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Vehicular Communications Over TV White Spaces in the Presence of Secondary Users

ADRIANA ARTEAGA[1], (Student Member, IEEE), SANDRA CÉSPEDES[1,2], (Senior Member, IEEE), AND CESAR AZURDIA-MEZA[1], (Member, IEEE)

[1]Department of Electrical Engineering, Universidad de Chile, Santiago 8370451, Chile
[2]NIC Chile Research Labs, Universidad de Chile, Santiago 8370403, Chile

Corresponding author: Sandra Céspedes (scespedes@ing.uchile.cl)

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ABSTRACT The lack of available spectrum for wireless communications is a threat to the successful deployment of applications designed for intelligent transportation systems (ITSs). The ITS services should be available to a high number of road users and have a fast response time. The interworking between radio access networks is one way to increase spectrum availability. In particular, the joint operation of the dedicated short-range communication (DSRC) technology and TV white spaces (TVWS) has been proposed to increase the dissemination distance for safety messages in vehicular networking. However, previous works have often assumed that the only restriction on the opportunistic access of TVWS is the presence of a TV transmitter (i.e., the primary user). Other secondary users, such as the popular White-Fi networks to be deployed in TV bands, are omitted from the analysis of opportunistic channel access over TVWS. This is despite several proposals in the literature that use secondary networks for purposes other than vehicular networking over TVWS. In this paper, we analyze the opportunistic use of TVWS when other fixed users, such as White-Fi networks, are present. We estimate channel access opportunities and introduce a new metric, the channel availability for opportunistic vehicular access (CAFOVA), which relates the channel occupancy of the White-Fi network, the speed of the vehicle, and the channel verification distance. The results show that there are opportunities for vehicular access even when a White-Fi network occupies the TVWS. Vehicles may use these opportunities for transmission, instead of spending time looking for a new available TVWS and establishing a new link with another vehicle. Therefore, even when a White-Fi network occupies the same TVWS, it may be possible to exploit dynamic spectrum access to extend the available spectrum for vehicular communications.

INDEX TERMS TV primary user, TV white spaces, vehicular dynamic spectrum access, White-Fi network.

I. INTRODUCTION

Vehicular communications are considered one of the foundations to support the deployment of Intelligent Transportation Systems (ITS). Innovative applications for vehicular environments promise to help increase safety and comfort for passenger and drivers, to the point that government offices, such as the U.S. National Highway Traffic Safety Administration, are recommending the mandatory use of vehicular communications shortly [1]. Applications of vehicular environments can be classified according to three purposes [2]: active road safety, cooperative traffic efficiency, and information and entertainment (also known as Infotainment). As shown in Table 1, each category has different latency, coverage, and data rate requirements, but all categories are subject to performance challenges due to the different node speeds and network densities encountered in vehicular scenarios.

Channel availability is a fundamental requirement for the successful operation of vehicular applications, but the lack of available spectrum for wireless technologies is a threat for current and future applications designed for ITS. For example, in the presence of traffic congestion, the sending of a critical warning message may fail when concurrent transmissions

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TABLE 1. Technical requirements of vehicular applications. Adapted from [27].

Application	Technical Requirements
Active road safety	Low latency < 100 ms Short coverage < 300 m Transmission rate < 10 kbps
Cooperative traffic Efficiency	Medium latency < 200 ms Medium coverage < 300 m Transmission rate < 100 kbps
Information and entertainment (Infotainment)	High latency < 500 ms Coverage and transmission rate depending on content

overflow the control channel assigned to vehicular communications. Therefore, the dynamic and opportunistic use of available spectrum, coupled with cognitive radio technology, has been proposed to ensure more available channels and successful transmissions in both fixed and mobile environments. The opportunistic detection and usage of the available radio spectrum are known as Dynamic Spectrum Access (DSA) [3].

DSA for vehicular communication (VDSA) has been explored as an alternative or complementary option to dedicated short-range wireless communications (DSRC) [4], the technology for vehicular communications in the 5.9 GHz band. VDSA considers the use of available channels in TV frequency bands (470 MHz-806 MHz), known as TV White Spaces (TVWS), to exploit the propagation features of frequencies below 1 GHz, achieving higher transmission distances in vehicle-to-everything (V2X) scenarios. Among other reasons, TVWS may exist in a specific area when there are no TV transmitters using the channel in the area of interest or when a TV transmitter uses the channel in the area, but the TV transmission is OFF during specific hours (e.g., at night).

Spectrum regulators have defined the technical requirements for allowing DSA in TV bands to guarantee the protection of the primary user against harmful interference [5]–[7]. Secondary users interested in the TVWS have to make sure the channel is available before transmission and be ready to release the channel when a primary user requires it. Accordingly, IEEE has published two related standards for wireless communications for TVWS. The IEEE 802.11af standard is the specification of physical and medium access control layers for wireless local area networks employing TV bands [8], whereas the IEEE 802.22 standard specifies physical and medium access control layers for cognitive radio networks over TV bands [9]. IEEE 802.11af and IEEE 802.22 networks have been proposed to improve broadband access in rural areas [10], [11], provide connectivity in educational initiatives [12]–[14], support agricultural projects [15], and provide connectivity in emergency response plans [16].

The traditional approach to VDSA and the interworking between DSRC and TVWS has been to exploit TVWS as an offloading channel when traffic congestion causes the degradation of the DSRC control and data channels [17], and to provide an exclusive channel for Internet access [18]. Results have shown that the use of TVWS may increase the dissemination distance for safety messages in vehicular ad-hoc networks (VANETs), reducing collisions and latency caused by multi-hop dissemination [19], [20]. The work that has been done to date on vehicular dynamic spectrum access (VDSA) over TVWS reflects the fact that the TV channel is only occupied by a TV transmitter, and opportunistic access is available outside of the transmitter's coverage area [17], [21]–[25]. In these scenarios, vehicles travel across a route where the availability of TV channels depends on the distance between the TV transmitter and the vehicles. Channel availability is checked accessing a geolocation database with information of the spectrum occupation [17], [21], [22] or using a spectrum detection technique such as energy detection, cyclostationary analysis, or matched filter detection [23]–[26].

A more realistic VDSA scenario should take into consideration the presence of other secondary opportunistic networks when they operate over the TVWS, potentially affecting the vehicular communications when the vehicles meet with these secondary networks on the route. Since the TVWS provide resources for secondary spectrum usage, all the secondary devices have the same right to use the TVWS. However, the impact of other opportunistic networks on the dynamic spectrum access for vehicular networking over TVWS is still under exploration.

In this paper, we study the opportunistic usage of TVWS spectrum for vehicular communications. The scenario of study includes primary users and fixed secondary users (i.e., White-Fi networks) in urban, suburban, and rural environments, and considers the technical requirements for using the TV bands as defined by the spectrum regulators. The contributions of this work are twofold:

1) we introduce a new metric, the Channel Availability for Opportunistic Vehicular Access (CAFOVA) that relates the channel occupation policy over the White-Fi network, the vehicle's speed, and the channel verification distance. To the best of our knowledge, this is the first study that relates these variables to understand the impact of other opportunistic networks on the dynamic spectrum access for vehicular networking over TVWS; and
2) we analyze the impact of vehicle speed and channel verification distance on the perception of channel occupancy and the identification of transmission opportunities over the TV band.

