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Slotted IEEE 802.11p Contention for Overhead-Free Spectrum Sensing in CR-VANETs

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Abstract—**In this paper, we present the overhead-free (OHF) spectrum sensing and reporting protocol which counters the deficiencies in typical cognitive radio vehicular ad-hoc networks (CR-VANETs) in high density networks. The OHF approach allows each vehicle to randomly sense only one channel to reduce the amount of sensing performed in existing approaches in which each vehicle senses all or a subset of the channels. More importantly, the OHF protocol significantly reduces the time needed to collect the sensing information, and hence, the effort of producing the radio environment map (REM), by having only one vehicle out of those inferred the occupancy of the channel by its primary owner reporting such an information. When OR fusion is applied, it is sufficient to have a single vehicle with a positive decision to report such information. Such a simplified and implicit aggregation is implemented via slotted contention that can be easily incorporated with the IEEE 802.11p standard. By properly choosing its contention parameters, the proposed overhead-free protocol achieves constant and low REM time, and higher CR-VANET throughput with lower outages to the primary networks compared to IEEE 802.11p based CR-VANETs.**

Index Terms—**Cognitive radio; spectrum sensing; vehicular ad-hoc networks (VANETs); IEEE 802.11p, medium access.**

I. INTRODUCTION

Vehicular Ad-Hoc Networks (VANETs) are of utmost importance in intelligent transportation systems (ITS) as they enable diverse applications associated with active road safety, traffic efficiency and management, and infotainment (e.g., video and entertainment) applications.

Dynamic spectrum access (DSA) through cognitive radios (CR) has been recently considered as a key enabling technology to solve the shortage in the available channels in communication systems. Adopting cognitive radios in vehicular ad-hoc networks gave rise to CR-VANETs. CR-VANETs do not only face the traditional CR networking problems, such as the spectrum sensing problems [1]–[3], but also face new challenges that emerged due to the highly dynamic nature of VANETs. The main challenges of CR-VANETs are: *(1)* the tight timing requirements for the delivery of safety messages, *(2)* CR decisions become quickly outdated because of the high mobility of the vehicles, and *(3)* the need for coordination between a large number of moving vehicles [4].

In this paper, we present the overhead-free (OHF) approach for CR-VANETs that tackles the previously mentioned problems. This is achieved by *(1)* reducing the spectrum sensing time, and hence, overcoming the sensing results' fleeting lifetime, *(2)* decreasing the amount of exchanged cooperation control packets which does not only reduce the time needed to make the channel decisions and reduce collisions, but also increases the CR-VANET throughput. The proposed approach is easily implemented on top of the legacy IEEE 802.11p. Our OHF approach is composed of the following three main components:

Single-Channel Random Spectrum Exploration: Existing spectrum sensing protocols typically have each vehicle sensing the whole (or a subset of) the available channels which consumes significant time [5]–[11]. In contrast, we propose applying single channel sensing in which each vehicle randomly selects one of the available channels to sense with equal probability. Hence, the sensing process is distributed among the vehicles.

Slotted Contention: After channel sensing, each vehicle in traditional approaches will compete to send its channel sensing information [12]–[17]. In high density networks, collecting all such packets will require significant time. Furthermore, multiple transmission attempts will lead to a high collision rate which will introduce extra delays and reduce the system throughput. Therefore, we propose a slotted contention mechanism, wherein each vehicle is allowed to compete for a certain time interval that corresponds to the sensed channel. This reduces the contention, and hence, decreases the delay and increases the throughput.

Implicit Aggregation: The proposed protocol limits the information needed for aggregation instead of using data from all vehicles which facilitates the role of the aggregating node and speeds up the decision making process.

Our simulation results show that the proposed OHF protocol results in a significant reduction in the time needed to obtain the radio environment map by up to 94.38% compared to IEEE 802.11p based CR-VANETs. The CR-VANET throughput increases in OHF by multiple folds depending on the primary network activity. A significant reduction in the primary outage by up to 27.93% which can be controlled through the contention window size.

The remainder of this paper is organized as follows: In Section II, we summarize the related work and motivate our work. The system model is described in Section III. The OHF protocol is presented in Section IV. Performance evaluation is discussed in Section V, and we conclude in Section VI.

II. RELATED WORK AND MOTIVATION

In this section, we discuss the literature of related CR-VANET approaches. The authors of [13] proposed a co-operative sensing cognitive vehicle-to-vehicle framework via random channel sensing. The vehicles share the channel status periodically along the segmented road. The authors further proposed two enhancements in [14] to change the selection of the channels to be sensed. The new selection strategies are based on the number of samples instead of being randomly chosen while taking the spatial correlation into account.

