

WhiteFi Infostation: Engineering Vehicular Media Streaming With Geolocation Database

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Abstract—The TV white spaces (TVWS) enabled infostation has received significant attention due to its wide area coverage for cost-effective and media-rich content dissemination. In this paper, we engineer WhiteFi infostation, which is dedicated for Internet-based vehicular media streaming by leveraging geolocation database. After demonstrating the empirical observations of unique TVWS features and analyzing the real-world TVWS data collected from geolocation database, we first propose an optimal TVWS network planning to deploy WhiteFi infostation with the objective of maximizing network-wide throughput. The proposed TVWS network planning jointly considers the multi-radio configuration and the channel-power tradeoff, which can be realized by decentralized Markov approximation. Furthermore, we introduce a location-aware contention-free multi-polling access scheduling scheme for vehicular media streaming, which considered both the realistic vehicular applications and dynamics of wireless channel conditions. Through extensive simulations with real-world empirical TVWS data and urban vehicular traces, we demonstrate that our WhiteFi infostation solution can well support both the delay-sensitive and delay-tolerant vehicular media streaming services.

Index Terms—TV white spaces, geolocation, media streaming, Markov approximation, multi-polling.

I. INTRODUCTION

WITH the penetration of broadband Internet access and advance of automotive mobile operating systems, it is foreseeable that the Internet-based on-board multimedia

services, e.g., real-time navigation video reporting for traffic conditions, online multimedia streaming for social networking and location-aware video advertising, would become a necessity in Vehicular Ad-hoc NETWORKS (VANET) in the very near future to facilitate better road safety, provide in-car entertainment, and improve driving experience [1], [2]. To be concrete, the Internet-based vehicular tailor-made multimedia streaming applications can provide more precise, comprehensive and user-friendly services compared with plain text based applications, which can be distributed through 3G/4G-LTE cellular networks [3] or Wi-Fi hotspots [4]. However, cellular networks faces an uphill battle against the explosive growth of mobile data traffic and with relatively expensive cost; while “drive-thru” Wi-Fi is ill-suited to support vehicular multimedia streaming due to the intermittent connectivity [5]. Therefore, it is imperative to explore viable solutions providing ubiquitous, high-rate, cost-effective connectivity for vehicular media streaming [6].

TV White Spaces (TVWS) exploitation has opened up a promising opportunity for wireless connectivity because of the abundant unlicensed spectrum resource at VHF/UHF bands and better signal penetration property for long-range wireless broadband access [7] compared with the higher frequency bands, such as 2.4 GHz and 5 GHz ISM bands. It has been shown in [7] that a 6 MHz-wide TV channel with 4 W transmission power can robustly propagate at least 1200 m with more than 80 Mb/s capacity. With specially deployed Internet-based TVWS infrastructure, referred to as WhiteFi Infostation, diverse contents can be disseminated to vehicles via long-range connectivity in the white spaces networks. To enable effective vehicular content distribution, especially for media streaming by utilizing the TVWS, the first challenge is to efficiently plan the TVWS network for WhiteFi Infostations deployment based on the availability of local TVWS channels which changes over time and location. Especially, power-spectrum tradeoff for TVWS is observed in [8], i.e., with the increase of transmission power, the number of available TVWS channels acquired in Geolocation database (GDB) will be reduced accordingly because of the FCC’s policy for protecting the incumbent TV users. The set of available TVWS channels for a WhiteFi Infostation, which is queried from the GDB, is therefore subject to for particular time and location, transmission power, as well as the permitted level of inter-Infostation interference. Such dynamics of channel availability imposes considerable challenge in configuring WhiteFi Infostations in terms of transmission power and communication channels to enhance the TVWS utilization. This motivates

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us to jointly investigate the multi-radio configuration and the channel-power tradeoff for WhiteFi Infostations deployed in a given geographic area with the objective of maximizing the network-wide throughput.