From this study, we intend to shed light on the type of vehicular applications that could exploit the opportunistic use of TVWS, even in the presence of other secondary users such as White-Fi networks.

The remainder of this article is organized as follows: in Section II we provide an overview of related work including the allocated spectrum for vehicular communications and the estimation of channel availability for vehicular networking.

In Section III we describe the scenario of study that includes the presence of primary and secondary users over TV bands, including the vehicular network. In Section IV we describe the evaluation scenario to perform the study. We present the simulation results and discuss our findings in Section V and present concluding remarks in Section VI.

II. RELATED WORK

Vehicular networking has been carried out through technologies and standards that define the physical and medium access layers for vehicle-to-everything (V2X) communications. Spectrum regulators allocated specific frequencies for vehicular communications providing interference-free frequency bands. Also, opportunistic access has been explored to extend the spectrum for V2X services. In this section, we present an overview of the allocated spectrum for vehicular communications in several frequency bands and the techniques to estimate channel availability for vehicular dynamic spectrum access (VDSA).

A. SPECTRUM ALLOCATION FOR VEHICULAR COMMUNICATIONS

Different frequencies have been proposed to enable vehicular communications. Some are explicitly allocated to vehicular networking, whereas others could be used through opportunistic access. DSRC is the technology for vehicular communications in the 5.9 GHz band. The FCC in the USA allocates 75 MHz (5.850-5.925 GHz) for V2V and V2I applications. The IEEE 802.11-2016 standard specifies the physical and medium access control layers for wireless local area networks and incorporates what was previously known as 802.11p. The IEEE 1609.4 standard defines the medium access control sublayer functions to support the multiple-channel access in Wireless Access in Vehicular Environments (WAVE). In Europe, the CEN-EN 12795 standard [28] establishes the data link layer for DSRC. The use of DSRC technology has been mostly oriented to safety applications, emergency message dissemination, low data rate applications, and beaconing for the monitoring of the user and network status.

In the millimeter wave spectrum that corresponds to the 60 GHz frequency band, the operation of anti-collision radars and other short-range ITS applications in vehicle-to-vehicle communications (V2V) scenarios is allowed [29]–[31], following the IEEE 802.11ad standard [32]. This technology offers a channel with bandwidth up to 2.5 GHz in the 59-66 GHz band and a coverage range of a few meters, increasing the available bandwidth for short-range vehicular applications.

LTE-based V2X services are being specified by the Third Generation Partnership Project (3GPP) to take advantage of widely deployed LTE networks and the low cost of the user equipment (UE) [33]. Release 14 LTE supports one-to-many communications that are useful for broadcasting, and device-to-device (D2D) communications based on the sidelink, enabling V2V links without routing via the base station (also known as evolved NodeB, or eNodeB) [34]. The standard is commonly referred to as LTE-V, LTE-V2X, or cellular V2X. Release 15 will support fifth-generation (5G) V2X communications and is under discussion. At the moment new use cases will be considered in Release 15, including autonomous driving, platooning, sensor and map sharing, information sharing for partial/conditional and high/full automated driving, and remote driving, among others [35]. In [36], the authors show a comprehensive study of LTE-V V2V communications as a potential alternative to DSRC.

To obtain opportunistic access for vehicular networking, the available or underutilized frequencies in the TV service may also be used to have a broader coverage for vehicular applications. Both the FCC [5] and the CEPT [6] allow fixed and mobile/portable devices in secondary use of TV bands, which facilitates the operation of V2I and V2V communications. In [37], the authors present a TV spectrum measurement campaign to analyze the availability of vacant channels from a vehicular perspective. Also, several experimental V2V studies have been conducted to examine the feasibility of using TVWS for vehicular communications [22], [38], [39].

B. ESTIMATION OF CHANNEL AVAILABILITY FOR VDSA

Reports on the use of radio spectrum show high occupancy in the bands allocated to cellular services and unlicensed communications [40], while there is low occupancy in the frequencies assigned to the television service (470 MHz-806 MHz) [41]. The TV service characteristics and the deployment of the TV network result in temporary (or permanent) switch-off of services or lack of coverage in some areas. Moreover, some frequencies will become vacant due to the transition from analog to digital TV [42]. This would allow other services to use the available channels as long as no harmful interference to the primary service occurs. DSA could thus be a solution for finding and accessing the idle TV spectrum in cases of congested vehicular networks. The estimation of available spectrum involves techniques to detect a channel status as busy or available.

Channel availability can be determined in two ways. One uses a system based on a geolocation database with information of channel allocation. Every time a secondary user wants to use a TVWS, it must ask for the list of available channels in its location. This technique requires secondary users to always have access to the database, and the database to be continuously updated. The use of geolocation databases has been widely proposed for VDSA [17], [21], [22]. However, such a dependency for enabling V2V communications over TWVS could be unsuitable due to the additional latency required for accessing the database, not to mention that it is not clear where the geolocation database should be stored to guarantee that vehicles always have access to it, especially if there is no connection to the infrastructure.

The other way to verify channel availability is using a spectrum detection technique to recognize the presence of a signal in the channel. The complexity of a detection technique depends on the knowledge of the signal features (e.g., modulation, packet format, pulse shape, etc.), the signal processing required on the received signal, and the number of receivers needed. Naturally, the detection process is more reliable when there is more information available about the primary user signals. In VDSA, spectrum detection techniques have been proposed in V2V scenarios as a way to verify channel status locally, in particular when the nature of the ad-hoc network restricts the access to a geolocation database. In the following, we revisit three of the most frequently used spectrum detection techniques employed for general opportunistic spectrum detection [43] (energy detection, cyclostationary analysis, and waveform-based detection) and discuss how they apply to VDSA.

1) ENERGY DETECTION

This is a simple spectrum detection technique because of its low computational cost and low implementation complexity [44]. A signal is detected by comparing the energy in the channel with a threshold λ_E [dB], which in its simplest definition depends on the noise floor. If the energy in the channel exceeds λ_E, it means that a user is occupying the channel; otherwise, the channel is available to a secondary user. If $y(n)$ is the received signal, its energy is defined as:

$$E = \frac{1}{N}\sum_{n=0}^{N}|y(n)|^2, \tag{1}$$

where N is the number of samples of the signal. The threshold definition is an essential aspect for achieving an effective detection if there are low Signal-to-Noise ratio (SNR) conditions in the channel. The receiver does not need a priori knowledge of the primary user signal, but the accuracy of detection is affected if the SNR is low. Improved versions of this technique are proposed for VDSA, where cooperative sensing increases the probability of primary user detection [23], [24].

2) CYCLOSTATIONARY ANALYSIS

This technique is based on the cyclostationary characteristics of the received signal, which are modeled by its periodic behavior with period T_0, the mean value $M_x(t)$, and the auto correlation function $R_x(t,\tau)$, calculated in (2) and (3), respectively, as follows [45]:

$$M_x(t) = M_x(t+T_0), \tag{2}$$

$$R_x(t,\tau) = R_x(t+T_0, \tau+T_0). \tag{3}$$

With this technique, it is possible to differentiate a primary signal from noise, since the noise is a random process and its autocorrelation function is not periodic. The detector calculates the autocorrelation function of the received signal and compares it with a known value λ_C [Hz], which can be the cyclic frequency of the signal [46]. The technique is considered of medium complexity because it is robust to noise uncertainty, but a priori knowledge of the primary signals is required.