A collaborative algorithm based on belief propagation was proposed in [18] for CR-VANETs on highways to avoid spatial and temporal redundancies. In such an algorithm, each vehicle sends 3-bit messages that contain its belief of the existence of a primary network to its neighbors. Then, each vehicle fuses its own beliefs resulting from the vehicle's local sensing with the other beliefs received from other vehicles. After some iterations in one time slot, each vehicle will have a stable belief whether the primary network exists or not.

The consensus approach is applied using the random walk mobility model in [19]. Local sensing at each vehicle is performed via energy detector. Consequently, each vehicle/node creates links between itself and its neighbor within a 10 meters distance only to share a local estimate energy level of the i^{th} user at discrete time instants. Similarly, [20], [21] also used consensus based algorithm. The two approaches differ in the method used in determining the legitimate neighbors. While [19] specifies a 10 meters range list which is not practical, especially with a varying node density, [20] uses a maximum deviation from a mean value to identify the neighbors while considering a stationary node. In [21], a weight is associated with every node to identify the allowable neighbors. However, this work was limited to only 10 nodes and the impact of higher node densities was not taken into consideration.

In [22], the authors proposed a sensing technique which provides a database for road segments, that is updated in a time-slotted manner. Future spectrum utilization is provided through this database. The authors in [17] applied cooperative game theory via Nash bargaining to allow cognitive-enabled road side units (RSUs) to cooperate in inter-cell spectrum allocation after satisfying minimum rate requirements. The authors also proposed a framework to decrease the resulting overhead in spectrum sensing.

A. *Motivation*

All of the aforementioned approaches use explicit cooperation via significant message exchange using the IEEE 802.11p standard [23]. The IEEE 802.11p standard was not originally designed as enabler for cognitive radios. Existing CR-VANET approaches developed to enable the IEEE 802.11p to exploit the CR gains have all the vehicles either sensing the entire channel set or a part of it [5]–[11]. Then, the vehicles cooperate to decide which channels to use by sharing their local sensing results as in [12]–[16], [24]. For the rest of the paper, we will refer to such protocols as conventional IEEE 802.11p CR-VANETs.

The existing conventional IEEE 802.11p techniques suffer severe drawbacks including:

- A considerable amount of time is dissipated in the complete channel exploration. Since each vehicle will have to *sequentially* sense all the available channels, the channel sensing time will increase with increasing the number of channels as shown in Fig. 2(a). This makes the sensing information outdated and degrades the CR-VANET throughput.
- The time needed to obtain the radio environment map (REM) will increase with the vehicular density. Furthermore, the REM delay and the required contention period will vary with the vehicular density.
- In case of a high vehicular density, multiple collisions and thus, multiple retransmissions will occur.

Therefore, we aim to develop an over-head free protocol that can be incorporated with the IEEE 802.11p to allow a short and fixed REM time, which leads to more updated results and a higher CR-VANET throughput.

III. SYSTEM MODEL

Our system model is as follows:

1) Road and Traffic Model: We assume a multi-lane highway of length L with a high bidirectional homogeneous dense traffic as shown in Fig. 1. We divide the highway into a number of identical segments each of length $d \ll L$. Each segment is equipped with a road side unit (RSU) that controls the vehicles within the segment as in [13]. The segment boundaries are known to all vehicles. Each vehicle is equipped with a Global Positioning System (GPS) so that it is aware of its current segment.

We assume that each vehicle moves with a uniform speed v driven from a uniform distribution. The vehicles' arrivals are independent and thus can be modeled by a Poisson process [25]. The inter-arrival times of vehicles on the highway have an exponential distribution with mean λ_v.