To efficiently disseminate vehicular media streaming from WhiteFi Infostations, the second challenge we aim to address in this paper is to design efficient vehicular access scheme by considering the following aspects: 1) Different vehicular media streaming applications have different delay and throughput constraints, e.g., the deadline-sensitive navigation video reporting for traffic conditions and delay-tolerant video file downloading. It is necessary to coordinate the vehicle access within the coverage of WhiteFi Infostation according to different Quality-of-Service (QoS) requirements of vehicular media streaming applications; 2) As indicated by [9] that the Distributed Coordination Function (DCF) based access scheme does not work well in the Wi-Fi-like TVWS deployment due to the increased contending number in the long-distance coverage range of white spaces networking. To avoid the Medium Access Control (MAC) performance deterioration due to the contention and guarantee the time-bounded vehicular access for deadline-sensitive vehicular media streaming, a centralized scheduling is preferred; and 3) Vehicle mobility introduces significant dynamics of wireless channel conditions for the long-range vehicular connection to WhiteFi Infostations in terms of location-dependent data rate. Intuitively, mobility-aware access control consideration can be helpful to improve the vehicular media streaming performance, particularly for improving the transmitting throughput of delay-tolerant vehicular traffic services [10].

For the aforementioned considerations and to well address the two aiming challenges in this paper, we first demonstrate the empirical observations of unique TVWS features by analyzing the real-world TVWS data collected from the Geolocation database. Based on our observations, we jointly consider a multi-radio configuration and channel-power tradeoff for WhiteFi Infostation deployment and formulate the generalized white spaces planning into a Maximum Weight Clique (MWC) problem, which can be realized by decentralized Markov approximation. For the vehicular media streaming within the coverage of WhiteFi Infostation, we consider the Point Coordination Function (PCF) based Wi-Fi-like scheduling mechanism, in order to guarantee the delay-bounded vehicular media streaming applications. We introduce the contention-free multi-polling scheduling scheme to reduce the polling overhead in the PCF scheme. More importantly, we elaborately design the location-aware multi-polling vehicular access scheduling scheme to better support both the deadline-driven and delay-tolerant vehicular media streaming applications and adapt to the wireless channel variations due to the vehicular mobility. We highlight our contributions in two-fold in the light of previous literature works:

- *Generalized multi-radio and channel-power joint optimization in the white spaces planning*: Observed from the real-world empirical TVWS data collections, we formulate the generalized multi-radio and channel-power joint optimization, and solve the NP-hard planning problem with the decentralized Markov approximation, which can

provide guidance in the general white spaces networking designs, including the VANET.

- *Location-aware contention-free multi-polling scheduling for vehicular media streaming*: Explicitly taking into account both the realistic vehicular media streaming applications and dynamics of wireless channel conditions, we design the mobility-aware contention-free multi-polling vehicular scheduling scheme to support both delay-sensitive and delay-tolerant vehicular media streaming services. The proposed vehicular content distribution scheduling approach in essence is compatible with the classic IEEE 802.11 PCF scheme.

The reminder of this paper is organized as follows. Section 2 reviews the related works. Section 3 describes the WhiteFi Infostation framework for VANET. Section 4 introduces the optimal white spaces planning. Section 5 presents the vehicular access scheduling in WhiteFi Infostations. Section 6 gives the simulation results, and Section 7 concludes the paper.

II. RELATED WORKS

Regarding the white spaces utilization, there have been active theoretical researches on two types of classical approaches, i.e., conventional spectrum sensing based approach [11]–[13] and database-assisted approach. Spectrum sensing based approach is expensive in terms of energy consumption cost and circuitry complexity, and the problem of TV signals detection accuracy using spectrum sensing remains. In contrast, the Geolocation based approach does not require any hardware and is easier for implementation, since it only needs devices to report their locations to a web service, which in turn returns the available TV channels at the locations. FCC has approved the IEEE 802.11af standard to provide Geolocation database assisted dynamic white spaces access [7]. For the up-to-date research works, Murty *et al.* [14] indicated the Geolocation database assisted white spaces networking can provide mobile users with more convenient and stable dynamic access. Gao *et al.* [15] proposed the Geolocation database-driven opportunistic spectrum access approach to support the mobile users, which is designed for the vehicle-to-vehicle communication scenario. Chen and Huang [16] proposed the single-channel white spaces networking deployment with the support of Geolocation database. Madhavan *et al.* [8] introduced the utilization approach of low-power TVWS channels for small-coverage-range cellular networks. In addition, Ameigeiras *et al.* [17] investigated how to dynamically deploy the small cells in TV white spaces. The proposed small-coverage white spaces networking solutions are more suitable to support the static users due to the limited communication coverage range.