Performance of this technique does vary depending on channel noise. If the channel noise is stationary, the performance of this technique is low; nevertheless, this technique performs well when the SNR is low because λ_C does not depend on the signal level, but on the periodic behavior of the signal. However, a long sensing time is required for accurate detection results, which is inconvenient when vehicles move at high speeds since sensing data may become outdated very fast. Studies in [25], [47] show the performance of the cyclostationary analysis in fading channels, with similar conditions to the ones expected for vehicular communications.

3) WAVEFORM BASED DETECTION

This technique is applicable when some of the signal patterns are known (e.g., preamble, spread spectrum sequence, pilot signal, etc.). Identifying a primary user requires that the receiver calculates the correlation between one of the known patterns of the received signal and a bank of known patterns of the possible primary signals. If $y(t)$ is the received signal, $s(t)$ is a known signal, and $w(t)$ is the white Gaussian noise, the correlation between both signals is calculated as follows [43]:

$$M = R_e[\sum_{n=0}^{N} y(n)s^*(n)], \tag{4}$$

where * is the conjugate. Correlation when the primary user is present or absent can be expressed according to (5) and (6), respectively, as follows:

$$M = \sum_{n=0}^{N}|s(n)|^2 + R_e[\sum_{n=0}^{N} w(n)s^*(n)], \tag{5}$$

$$M = R_e[\sum_{n=0}^{N} w(n)s^*(n)]. \tag{6}$$

M is compared with a λ_W value to determine if the correlation is high, indicating there is a primary user in the channel; if the correlation is low, it means there is only noise in the channel. The complexity of waveform- based detection is high because in some cases it needs to demodulate the signal to obtain the preamble, so the cognitive device must support the processing of all possible primary signals.

Waveform-based detection can rely on the mechanisms used by the primary communications systems to correct possible errors and use corrected information for detection when the SNR is low. This technique is similar to a matched filter with a perfect knowledge of the primary user; before sensing, features such as channel bandwidth, modulation scheme, or packet format are required. The sensing time is low because the features are known in advance, but the reliability of the technique depends on the level of knowledge of both users and signal patterns. The technique has been evaluated for fading channels, showing that time variations introduce degradation in the detection performance [26].

A strategy called Cooperative Sensing has also been introduced as an alternative to increase the detection reliability

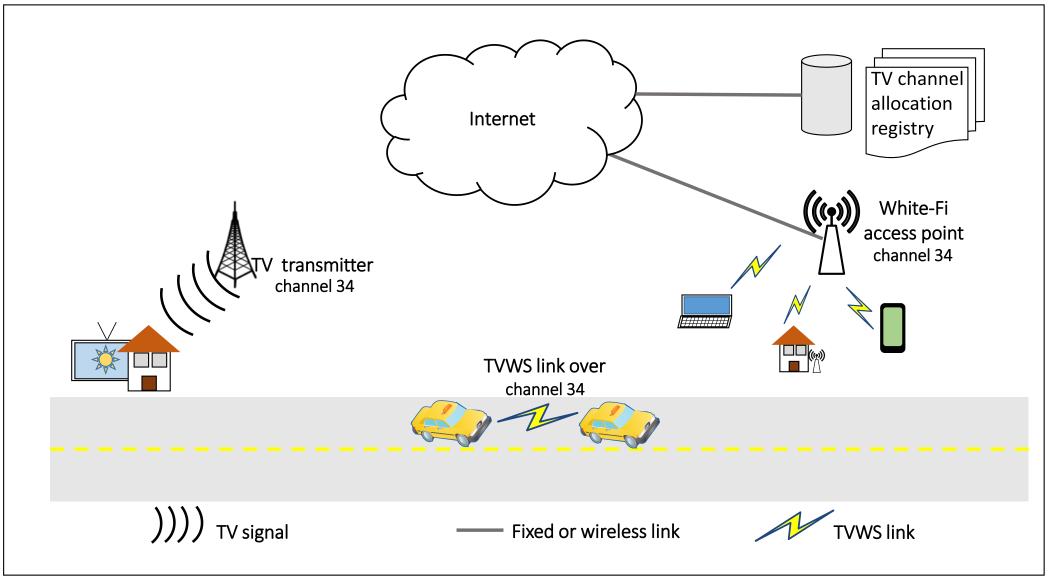

FIGURE 1. Scenario of study: Opportunistic access for vehicular networking considering the presence of primary TV users and secondary White-Fi networks over the TV band.

in highly mobile scenarios, where several detection techniques are combined to avoid missing a detection or producing a false alarm that prevents the use of available channels [24], [48], [49].

In the particular context of V2V scenarios, the energy detection technique has become predominant [23], [24], [38] because it provides a low latency execution; hence, it allows each vehicle to sense the channel status across the route while reducing the latency of continuous access to the geolocation database.

III. SYSTEM DESCRIPTION

Considering the proposals for employing TV frequency bands in the provision of long-range Internet access via White-Fi networks, our scenario assumes that it is highly probable that Internet access will become a popular form of secondary use of TVWS. Therefore, VDSA needs to consider both primary and secondary users (i.e., White-Fi networks) in the estimation of the available spectrum for the opportunistic access. Figure 1 illustrates the scenario of study, where there is an active TV transmitter providing TV services using, for example, channel 34. Outside the coverage area of the TV transmitter, there is a V2V link established over the same channel because it has become a white space in that area. However, there is a White-Fi network farther along on the route, which is also using channel 34. In the following, we model in more detail the TV primary users, the White-Fi network, and the vehicular network intending to access the TV channel.

A. DESCRIPTION OF TV PRIMARY USERS

Primary users of TV bands are the analog and digital TV transmitters, which are located in valleys or low to medium-sized mountains, providing directional coverage toward densely populated areas. When there is an active TV transmitter in the area, the channel assigned to the transmitter remains busy within the TV transmitter's coverage area, which means the channel cannot be used for secondary users inside that coverage area. However, spectrum regulators define that a TVWS may be used if the received power of the TV signal is lower than a specific threshold; in the case of the FCC, the detection threshold is −114 dBm [5].

In the presence of an active TV transmitter, opportunities for VDSA must be located outside the TV transmitter's coverage area. One way to estimate the TV transmitter's coverage area is by calculating the maximum distance between the transmitter and the potential receivers, in which the received power is higher or equal to the detection threshold. The received power is calculated using a long scale path loss model since the frequencies of TV service (470-806 MHz) have a high obstacle penetration. In [50], several path loss models to predict TV service coverage for secondary use are compared with path loss measurements in urban, suburban, and rural environments. Among the evaluated models, Hata [51] and Hata-Davidson [52] models showed similar results regarding path loss. The Hata model is used for frequency ranges of 100 MHz to 1500 MHz, distances of 1 km to 20 km, base station antenna heights between 30 m and 200 m, and reception antenna heights between 1 m and 10 m.