2) Primary Network Model: We assume M TV broadcasters as our primary networks (PNs) operating over M non-overlapping channels in the UHF TV band. The PN activity on its channel is modeled with a random ON-OFF process. The locations of the PNs are fixed, and the vehicles are not aware of such locations. Each PN transmits with a power of P_{tx} dBm. All PNs have the same transmitting range $R \gg d$ that

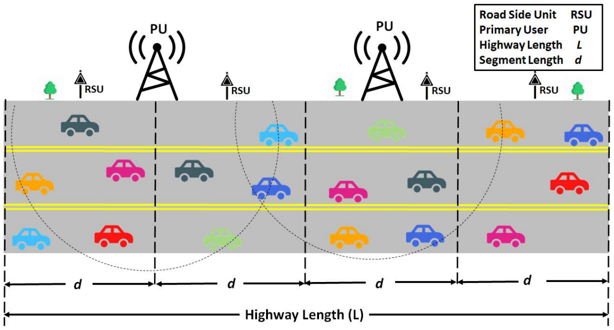
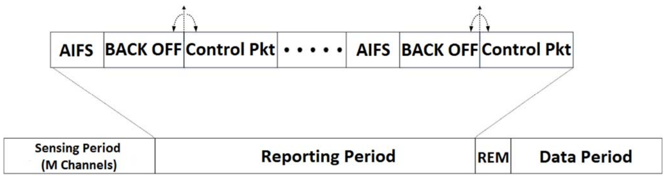


Fig. 1. System model.

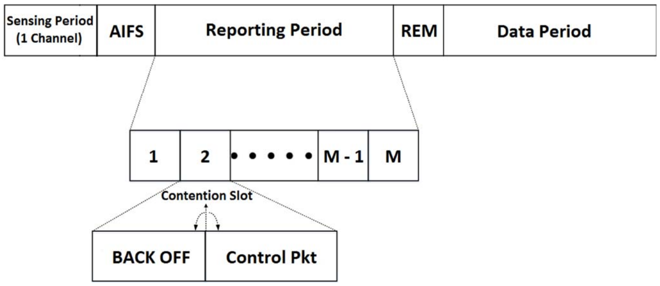
may cover more than one segment, especially if the transmitter is located on the border of two adjacent segments.

3) Secondary Network Model: A single CR-VANET (also referred to as the secondary network) coexists within the service area of the M primary networks. The secondary network is composed of the vehicles moving along the highway. The vehicles receive the available spectral opportunities from the serving RSU sent via the Radio Environment Map (REM) message. The vehicles can use any of the M channels for their data transmission in the absence of PN transmissions.

4) Frame Structure: We assume that time is divided into frames as shown in Fig. 2. A frame is composed of four phases: channel sensing phase, reporting phase, radio environment map broadcast, and data transmission phase. In the channel sensing phase, the vehicles sense the channel(s) of interest based on the adopted sensing algorithm. Then, they report such sensing information to the RSU on a common control channel for decision making. Vehicles compete for the common control channel access using carrier sensing multiple access (CSMA) contention. Once the RSU captures the needed channel sensing information, it produces a radio environment map (REM) that indicates which channels can be used by the vehicles in the RSU's segment and which channels are currently used by their respective primary owners. Once the vehicles receive the REM, data transmission on the available channels takes place. We only focus on the first three phases that handle spectrum sensing and reporting activities. Since the data transmission phase is common in all approaches, we assume that the RSU applies the same spectrum decision, sharing and mobility algorithms for all approaches in the data transmission phase.



(a) Conventional IEEE 802.11p.



(b) Overhead-Free protocol.

Fig. 2. Frame structure of different CR-VANET approaches.

IV. OVERHEAD-FREE (OHF) PROTOCOL

In this section, we present the OHF protocol that is designed for highways with a high-density homogeneous traffic. The proposed OHF protocol is composed of three main pillars, each addressing one of the aforementioned problems of conventional IEEE 802.11p based protocols.

A. Single-Channel Random Spectrum Exploration

In the channel sensing phase, vehicles use energy detectors to determine the existence of PN transmissions. Unlike the prior works which have *all* the vehicles sensing *all (or a subset)* of the channels [5]–[11], the OHF protocol will allow each vehicle to randomly select only one channel out of the available M channels to sense with unbiased probability of $1/M$. If the time needed to sense one channel is T_s, the sensing phase of the OHF protocol will be only T_s, while the sensing phase in the IEEE 802.11p based CR-VANET protocols will be of length $M \times T_s$. Thus, the OHF protocol reduces the channel sensing phase by a factor M. As the number of channels M increases, the sensing phase of the conventional IEEE 802.11p will significantly increase, unlike the OHF protocol sensing phase that does not depend on M.

B. Slotted Contention

Existing CR-VANET protocols have the nodes that performed channel sensing cooperating in the REM decision making process by reporting their channel occupancy assessment to a central node or to each other [12]–[16]. Vehicles typically compete for a common control channel for this purpose using IEEE 802.11p random access. As the number of competing vehicles increases, the time needed to allow all of them to report their measurement increases. Furthermore, the number of collisions of the control packets will increase, which further increases the required reporting period.