It has been well demonstrated in [18] that the content dissemination challenge is to balance the cost and ubiquity for wireless data delivery. To study the efficient Internet-based vehicular multimedia streaming, Lee *et al.* [19] and Xu *et al.* [20] investigated a cellular network and Dedicated Short Range Communications (DSRC) combined hybrid vehicular networks framework. In addition,

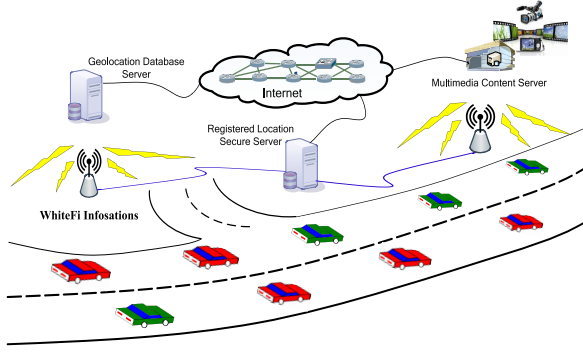


Fig. 1. Geolocation database assisted vehicular content distribution scenario with WhiteFi Infostations.

Liang and Zhuang [21] introduced a cellular/Infostation integrated networking framework for on-demand data service delivery. To further reduce the multimedia content distribution cost, Li *et al.* [22], Soldo *et al.* [23], and Asefi *et al.* [24] investigated the joint Wi-Fi and inter-vehicle communication supported hybrid vehicular networks framework. However, the all above proposed hybrid vehicular network frameworks are ill-suited to support the delay-sensitive vehicular multimedia streaming applications due to store-carry-and-forward content distribution feature. For the up-to-date research works, in terms of the vehicular content disseminate with the support of white spaces infrastructure, Yu *et al.* [13] studied the bandwidth efficient and rate-adaptive video delivery by using the dynamically sensed TVWS channels. By fully considering the TVWS spatial spectrum reuse, Chen *et al.* [25] introduced a vehicular Infotainment service provisioning approach with the goal of content delivery throughput maximization and spectrum efficiency enhancement. Lim *et al.* [26] only considered the delay-sensitive emergency safety message (ESM) dissemination by utilizing the TVWS channels.

III. WhiteFi INFOSTATION FOR VANET

We investigate the potentially deployed WhiteFi Infostations for vehicular media streaming by utilizing the TVWS channels in urban city scenario, which is shown in Fig. 1. To make a full use of the available local TVWS spectrum resource, we consider a set of N WhiteFi Infostations denoted by $\mathcal{N} = \{1, 2, \dots, N\}$, which can operate on most M TVWS channels simultaneously with multi-radio configuration [27]. We assume the locations of N WhiteFi Infostations are fixed which are distributed in a $D \times D$ squared region. The location of WhiteFi Infostation n is denoted by $\mathcal{L}_n$, and $n \in \mathcal{N}$. Based on the IEEE 802.11af standard, we consider the location-dependent white spaces networking specifically for vehicular media streaming, which is composed of the Geolocation Data Base Server (GDBS), Registered Location Secure Server (RLSS) and WhiteFi Infostations. Specifically, GDBS can perform the local vacant TVWS channel query to the Geolocation database via Internet. RLSS can coordinate the optimal dynamic TVWS spectrum resource utilization among different WhiteFi Infostations, including the TVWS spectrum assignment/coordination for the co-channel and adjacent channel interference avoidance. In this paper, GDBS is