Nevertheless, the TV transmitter's coverage is expected to be larger than 20 km in some rural areas. Therefore, we adopt the Hata-Davidson model in our system, which incorporates a correction factor to increase the distance between the transmitter and the receiver up to 300 km. The received power P_{Rx} corresponds to:

$$P_{Rx}(dB) = P_{Tx} - PL_{HD}, \quad (7)$$

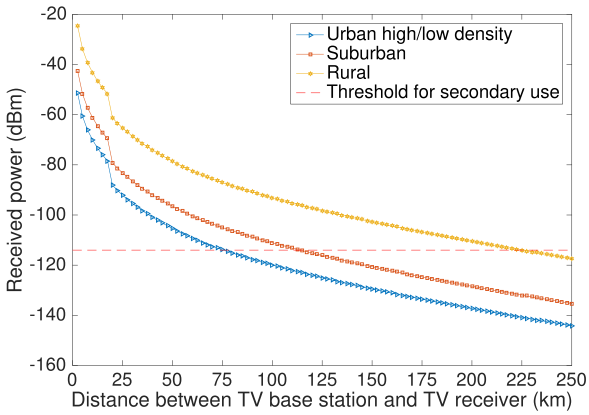

FIGURE 2. **Received power depending on the distance between a TV transmitter and a potential receiver.**

where P_{Tx} is the transmitted power and PL_{HD} is the Hata-Davidson path loss. PL_{HD} is calculated as:

$$PL_{HD}(dB) = PL_{Hata} + K_{Davidson}, \qquad (8)$$

where $K_{Davidson}$ corresponds to the correction factor (see Annex A).

According to the path loss calculated in (8) and the detection threshold established by the FCC, we estimate the coverage area of a typical TV transmitter in urban, suburban, and rural areas. Figure 2 shows the received power for distances up to 100 km between the TV transmitter and receiver. Table 2 lists the parameters for transmission and reception of the primary users. Results show that a channel assigned to an active TV transmitter remains busy for reception distances up to 75 km, 125 km, and 220 km in urban, suburban, and rural environments, respectively. For greater distances, the channel can be considered as TVWS and could be used opportunistically. However, the vehicle should use the energy detection VDSA technique to sense the channel occupation. As mentioned in Section II-B, energy detection is the predominant spectrum detection technique in V2V scenarios because of its low latency execution. Since the FCC determines that a portable secondary device must verify the TV occupation every 100 m to protect TV primary users against harmful interference, a spectrum detection technique with low-latency is more convenient for vehicular secondary users that travel at 30-120 kph. Note that Figure 2 shows a jump of the received power between kilometers 19 and 20; this is because the distance correction factor, $A(h_{bs}, d)$, employed in the Hata-Davidson model is a piece-wise function defined for the intervals [1, 20) km and [20, 300) km.

B. DESCRIPTION OF SECONDARY USERS: THE WHITE-FI NETWORK

Considering the deployment of a White-Fi network (i.e., 802.11af or IEEE 802.22 networks) in a TVWS, our interest is to analyze if there are possible opportunities for vehicular communications even in the presence of such secondary users. In this case, it is necessary to estimate the coverage area of the White-Fi access point (AP) to define a bounded area where the TVWS could be busy. In our scenario of study we consider an AP antenna height of 30 m, which is the height of a 10-floor building in an urban area, or an antenna on a water tank or a small hill in a rural area. All of the receivers of the secondary users (i.e., White-Fi users or vehicular users) are assumed to have an antenna height of 1.5 m.

Fixed secondary users must limit the transmission power up to 36 dBm [5] according to the FCC. To estimate the AP coverage we calculate the received power depending on the distance between the AP and the potential receivers according to the Hata-Davidson model. Since the White-Fi AP is also a secondary user, there is no specific detection threshold from the transmissions of the secondary users to determine that a TVWS is available. Hence, we employ the receiver sensitivity to determine the area of coverage of the White-Fi network. According to the IEEE 802.22 standard, the receiver sensitivity for a successful reception is -90 dBm. Table 2 shows the parameters employed for transmission and reception of the White-Fi network system.

Figure 3 illustrates the received power when the distance between the AP and the potential receiver increases. According to the Hata-Davison model, the White-Fi network has a radio range of approximately 2 km in urban areas, 3.2 km in suburban areas, and 11 km in rural areas. Vehicular

TABLE 2. **Evaluation parameters.**

Parameter	Value
Primary users	
TV transmission power	70 dBm [55]
TV transmitter antenna height	70 m
Receiver antenna height	3 m
Channel frequency	590 MHz
Route length	100 km
Detection threshold	-114 dBm [5]
White-Fi network	
AP power transmission	36 dBm [5]
Channel frequency	590 MHz
Height of the base station	30 m
Height of the receiver	1,5 m
Receiver sensitivity	-90 dBm [9]
Busy channel probability	10%, 30%, 50%, and 70%
Mean burst duration (Pareto distribution)	10 ms, 20 ms [54]
Mean burst inter-arrival time (Pareto distribution)	10 ms, 20 ms [54]
Pareto shape parameter	1,5 [54]
Vehicular network	
Vehicle speed	10 to 120 kph
Height of the receiver	1,5 m
Receiver sensitivity	-90 dBm [9]
Channel frequency	590 MHz
Channel verification distance	25, 50, 100, and 200 m

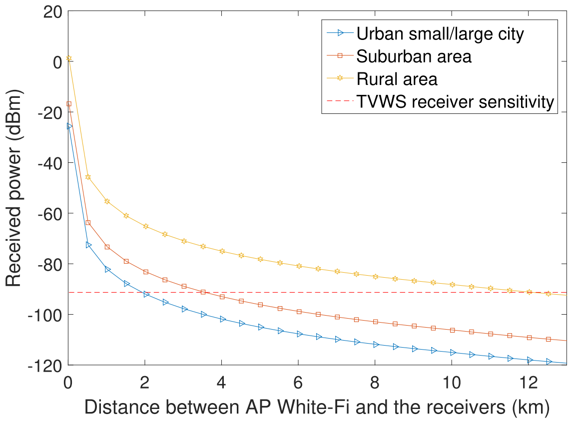

FIGURE 3. Received power depending on the distance between the White-Fi access point and a potential receiver.

communications intending to use the TVWS inside such coverage areas should consider the channel occupation derived from the White-Fi network users' traffic.

C. WHITE-FI NETWORK TRAFFIC

A White-Fi network is expected to be used for similar purposes as a typical WiFi network with Internet access as the most prominent application. White-Fi could be also used to extend the coverage area of a monitoring network. We model the White-Fi network traffic in two ways. First, with sources of traffic that occupy the channel following a uniform distribution probability. We define four channel occupation policies with 10%, 30%, 50%, and 70% probabilities of busy channel (P_{bc}). The probability density function of the uniform distribution $f(x)$ is:

$$f(x) = \begin{cases} 0, & x < a \\ \dfrac{1}{b-a}, & a \leq x \leq b, \\ 0, & x > b \end{cases} \tag{9}$$

where a and b are two boundaries that depend on the observation time, for example, from 0 to 100 ms. Figures 4a and 4b show examples of the 10% and 50% occupation policies. Second, with sources of bursty traffic that represent the Internet traffic. This traffic follows a Pareto ON/OFF distribution, where packets are sent during ON periods according to the mean burst time (b_t), and no packets are sent during the OFF periods defined by the mean inter-arrival time (i_t). Figure 4c shows an example of the Pareto occupation policy.

