforts to facilitate vehicular communications in the

DSRC band, which includes standards such as IEEE 802.11p [21] for physical layer and low MAC layer and IEEE 1609.4 for upper MAC layer. Some field experiments have been performed to demonstrate the feasibility of TVWS-enabled vehicular networking (e.g., in [12], [13]). In particular, the field test results show that the TVWS-enabled vehicular network is able to support both safety-related applications [12] and nonsafety applications [13]. However, these experiments are limited both in terms of the number of test cases and scale due to their high cost. In this article, we address this issue by studying more networking problems through network simulations. As a widely used approach in networking research, network simulation is much cheaper and more flexible than field experiments, which makes it particularly suitable for studying complex and large-scale networks.

The network simulator 2 (ns-2) with a dedicated cognitive radio module [14] is used as our main simulation tool. In our simulation setting, the WAVE standard family is adapted to work in TVWS by incorporating the cognitive radio functionality. More specifically, the ns-2 cognitive radio module ensures that vehicles evacuate from a TVWS channel when incumbent users return to that channel [14]. Moreover, all the mobility models in our simulations are generated using the open-source software Simulation of Urban Mobility [15]. In [14], the availability of a TVWS channel is realized through an on–off Markov process, in which a channel is in the on state when incumbent users are transmitting on the channel. Hence, vehicles are allowed to utilize the channel only when it is in the off state. Before discussing simulation details, we introduce a new metric called *channel idle ratio (CIR)* to characterize the availability of a TVWS channel, i.e.,

$$CIR = E[t_{OFF}]/(E[t_{ON}] + E[t_{OFF}]), \qquad (1)$$

where t_{ON}, t_{OFF} denote the on and off times, respectively.

A simple simulation example is studied to validate the ns-2 cognitive radio module. As shown in Figure 2, we consider a cognitive vehicular network on a highway with six vehicles and one TVWS channel. Since the vehicles move with the same speed, they are relatively static to each other. At time 0, the three vehicles on the left side start transmitting user datagram protocol (UDP) packets to their corresponding same-lane vehicle on the right side with constant bit rates of 100 kb/s, 200 kb/s, and 300 kb/s, respectively. In particular, five PU transmissions are injected during the simulation.

Figure 3 shows that vehicular transmissions are significantly affected by the five PU transmissions. Specifically, all transmitters stop transmitting when incumbent users return to the TVWS channel, and restart transmitting after incumbent users leave. Next, we study the performance of the WAVE standard family under different CIR values. Two metrics are used in the evaluations, namely overall network throughput and average packet loss ratio (PLR). In addition, we compare the IEEE WAVE scheduler with an ideal cognitive scheduler, which is able to utilize all spectrum opportunities.

Figure 4 illustrates that there is a performance gap (around 20%) between the ideal scheduler and the IEEE WAVE scheduler. The PLR is always high when PU activities are present (Figure 5). Figures 4 and 5 indicate that the IEEE WAVE standard family is not able to ensure high-throughput and reliable vehicular communications in the TVWS band.

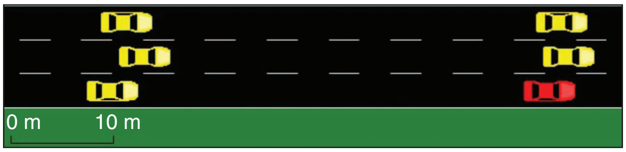

FIGURE 2 A cognitive vehicular network on a highway.

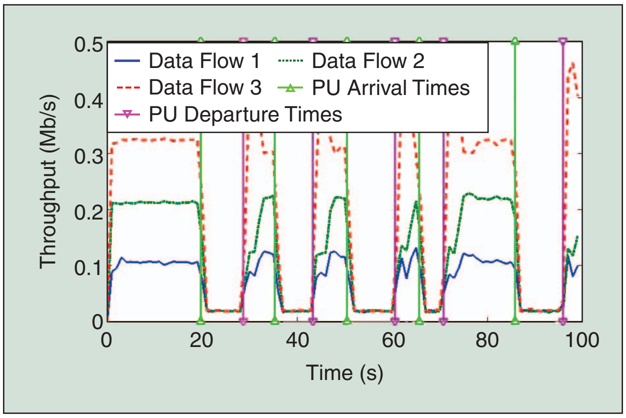

FIGURE 3 Five PU transmissions on the TVWS channel.

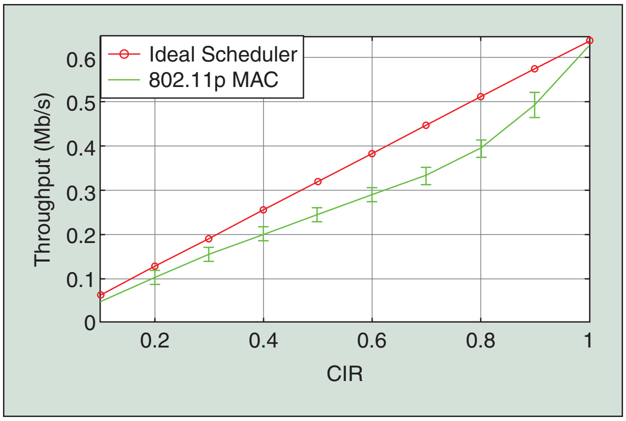

FIGURE 4 The overall network throughput of the standard DSRC network.

CONVENTIONAL CHANNEL EVALUATION METRICS LIKE PACKET ERROR RATE AND PACKET COLLISION PROBABILITIES ARE NOT APPROPRIATE DUE TO THE RANDOM AVAILABILITY OF THE TVWS CHANNELS.