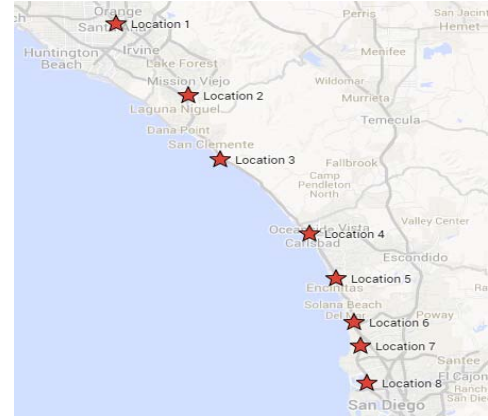


Fig. 2. The investigated Geolocation database located on the Route.5, USA.

considered to function as Geolocation database. RLSS can be considered as the implementation entity of white spaces planning. WhiteFi Infostations will provide the Internet-based long-range broadband access for vehicular media streaming considering both the delay-sensitive and delay-tolerant vehicular service requirements. The many symbols used in this paper have been summarized in Table I.

A. WhiteFi Channel-Power Dependent Map

According to the FCC's regulation rules, there are three types of TVWS channels that can be utilized for the white spaces networking, i.e., fixed devices, mode-II devices and mode-I devices, which can be denoted by $\mathcal{S}_n^F$, $\mathcal{S}_n^{II}$ and $\mathcal{S}_n^I$, respectively. For fixed devices, the available operation channels are ranging from channel 2 to channel 51 except the channel 3, 4 and 37, i.e., $\mathcal{S}_n^F \triangleq \{\mathcal{T}_n | n = 2 : 1 : 51 \setminus \{3, 4, 37\}\}$. For the mode-II devices and mode-I devices, the available operation channels are ranging from the channel 21 to channel 51 except the channel 37, i.e., $\mathcal{S}_n^I = \mathcal{S}_n^{II} \triangleq \{\mathcal{T}_n | n = 21 : 1 : 51 \setminus \{37\}\}$. We denote the complete set of available TVWS channels queried from the Geolocation database by $\mathcal{S} = \{\mathcal{T}_2, \mathcal{T}_3, \dots, \mathcal{T}_{51}\}$, and denote the bandwidth of each TV band by $B_w = 6$ MHz. For WhiteFi Infostation n deployed at the location $\mathcal{L}_n$, the set of available TVWS channels can be denoted by $\mathcal{S}(\mathcal{L}_n)$. Here, we assume that each WhiteFi Infostation is associated with a fixed location, and we can simplify the notion of $\mathcal{S}(\mathcal{L}_n)$ into $\mathcal{S}_n$, and $\mathcal{S}_n \subset \mathcal{S}$. There are at most three types of configurable TVWS channels at location $\mathcal{L}_n, n \in \mathcal{N}$, depending on the transmission power constraint. The allowed power window of available TVWS channels are $(0, 4000mW]$, $(0, 100mW]$ and $(0, 40mW]$, respectively. Accordingly, the sets of allowed transmission power for the three types of TVWS channels can be denoted by $\mathcal{P}_n^F$, $\mathcal{P}_n^{II}$ and $\mathcal{P}_n^I$, respectively. By utilizing the two widely recognized white spaces database pilots hosted by Spectrum Bridge [28] and Telcordia [29], we study the availability of TVWS channels of 8 different locations along the Route No.5 between the San Diego and Los Angeles, which is shown in Fig. 2. Based on our double-week data collections, Figs. 3-4 show the significant rules/phenomena of database-assisted white spaces for the dynamic sharing. We have the following two important observations:

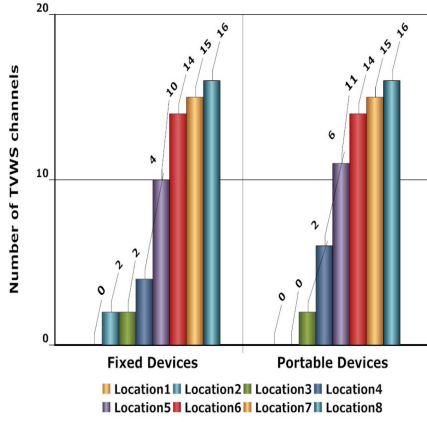


Fig. 3. The TVWS channel statistics at 8 locations of Route.5, USA.