To establish the ON/OFF periods in the Pareto distribution, the packet duration p_{dur} and burst length b_l (in packets) are calculated according to:

$$p_{dur} = \frac{p_s}{R}, \tag{10}$$

$$b_l = \frac{b_t}{p_{dur}}, \tag{11}$$

where p_s is the packet size in bits, R is the data rate in bits per second during the burst, and b_t is the mean burst time.

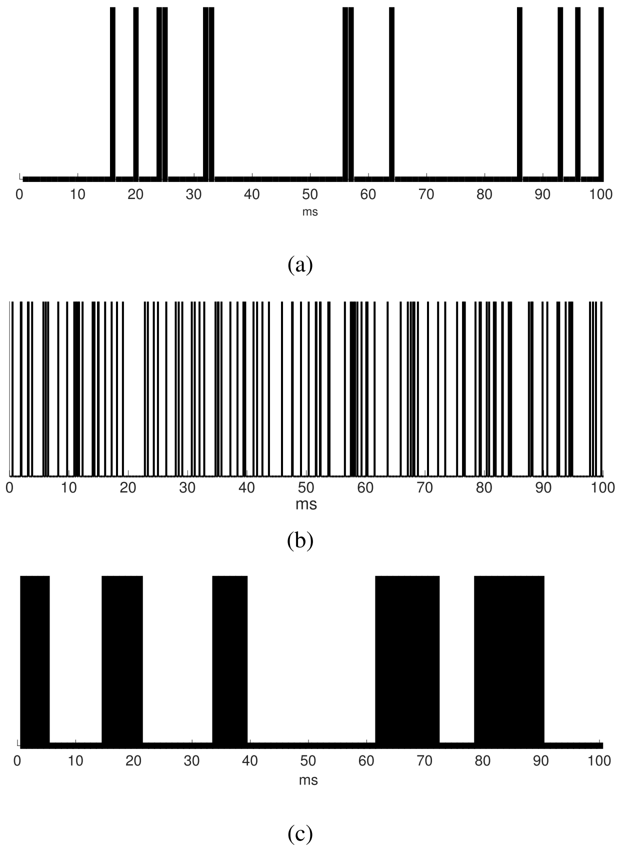

FIGURE 4. Examples of channel occupation policies: (*a*, *b*) Uniformly distributed probability of busy channel and (*c*) burst traffic.

The burst length b_l and the idle time i_t correspond to the expected value $E(X) = b_l$ and $E(Y) = i_t$ of the Pareto distribution for each variable:

$$E(X) = b_l = b_1 * \frac{a}{(a-1)}, \tag{12}$$

$$E(Y) = i_t = b_2 * \frac{a}{(a-1)}, \tag{13}$$

where $a > 1$ is the Pareto shape parameter. The Pareto scalar parameters b_1 and b_2 are extracted from $E(X)$ and $E(Y)$ as follows:

$$b_1 = b_l * \frac{(a-1)}{a}, \tag{14}$$

$$b_2 = i_t * \frac{(a-1)}{a}. \tag{15}$$

We define 3 configurations of the Pareto distribution to model the bursty traffic according to values previously reported in the literature [53], [54]: $b_t = 10$ ms and $i_t = 20$ ms; $b_t = 20$ ms and $i_t = 10$ ms; and $b_t = 20$ ms and $i_t = 20$ ms.

D. DESCRIPTION OF THE VEHICULAR NETWORK

In the scenario of interest, we intend to analyze the impact of the vehicles' speed on the perceived spectrum availability for vehicular dynamic spectrum access. The FCC determines that portable/mobile secondary devices in TV bands must verify the channel occupation every 100 m, to detect the possible presence of a primary user. In this study, the verification distance is also used to establish the presence of other users within the White-Fi network. Considering that the time it takes for a vehicle to travel 100 m depends on its speed, two vehicles with different velocities will meet the verification time (i.e., will cover the 100 m) at different moments. This situation causes the vehicles to have different perceptions of channel occupation, which is illustrated in Figure 5. For example, two vehicles moving at 30 kph and 90 kph, respectively, and both traveling 400 m, detect different channel occupations as follows: the vehicle moving at 30 kph travels 100 m in 12 seconds, whereas the vehicle moving at 90 kph travels 100 m in 4 seconds. If the channel occupation along a route is represented on a timeline, the opportunities for VDSA could be different for each vehicle as shown in Figure 5.

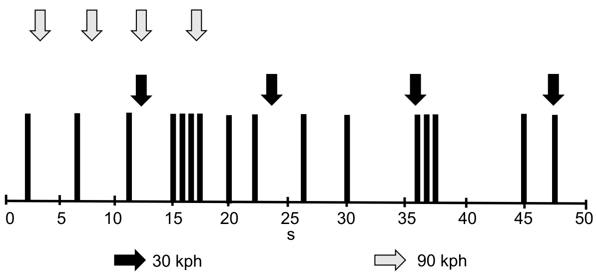

FIGURE 5. Differences in channel verification times for two vehicles traveling at 30 kph and 90 kph to cover a distance of 400 m. The channel occupation policy follows a Pareto distribution.

IV. EVALUATION

The evaluation scenario for this study is presented in Figure 6, where there is a TV transmitter offering the TV service, a White-Fi network outside the TV transmitter coverage area, and a V2V link over the same TVWS coverage area as the White-Fi network. Table 2 presents the parameters employed in our scenario to model the primary TV service, the White-Fi network and traffic, and the vehicular network. The parameters follow the FCC requirements for TVWS [5], the IEEE 802.22 standard [9], and typical speed values employed in vehicular urban, suburban, and highway scenarios.

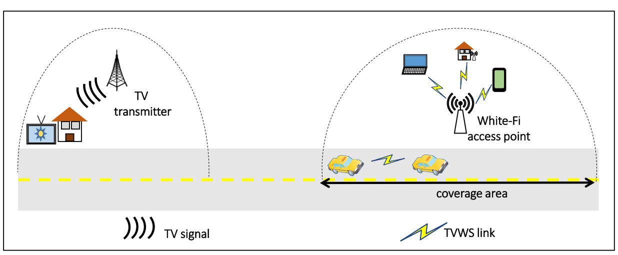

FIGURE 6. Evaluation scenario.

According to the White-Fi access point (AP) coverage range calculated in Section III, the maximum White-Fi AP coverage is around twice the coverage radio (i.e., 4 km, 8 km, and 24 km, in urban, suburban, and rural areas, respectively). The channel occupation of the White-Fi network traffic is represented by a timeline where each millisecond is set to busy or idle according to the channel occupation policies described in Section III-C. The vehicle moves along a straight route within the White-Fi coverage area. We consider several speed values to analyze the effect of the speed in the channel occupation perception. A vehicle senses the channel status every time it meets the channel verification distance; this is to ensure there is no TV primary user around, and also to determine if the TVWS is available or busy according to the channel occupation policy of the White-Fi network. The scenario is evaluated with several verification distances, including the 100 m specified by the FCC. The number of channel sensing verifications (C_{sv}) depends on the length of the route (R_l), and the channel verification distance (l), as follows:

$$C_{sv} = \frac{R_l}{l}. \tag{16}$$

To calculate the channel access opportunities, we introduce a new metric, known as *channel availability for opportunistic vehicular access (CAFOVA)* along the route, which represents the percentage derived from the number of times the TVWS is available (C_{sv}^A) with respect to the number of channel sensing verifications ($C_{sv} = R_l/l$) as follows:

$$CAFOVA = \frac{C_{sv}^A}{C_{sv}} * 100\%. \tag{17}$$

CAFOVA considers the channel occupation policy of the White-Fi network, the speed of the vehicle, and the channel verification distance.