Moreover, vehicular ad-hoc networks are highly dynamic ones, where the network traffic density significantly varies based on location, time, etc. These changes in the network will necessitate a variable size reporting period, and hence, a variable length frame, in order to adapt to the traffic density. Therefore, the decision making node will broadcast the REM in aperiodic manner. Such a REM aperiodicity will introduce variation in the delay of the data packets at the receiver side, and thus, intermittent in the flow of data which might degrade the performance of some application such as videos.

In order to solve such an issue, the contention-based reporting period should be maintained constant. Therefore, it must be chosen large enough to accommodate all the possible cooperating vehicles. Increasing the reporting period will degrade both the data throughput and sensing accuracy. As the contention period increases, the time available for data transmission will decrease. In addition to affecting the sensing accuracy, the primary network may have already changed its state which will results in a false outdated data.

In the overhead-free protocol, we propose to have the sensing information reporting period to be of a fixed duration. The reporting period in OHF is further divided into M contention slots of equal durations as shown in Fig. 2(b). The i^{th} contention slot is dedicated to those vehicles which want to report the sensing information regarding the i^{th} channel.

In other words, a vehicle that randomly selected channel i to sense will only compete to access the i^{th} contention slot. Thus, the proposed slotted contention mechanism is independent of the vehicular network topology and the vehicle density, unlike the conventional 802.11p based protocols.

Each contention slot is further divided into two intervals: one dedicated to the backoff process and the other is for sending the control packet that includes the local sensing information as shown in Fig. 2(b). The backoff part of a contention slots is composed of CW mini-slots. A vehicle competing for the i^{th} contention slots will choose a random number in $[0, CW-1]$. The vehicle will listen to the common control channel for the selected number of mini-slots. If no other vehicle has already won contention over this contention slot, the vehicle will transmit its control packet containing the sensing information of the i^{th} channel. Otherwise, if another vehicle has won the contention by selecting a smaller number in $[0, CW-1]$, the vehicle will abandon the contention process since some other vehicle has already reported the channel sensing information of this particular channel. Recall, that the competing vehicles are in close proximity and their sensing information are high correlated. Therefore, the slotted contention time proposed in the OHF protocol will depend only on the number of available channels M and the contention window size CW. However, the contention period will not vary with the vehicle density.

It is worth noting that in legacy IEEE 802.11p, each vehicle has to sense the medium for an Arbitrary Inter Frame Spacing (AIFS) duration before starting the count down in order to make sure that no other vehicle is currently transmitting its packet. In contrast, all vehicles in the OHF slotted contention will sense the control channel only once for AIFS duration to make sure no other packets (e.g., emergency information) is currently using the control channel. If the control channel is not busy, each vehicle will wait and compete only for its respective contention slot. This further reduces the reporting period of the OHF protocol compared to IEEE 802.11p.

C. *Implicit Aggregation*

The RSU centralized decision making node collects all the local sensing information, and combine them using an aggregation rule. The RSU then broadcasts a radio environment map (REM) that reflects the status of all the available M channels (whether available for use or not). Several aggregation rules to combine the individual decision exist such as the AND, OR, Majority, and m out of n rules. The OR aggregation rule was proven to have the highest PN detection probability [26]. In the OR rule, each vehicle sends its binary local sensing result (either 1 or 0). The RSU announces the presence of a primary network if *at least* one vehicle sensed the medium as busy (i.e., reported 1 for this channel).

We classify the local sensing information into 3 categories:

- **Useful Information:** That is produced by Vehicles identifying the presence of the PN.
- **Useless Information:** That is produced by Vehicles identifying the absence of the PN.
- **Redundant Information:** Multiple versions of data are of high importance in shaded-noisy environment like in urban areas. However, in rural areas such as the system at hand (where noise levels and shadowing effect are relativity low and in which hidden terminals almost do not exist) such data is highly correlated. These multiple versions of data, in spite of increasing system accuracy, will lead to excessive processing overhead in addition to frequent collisions and retransmissions which leads to longer contention periods. Recall that in the OR aggregation, it is sufficient that one vehicle reports the existence of the PN. Hence, the sensing information of all the other vehicles identifying the presence of the PN is redundant and does not affect the decision.