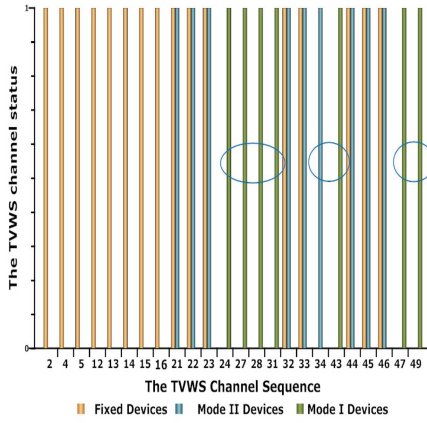


Fig. 4. The TVWS channel distribution of mode I/II and fixed devices.

Observation 1: The available TVWS channels queried from Geolocation database is with spatial variation, which is foreseen from the data statistics of Fig. 3 in the 8 investigated locations.

Observation 2: With the decrease of transmission power, there will be more available TVWS channels in the designated locations, which is claimed in as the power-spectrum tradeoff curve phenomenon as well. This power-spectrum tradeoff curve phenomenon cannot be applied for mode-II devices. Fig. 4 further manifests that the fixed devices and mode-II devices have almost the same available channels in $\mathcal{S}_n^F$ and $\mathcal{S}_n^{II}$ from the channel sequence $\mathcal{T}_{21}$ to $\mathcal{T}_{51}$.

The two observations can provide meaningful guidance for the white spaces planning. Observation 1 suggests the Geolocation database assisted dynamic spectrum access will become more convenient and stable due to the gradual temporal variation of available TVWS channels. To maximize the TVWS utilization, a general white spaces planning including both the fixed TVWS channel and mode II/I TVWS channel configuration is a necessity by considering the spatial variation and power-spectrum tradeoff phenomenon of available TVWS channels in Observation 2. In addition, based on the TVWS usage rules from FCC, the transmission power for each type

of defined TVWS device is with a consecutive window range. Considering the discrete power control realization, we can set effective segmentation step for power transmission range division. For more exactly approaching to the continuous power control optimization, we define different segmentation parameters for different power control adjustments of the three types of TVWS devices, which are denoted by $\ell^F, \ell^I, \ell^{II}$, respectively, and we have $\ell^I < \ell^{II} < \ell^F$. Hence, we can get the transmission power selection sets of three types of TVWS devices, i.e., $\mathcal{P}_n^F, \mathcal{P}_n^{II}$ and $\mathcal{P}_n^I$, shown as follows, respectively,

$$\mathcal{P}_n^I \triangleq (0mW : \ell^I mW : 40mW)$$

$$\mathcal{P}_n^{II} \triangleq \mathcal{P}_n^I \cup (40mW : \ell^{II} mW : 100mW)$$

$$\mathcal{P}_n^F \triangleq \mathcal{P}_n^{II} \cup (100mW : \ell^F mW : 4000mW) \quad (1)$$

We denote the channel-power dependent selection for WhiteFi Infostation n by $(c_n, p_n(c_n))$, i.e., the WhiteFi Infostation n selects the TVWS channel c_n from the available TVWS channel set $\mathcal{S}_n$ with the transmission power $p_n(c_n)$ for the local WhiteFi Infostation channel configuration, and the dependent channel-power relationship satisfies the following relationship:

$$p_n(c_n) \in \begin{cases} \mathcal{P}_n^F, & c_n \in \mathcal{S}_n^F \\ \mathcal{P}_n^I, & c_n \in \mathcal{S}_n^I \\ \mathcal{P}_n^{II}, & c_n \in \mathcal{S}_n^{II} \end{cases} \quad (2)$$