We built the evaluation scenario in Matlab and ran simulations to estimate the opportunities for VDSA across a route on urban, suburban, and rural areas. A Monte Carlo simulation was used to simulate the scenario 100 times for each combination of parameters, for a total of 28,000 simulations.

V. RESULTS

In this section, we discuss the behavior of the CAFOVA metric under different channel occupation policies. We also show the impact on the CAFOVA of the following variables: the type of area of deployment, vehicle speed, and channel verification distances.

A. IMPACT OF THE TYPE OF DEPLOYMENT AREA

Results in Figure 7 show the CAFOVA metric within the White-Fi network coverage in *a)* urban small/large city, *b)* suburban area, and *c)* rural area. The channel occupation policy follows a uniform distribution whereas the verification distance l is set to 100 m, according to the FCC specifications. The CAFOVA obtained is around the complement of P_{bc} in all environments. Note also that the percentage of opportunities

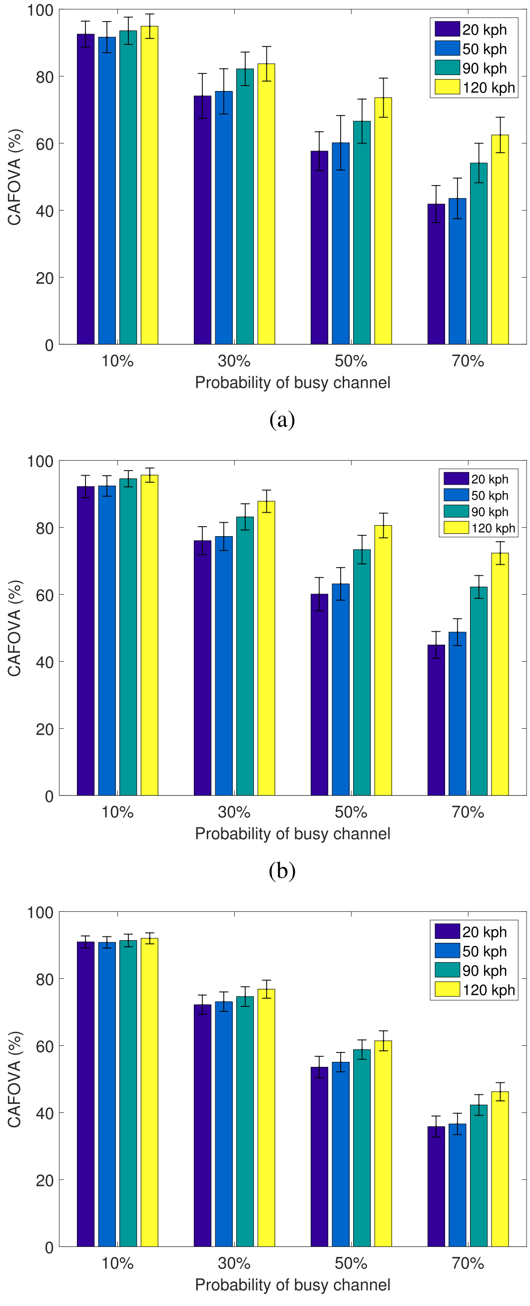

FIGURE 7. CAFOVA in uniformly distributed channel occupations P_{bc}, when v is set to 20 kph, 50 kph, 90 kph, and 120 kph. l = 100 m. (a) Urban small/large city. (b) Suburban area. (c) Rural area.

for vehicular access increases as the speed of the vehicle increases in the three areas under evaluation.

A statistical analysis was performed to understand the relationship between the CAFOVA, P_{bc} (10%, 30%, 50%, and 90%), the speed of the vehicle v (20, 50, 90, and 120 kph), and the number of channel sensing verifications C_{sv} when $l = 100m$ (i.e., 41 verifications in urban scenarios, 84 verifications in suburban scenarios, and 241 verifications in rural scenarios). Table 3 shows the correlation analysis among the variables. The Pearson correlation value (P_c) indicates the extent to which two variables are linearly related. The p-value (P_v) determines if the correlation between the variables is statistically significant.

The analysis shows that the linear relationship between the CAFOVA and P_{bc} is -0.913, which means that the CAFOVA decreases when P_{bc} increases. Since the p-value is 0.00 and it is lower than the significant value 0.05, the correlation between these variables is statistically significant. Since the P_c between CAFOVA, v, and C_{sc} is 0.00, there is no linear relationship between these variables when they are analyzed together. The blank cells in Table 3 indicate the correlation and p-value are not calculated when it corresponds to the crossing of the same variable.

TABLE 3. Correlation between the CAFOVA, P_{bc}, v, and C_{sv}.

	CAFOVA		P_{bc}		v	
	P_c	P_v	P_c	P_v	P_c	P_v
P_{bc}	-0.91	0.00			0.00	1.00
v	0.19	0.00	0.00	1.00		
C_{sv}	-0.17	0.00	0.00	1.00	0.00	1.00

In the analysis for bursty traffic, there are three different occupation policies: A (b_t = 20 ms, i_t = 10 ms), B (b_t = 20 ms, i_t = 20 ms), and C (b_t = 10 ms, i_t = 20 ms). A separate evaluation for urban, suburban, and rural areas is also provided. In this scenario, the vehicle is traveling at 50 kph and the channel verification distance is 100 m. Results in Figure 8 show that the CAFOVA increases substantially when i_t is higher than b_t, regardless of the type of area. This is because the channel remains available more time between two data transmissions that are short. When b_t and i_t are the same, the CAVOFA is around 50% in all areas. The Pearson correlation and the p-value between CAFOVA, b_t, i_t, and v are shown in Table 4. The correlation shows the positive linear relationship between CAFOVA and the inter-arrival time, and the negative linear relationship between the CAFOVA and the burst time.

B. IMPACT OF THE VEHICLES SPEED

Table 5 presents the statistical analysis based on Pearson correlation P_c and the p-value P_v when CAFOVA and v are analyzed for each P_{bc}, and for v between 10 to 120 kph in the urban scenario. Since the correlation for both variables is 0.78 and the p-value is 0.00, there is a positive linear relationship between both variables. This means that the CAFOVA increases when the speed of the vehicle increases in scenarios where the White-Fi network traffic follows a uniformly distributed channel occupation P_{bc}.