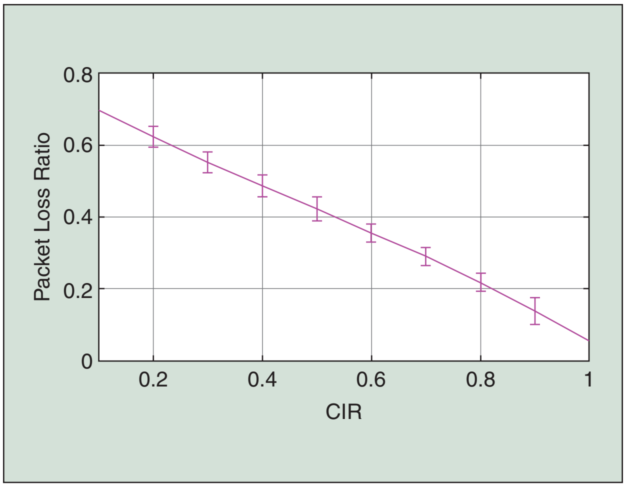

FIGURE 5 The average PLR of the standard DSRC network.

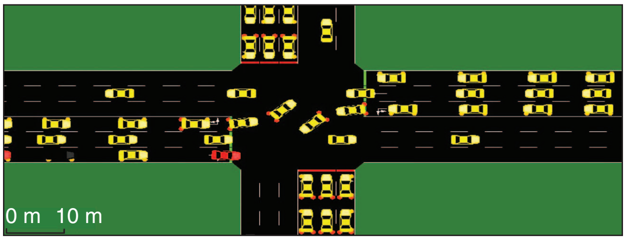

FIGURE 6 A road intersection model.

Next, we compare the performance of a DSRC vehicular network with a TVWS-enabled DSRC vehicular network. In addition to the DSRC band, a TVWS channel with a CIR of 0.5 is available in the TVWS-enabled network. As shown in Figure 6, we consider a road intersection model with traffic lights, in which vehicles repeatedly move from one end to the other three ends of the intersection. For example, among the vehicles departing from the left end, vehicles in the left lane will turn left (to the top end) at the intersection, vehicles in the middle lane will go straight (to the right end) at the intersection, and vehicles in the right lane will turn right (to the bottom end) at the intersection. Each vehicle keeps sending UDP packets to one of its neighbors with a constant rate of 100 kb/s.

Figures 7 and 8 show that the TVWS-enabled network outperforms the standard DSRC network in terms of both network throughput and PLR, which verifies that TVWS access is a promising approach to alleviate the DSRC spectrum scarcity problem. Figure 7 also shows that the network throughput decreases when the vehicle density is too high. This is caused by the contention-based carrier sense multiple access with collision avoidance channel access scheme defined in IEEE 802.11p. Specifically, multiple vehicles can switch to the TVWS channel simultaneously when it becomes available. As the number of vehicles increases, the TVWS channel can become congested such that all vehicles increase their back-off times. Hence, more efficient MAC protocols need to be developed to accommodate the medium control requirements in the TVWS-enabled vehicular network.

Conclusions

In this article, we presented an overview of TVWS-enabled vehicular networking. In addition, a simulation study illustrated the performance of the IEEE WAVE standard family extended with cognitive functionality on TVWS access. The

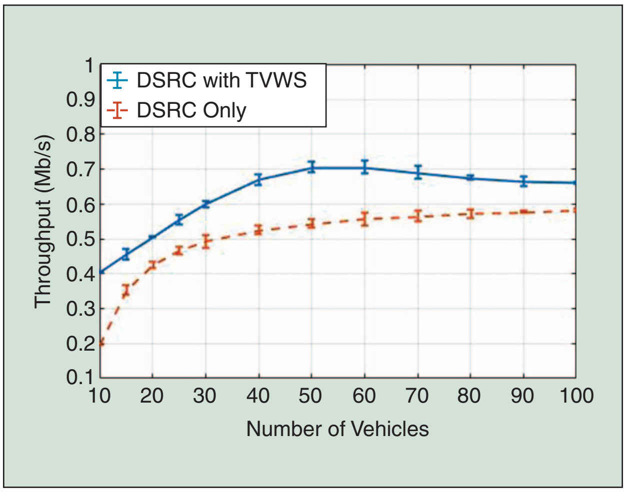

FIGURE 7 The overall network throughput of the TVWS-enabled network compared with the standard DSRC network.

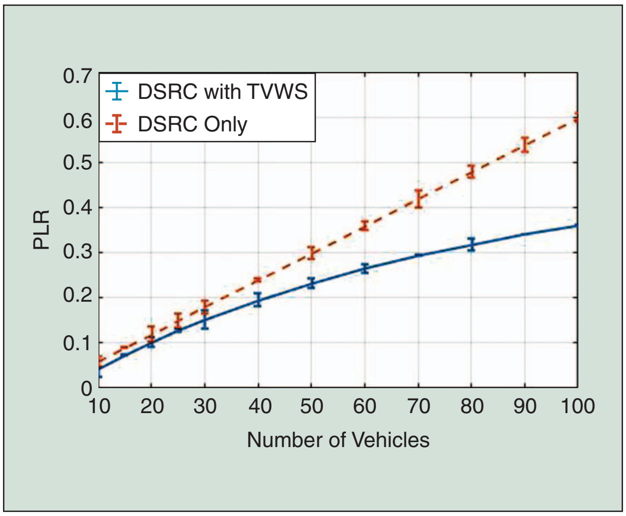

FIGURE 8 The average PLR of the TVWS-enabled network.

simulation results showed that the TVWS-enabled DSRC vehicular network outperformed the standard DSRC network in terms of network throughput and PLR, and the cognitive WAVE standard family is insufficient to provide reliable vehicular communications.

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