In the proposed OHF protocol, only the vehicles that infer the existence of the PN are allowed to compete on seizing the control channel in the corresponding contention slot. Meanwhile, those vehicles that infer the absence of the PN will discard their packets as their information are useless in the REM decision. This will reduce the collision probability over the control channel. Furthermore, we allow only one node to report the existence of the PN. Since all vehicles which have sensed channel i will compete for the i^{th} contention slot, and each will choose a number in $[0, CW-1]$, the vehicle that has chosen the smallest number will start its control packet transmission. In the OHF protocol, all the remaining vehicles will drop their control packet as their information now is considered redundant.

It is worth mentioning that the proposed OHF slotted contention does not guarantee a zero probability of collision as two or more vehicles may simultaneously choose the same number of mini-slots. When collisions occur, the RSU will act cautiously and assume the existence of PN activity on the corresponding channel. These collisions are reduced by properly choosing a large enough value for the contention window CW. A high CW will decrease both the control packet collision and the PN outage probabilities. On the other hand, it will increase the contention slot duration, and hence, the reporting period. However, as long as the number of vehicles is larger than the number of channels M, the slotted reporting period of the OHF protocol will be less than that of the other approaches that use the legacy IEEE 802.11p.

V. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the OHF protocol against the conventional IEEE 802.11p approach.

A. *Simulation Setup*

We use Matlab [27] to build a CR-VANET following the system model described in Section III. We simulate a rural highway that has three-lanes. The highway is further divided into segments of 250 m length. Each segment is equipped with a road side unit that serves as the aggregation node and the radio environment map broadcaster. Five UHF TV primary networks overlap with the road, and their non-overlapping channels can be used by the CR-VANET whenever possible.

The PN activity factor (defined as the ratio of the ON time to the entire period) varies from 0% to 100%. The transmit powers of the PNs, P_{tx}, are set to be 26 dbm. Channel fading and noise may cause a vehicle to be out of range of some PNs as the vehicle moves along the road. The secondary CR-VANET is composed of vehicles moving with a uniform speed $v \in$ U $\sim$ [80, 120] km/h along the highway depending on the vehicular density. We vary the vehicular traffic density from 25 to 125 vehicles per segment. We implement 2 instances of the OHF approach with 2 different CW size of 32 and 64 slots. The reported results are the average of several runs, each of 13 seconds length. Table I summarizes the system parameters.

TABLE I
SYSTEM PARAMETERS.

Parameter	Value
Highway / Segment Length	2 km / 250 m
Vehicle Speed	U∼[80 :120] Km/h
Vehicle Density	Up to 125
Number of TV Channels	5
PNs Transmitting Power	26 dBm
Vehicle Transmitting Power	28 dBm
Path-loss Exponent (as in [28])	1.77
Data Rate	24 Mbps
IEEE 802.11p Slot Time,SIFS/DIFS	13/32/52 μs
IEEE 802.11p [CW_{min}, CW_{max}]	[15, 1023]
IEEE 802.11p AIFS Number	9

B. Performance Metrics

We consider the following three performance metrics:

- **REM Time:** Defined as the time required to deliver the local sensing results from the cooperating vehicles to the centralized aggregation node to form the REM packet.
- **Secondary Throughput:** Defined as the percentage of time in which the secondary network successfully delivers its data over the used channel normalized with respect to the total observation interval.
- **Primary Outage:** Defined as the percentage of time in which the primary data is not transmitted (during the ON time) due to secondary network transimssions normalized with respect to the total observation interval.

C. Simulation Results

1) Radio Environment Map Time: First, we study the effect of the vehicle density on the time to get the radio environment channels map. We vary the vehicle density from 25 vehicles per segment up to 125 vehicles per segment assuming 5 PNs. As shown in Fig. 3, the REM time of the OHF protocol is constant regardless the traffic density, unlike the conventional IEEE 802.11p in which REM time increases with the increase of the vehicular density since all nodes report their sensing channel information. The OHF protocol reduces the REM time by as low as 77.66% and 58.65% in low densities, and by up to 93.49% and 87.95% in high ones for $CW = 32$ and $CW = 64$, respectively. Recall that the REM time depends on the value of the contention window in the OHF protocol. Increasing the contention window size, increases the contention period size, and thus, increases the REM time. As shown in Fig. 3, increasing CW from 32 to 64 almost doubles the OHF REM time. However, it is still well below the REM time of IEEE 802.11p. Furthermore, such a small degradation in the OHF REM time significantly improves the primary outage as discussed later.