Furthermore, Table 6 shows the Pearson correlation and the p-value between the CAFOVA and speeds ranging from 10 kph to 120 kph for the A, B, and C bursty traffic policies. Since the correlation is near to 0 and the p-value is higher than 0.05, there is no linear relationship between the CAFOVA and

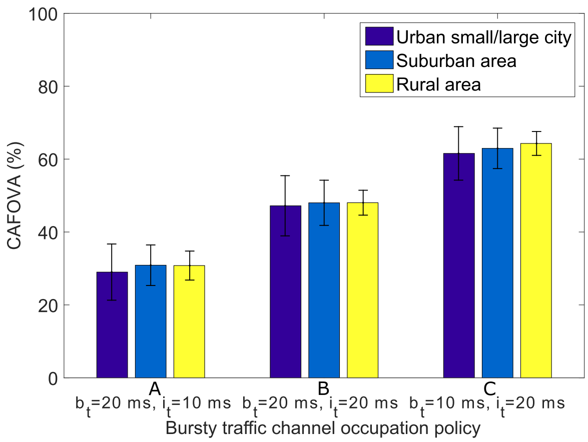

FIGURE 8. **CAFOVA in Pareto distributed channel occupations A, B, and C, when the area type is urban, suburban, and rural. $v = 50$ kph, $l = 100$ m.**

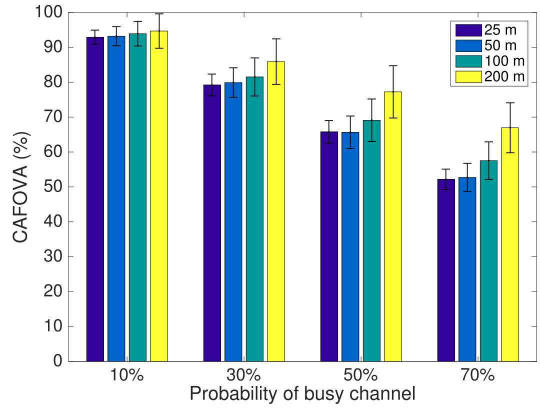

FIGURE 9. **CAFOVA in uniformly distributed channel occupations P_{bc}, when l is set to 25 m, 50 m, 100 m, and 200 m. $v = 50$ kph.**

TABLE 4. **Correlation between the CAFOVA, b_t, i_t, and v.**

	CAFOVA		b_t		i_t	
	P_c	P_v	P_c	P_v	P_c	P_v
b_t	-0.85	0.00			-0.50	0.00
i_t	0.88	0.00	-0.50	0.00		
v	0.00	0.98	0.00	1.00	0.00	1.00

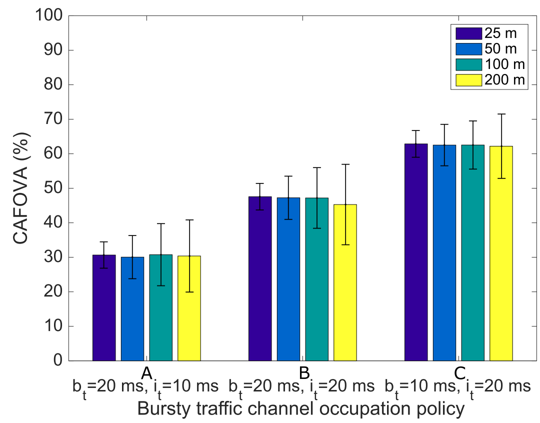

FIGURE 10. **CAFOVA in Pareto distributed channel occupations A, B, and C, when l is set to 25 m, 50 m, 100 m, and 200 m. $v = 50$ kph.**

TABLE 5. **Correlation between the CAFOVA and v for four different uniformly distributed traffic policies 10%, 30%, 50%, 70%. Urban scenario.**

	CAFOVA							
	P_{bc}=10%		P_{bc}=30%		P_{bc}=50%		P_{bc}=70%	
	P_c	P_v	P_c	P_v	P_c	P_v	P_c	P_v
v	0.78	0.00	0.78	0.00	0.78	0.00	0.78	0.00

TABLE 6. **Correlation between the CAFOVA and v for three different bursty traffic policies A, B, and C.**

	CAFOVA					
	A		B		C	
	P_c	P_v	P_c	P_v	P_c	P_v
v	-0.001	0.99	-0.002	0.99	-0.007	0.97

the speed of the vehicle when the White-Fi network traffic is bursty.

C. IMPACT OF THE CHANNEL VERIFICATION DISTANCE

To understand the effects of the channel verification distance, we evaluate the CAFOVA when the channel verification distance, l, differs from the one recommended by the FCC. Additional values of 25 m, 50 m, and 200 m are included in the evaluation. The number of channel verifications obviously depends on l and the route length. In the urban area where the route length is 4 km, the number of channel verifications is 161, 81, 41, and 21 times when l is 25, 50, 100, and 200 m, respectively. The vehicle is moving at an average speed of 50 kph.

On the one hand, if the traffic of the White-Fi network follows a uniformly distributed P_{bc}, the CAFOVA is calculated to be around the complement of P_{bc}, as mentioned previously. Also, when the spacing distance between the number of verifications is longer, the CAFOVA is higher. Such results are illustrated in Figure 9. On the other hand, if the traffic of the White-Fi network follows a Pareto distribution, the behavior of the CAFOVA seems not to be sensitive to the channel verification distance l. Nevertheless, the CAFOVA clearly varies depending on the values of b_t and i_t. Such results are illustrated in Figure 10.

D. DISCUSSION

According to the results, it has been confirmed that, as expected, the nature of traffic in the White-Fi network impacts the channel availability for opportunistic vehicular asccess. This study analyzed seven channel occupation policies to model the traffic in the White-Fi network and considered several types of applications running on the network. On the one hand, given a channel occupied by bursty traffic, when the idle time is longer than the burst time, CAFOVA improves, i.e., there are more opportunities for the vehicular access because the channel remains idle more time. On the other hand, when the probability of busy channel follows a uniform distribution, the CAFOVA metric is around the complement of the probability of a busy channel.

Speed has an impact on the CAFOVA when the channel occupation policy follows a uniformly distributed probability of a busy channel: the CAFOVA increases when the speed of the vehicle increases and the probability of a busy channel decreases. The reason is that the speed determines how long the vehicle will remain inside the White-Fi's coverage area. For example, a vehicle moving at 90 kph observes a shorter timeline compared to a vehicle moving at 120 kph. Although the probability of a busy channel is uniformly distributed, the number of busy milliseconds in a shorter timeline is proportional to the probability in the entire timeline. As a result, the percentage of opportunities for vehicular access is approximately the complement of the occupied channel probability, and increases linearly as the speed of the vehicle increases.

For bursty traffic, vehicle speed has little effect on the CAFOVA. Although vehicle speed determines when the channel occupation is sensed along the timeline, we analyzed the CAFOVA when the vehicle moves from 10 kph to 120 kph, and there are no changes in the CAFOVA due to vehicles moving faster or slower inside the White-Fi's coverage area.

We also analyzed the channel verification distance, considering distances different from the 100 m recommended by the FCC. For the same trip, changing the verification distance affects the number and frequency of channel verifications. On the one hand, the results have confirmed that the CAFOVA increases when the channel verification distance increases, when the channel occupation policy follows a uniformly distributed probability of a busy channel. On the other hand, the CAFOVA is insensitive to changes in the number of verifications when the traffic follows a Pareto distribution.