2) Secondary Network Throughput: We also study the CR-VANET throughput to assess the gain of using the overhead-free protocol. Figure 4 shows the relationship between the CR-VANET throughput and the primary network activity factor. For both protocols, the throughput decreases with increasing the primary activity until it reaches almost a zero value when the channel is fully used by the primary network. The frequent and shorter sensing time of the OHF protocol allows more data to be transmitted over the channel, and hence, increases its throughput. On the contrary, the conventional IEEE 802.11p consumes a lot of time in sensing all the channels and reporting such information to the RSU which leaves less time for data transmission. Such long sensing and reporting periods in IEEE 802.11p may results in outdated sensing results which will reduce the cognitive throughput. As shown in Fig. 4, the OHF protocol provides a multi-fold improvement in the cognitive vehicular throughput (depending on the PN activity pattern) when compared to the conventional IEEE 802.11p.

3) Primary Outage: We evaluate the amount of primary network outages caused by both the proposed OHF and the conventional IEEE 802.11p protocol. Figure 5 depicts the primary outage percentage versus the primary network activity factor. For both approaches, the probability that the secondary user attempts to transmit during the ON intervals of the primary network is low when the PN activity is low. Hence, no or few outages are caused for the PNs. As the PN activity increases, the CR-VANET transmissions start to interfere more often with the PN transmissions, thereby, increasing the PN outages. As the PN activities approaches 100%, the secondary CR-VANET will not frequently attempt to transmit since the channel is occupied by PN transmission. Hence, the PN outage will decrease again at very high PN activity factors. Both the proposed OHF and the IEEE 802.11p protocols follow the same trend as shown in Figure 5. However, the PN outages caused by the IEEE 802.11p are higher than those caused by the proposed OHF protocol. More specifically, the OHF protocol decreases the PN outages by 27.93% to 23.09% for CW equals to 32 and 64, respectively. The low PM outage of the proposed OHF protocol is attributed to its short sensing and contention periods compared to the IEEE 802.11p protocol which could experience outdated REMs.

VI. CONCLUSION

In this paper, we have highlighted the drawbacks of exiting CR-VANET approaches that are based on the conventional IEEE 802.11p. Then, we have presented the overhead-free (OHF) spectrum sensing protocol tailored for CR-VANETs with high-density traffic. OHF exploits single channel sensing

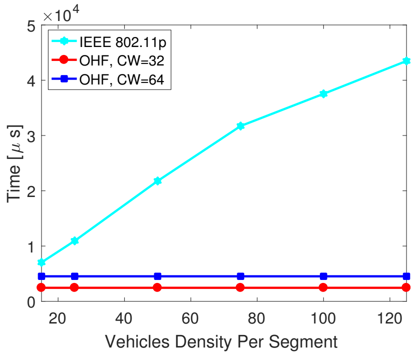


Fig. 3. REM time versus the vehicular density for 5 PNs.

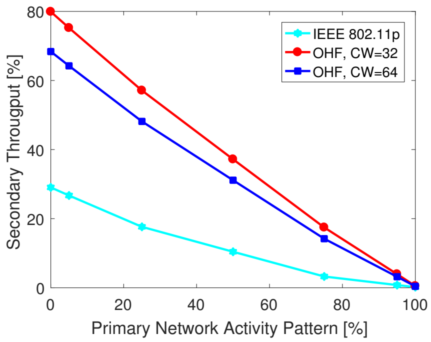


Fig. 4. Secondary Network Throughput versus Primary Network Activities.

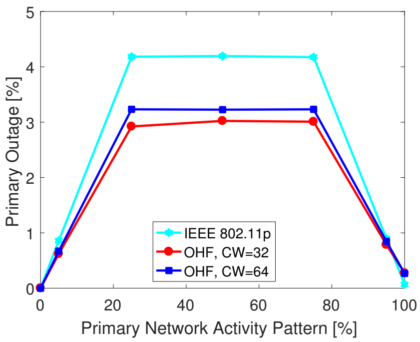


Fig. 5. Primary outage versus the primary network activity.

with a slotted contention mechanism to reduce the sensing time and collisions that consequently increases the CR-VANET throughput and spectrum utilization. Simulations results have demonstrated that the OHF protocol significantly decreases the radio environment map time by up to 94.38%, decreases the primary outage by up to % 27.9, and improves the throughput of the secondary networks by multiple folds which improves the spectrum utilization. A performance trade-off between the primary outage and throughput exists that can be managed by selecting an appropriate contention window size. For our future work, we intend to further study the performance of the OHF protocol with different channel fading models. Furthermore, we shall modify the OHF protocol to be applicable in distributed vehicle-to-vehicle network scenarios.

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