According to the results, it is possible to enable opportunistic vehicular communications in the presence of White-Fi networks sharing the same TVWS. Although this study is not focused on determining how long the channel is available along the route, one feasible type of use, considering the channel opportunities observed, would be to use the TVWS as a backup technology for sending duplicate messages when the DSRC channels are highly congested. Sharing the same TVWS with a White-Fi network is feasible when the vehicles spend short times within the White-Fi coverage area, to avoid delays in searching for a new TVWS and to ensure vehicles tune to the same TVWS to maintain communications. Future work includes determining how to estimate the time that the channel remains available depending on the White-Fi network traffic. Furthermore, it is necessary to define the channel access mechanisms that allow specific vehicular applications (e.g., emergency message dissemination or beaconing) to use the shared TVWS and meet the application requirements.

VI. CONCLUSIONS

This article presented a quantitative study of the opportunistic vehicular access over TV bands when both primary users and White-Fi networks are deployed in the area of interest. The scenario of study included the FCC technical requirements to allow connectivity from secondary mobile devices over the TV bands, as well as the considerations of a vehicular environment. We defined several channel occupation policies within the White-Fi coverage area to consider both bursty traffic (i.e., Internet traffic) and more periodic-type of traffic. To relate all the variables of interest, we have introduced a new metric, the CAFOVA, which corresponds to the percentage of channel availability for opportunistic vehicular access when there are other opportunistic networks over the same TVWS. Results demonstrated that the CAFOVA depends on the White-Fi channel occupation policy. When the traffic in the White-Fi network follows a uniformly distributed probability of busy channel, the percentage of opportunities is around the complement of the probability of occupation. On the other hand, the CAFOVA was shown to be insensitive to bursty traffic occupation policies. Furthermore, it has been shown that the CAFOVA increases both with faster vehicular speeds and with increased channel sensing distances in uniform channel occupancy. In the case of bursty traffic, the main impact on the CAFOVA comes from the relation between the inter-arrival time and the burst time, with virtually no effects due to the speed of vehicles or the channel verification distances. This study has demonstrated that vehicular networks may use the TVWS even if there are other opportunistic networks. The TVWS network may become a backup technology for sending duplicated messages when the DSRC channels are highly congested, even in the presence of fixed secondary users, such as White-Fi networks with varied channel occupation policies.

ANNEX A: DAVIDSON CORRECTION FACTOR DERIVATION

The Hata-Davidson path loss model includes correction factors to the well-known Okumura-Hata path loss model in order to expand the model's parameters [52]. The Hata-Davidson pathloss PL_{HD} is calculated as follows:

$$PL_{HD}(dB) = PL_{Hata} + K_{Davidson}, \tag{18}$$

where PL_{Hata} is the Hata path loss (derived in Section III) and $K_{Davidson}$ is the Davidson correction factor. $K_{Davidson}$ includes several terms to adjust the loss due to the expanded parameters: $A(h_{bs}, d)$ and $S_1(d)$ are distance correction factors; $S_2(h_{bs}, d)$ is the base station antenna height correction factor; $S_3(f)$ and $S_3(f, d)$ are the frequency correction factors. The equations to calculate the correction factors are given below. Table 7 depicts the main variables used for the $K_{Davidson}$ derivation.

$$K_{Davidson} = A(h_{bs}, d) - S_1(d) - S_2(h_{bs}, d) - S_3(f) - S_4(f, d) \tag{19}$$

TABLE 7. Summary of variables in Hata path loss model and $K_{Davidson}$ derivation.

Variable	Definition
PL_{HD}	Hata-Davidson path loss (dB)
PL_{Hata}	Hata path loss (dB)
$K_{Davidson}$	Davidson correction factor (dB)
PL_U	Hata path loss in urban area (dB)
PL_S	Hata path loss in suburban area (dB)
PL_R	Hata path loss in rural area (dB)
d	Distance between transmitter and receiver (km)
f	Transmitter frequency, $150 \leq f \leq 1000(MHz)$
h_{bs}	Transmitter antenna height (m)
h_m	Receiver antenna height (m)
$A(h_{bs}, d)$	Distance correction factor
$S_1(d)$	Distance correction factor
$S_2(h_{bs}, d)$	Base station antenna height correction factor
$S_3(f)$	Frequency correction factor
$S_4(f, d)$	Frequency correction factor

$$A(h_{bs}, d) = \begin{cases} 0, & d < 20km \\ 0.62317(d-20)[0.5+0.15\dfrac{h_{bs}}{121.95}], \\ \quad 20km \leq d < 300km \end{cases} \tag{20}$$

$$S_1(d) = \begin{cases} 0, & d < 64.38km \\ 0.174(d-64.38), & 64.38km \leq d < 300km \end{cases} \tag{21}$$

$$S_2(h_{bs}, d) = 0.00784 \left| log_{10}(\frac{9.98}{d})) \right| (h_{bs} - 300), \quad h_{bs} < 300m \tag{22}$$

$$S_3(f) = \frac{f}{250 log_{10}(\frac{1500}{f})} \tag{23}$$

$$S_4(f, d) = \left[0.112 log_{10}(\frac{1500}{f}) \right] (d - 64.38), \quad d > 64.38km \tag{24}$$

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ADRIANA ARTEAGA (S'11) received the B.Sc. degree in telematics engineering and the M.Sc. degree in informatics and telecommunication from Universidad Icesi, Colombia, in 2010 and 2015, respectively. She is currently pursuing the Ph.D. degree with the Department of Electrical Engineering, Universidad de Chile, Santiago, Chile. Her research interests include vehicular communication networks, cognitive radio networks, and dynamic spectrum access.

SANDRA CÉSPEDES (M'12–SM'17) received the B.Sc. degree in telematics engineering and the Specialization degree in management of information systems from Universidad Icesi, Cali, Colombia, in 2003 and 2007, respectively, and the Ph.D. degree in electrical and computer engineering from the University of Waterloo, Canada, in 2012. She is currently an Assistant Professor with the Department of Electrical Engineering, Universidad de Chile, Santiago, Chile. She is also a Researcher with the NIC Chile Research Labs and with the Institute of Complex Engineering Systems (ISCI). Her research interests include vehicular communications systems and networking, cyber-physical systems, smart grid communications, and routing and protocols design for the Internet of Things. She serves as an Associate Editor for the IEEE Internet of Things Journal.

CESAR AZURDIA-MEZA (M'14) received the B.Sc. degree in electronic engineering from the Universidad del Valle de Guatemala, Guatemala, in 2005, the M.Sc. degree in electrical engineering from Linnaeus University, Sweden, in 2009, and the Ph.D. degree in electronics and radio engineering from Kyung Hee University, South Korea, in 2013. He joined the Department of Electrical Engineering, University of Chile, as an Assistant Professor, in 2013. He has served as a Technical Program Committee (TPC) Member for multiple conferences, as well as a Reviewer in journals, such as the IEEE Communications Letter, the IEEE Transactions on Wireless Communications, *Wireless Personal Communications*, and the *EURASIP Journal on Advances in Signal Processing*. He is an IEEE Communications Society Member, as well as an IEICE Member. His research interests include Nyquists ISI criteria, OFDM-based systems, SC-FDMA, visible light communication systems, vehicular communications, 5G and beyond enabling technologies, and signal processing techniques for communication systems.