B. Vehicular Mobility Model

To analyze the vehicular sojourn time durations within the coverage of WhiteFi Infostation, here, we can apply the widely investigated Fluid Traffic Motion (FTM) model [30] to capture the macroscopic vehicular relationship between the traffic density δ and average vehicular speed $\bar{\Phi}$, shown as $\bar{\Phi} = \max\{\Phi_{\min}, \Phi_{\max}(1 - \delta/\delta_{jam})\}$, where $\Phi_{\min}$ and $\Phi_{\max}$ are denoted as the minimal and maximal vehicular driving speed, respectively; δ and δ_{jam} are the factual and jammed traffic density, respectively. As investigated in [31], the driving speed Φ_i of arbitrary vehicle i follows the normal distribution. We define a truncated Probability Distribution Function (PDF) of driving speed Φ_i to avoid generating the negative or zero speeds, which is expressed as

$$\begin{aligned} \widehat{f}_{\Phi}(\Phi_i) &= f_{\Phi}(\Phi_i) / \int_{\Phi_{\min}}^{\Phi_{\max}} f_{\Phi}(\Phi_i) d\Phi_i \\ &= \frac{f_{\Phi}(\Phi_i)}{\frac{1}{2}erf\left(\frac{\Phi_{\max}-\bar{\Phi}}{\varsigma\sqrt{2}}\right) - \frac{1}{2}erf\left(\frac{\Phi_{\min}-\bar{\Phi}}{\varsigma\sqrt{2}}\right)} \end{aligned} \quad (3)$$

where $f_{\Phi}(\Phi_i) = \frac{1}{\varsigma\sqrt{2\pi}} e^{-\left(\frac{\Phi_i-\bar{\Phi}}{\varsigma\sqrt{2}}\right)^2}$ and $erf(x) = \frac{2}{\pi} \int_0^x e^{-t^2} dt$, $\bar{\Phi} \in [\Phi_{\min}, \Phi_{\max}]$, $\varsigma = \gamma\bar{\Phi}$, $\Phi_{\min} = \bar{\Phi} - \varphi\varsigma$, and the typical value of two-tuple (γ, φ) depends on the traffic state [31].

We can get the PDF of vehicular residence time for a given connectivity range $\mathcal{D}_{v_i}$ of vehicle v_i within the coverage of WhiteFi Infostation, which is shown as:

TABLE I
SUMMARY OF IMPORTANT SYMBOLS

Symbols Associated with white spaces planning	
$\mathcal{N}$	The set of N WhiteFi Infostations.
M	The radio configuration number.
$\mathcal{S}_n^F, \mathcal{S}_n^{II}, \mathcal{S}_n^I$	The TVWS channel sets of fixed, mode-II and mode-I devices.
$\mathcal{S}_n$	The set of available TVWS channels for WhiteFi node n at the location $\mathcal{L}_n$.
$\mathcal{P}_n^F, \mathcal{P}_n^{II}, \mathcal{P}_n^I$	The sets of allowed transmission power for three types of TVWS channel sets.
$(c_n, p_n(c_n))^M$	M -radio and joint channel-power selection set for WhiteFi Infostation n .
$\mathcal{J}_n^M$	The feasible M -channel and joint channel-power selection space.
$\mathbb{T}^M$	The M -channel configuration profile for all the WhiteFi Infostations.
$\mathbb{P}^M$	The M -channel transmission power configuration for all the WhiteFi Infostations.
$\mathbf{E}_n(\Upsilon^M)$	The Shannon capacity of WhiteFi node n with M -channel configuration.
$\mathcal{J}$	The multi-channel and joint channel-power selection space of all N WhiteFi Infostations.
Symbols Associated with vehicular access scheduling	
$\mathcal{D}_{v_i}$	The sojourn distance of vehicle v_i within the coverage of WhiteFi Infostation.
$f(\Phi_i)$	The probability distribution function of arbitrary vehicle i 's speed Φ_i .
$F_{\mathcal{D}_{v_i}}(\tau)$	The cumulative distribution function of vehicle's speed $\widehat{F}_\nu$.
$\bar{\Gamma}_{\mathcal{D}_{v_i}}$	The mean vehicle's residence time within a fixed distance with a length $\mathcal{D}_{v_i}$.
T_{sf}	The constant superframe duration.
$\mathcal{R}_{v_k}$	The auto-rate function.
$SINR_{v_k,n}$	The received SINR of vehicular user k from WhiteFi Infostation n .
r_n	The coverage of WhiteFi Infostation n with the m -channel configuration.
$\mathcal{G}_{T,f}$	The vehicular access set.
$\mathcal{O}$	The targeted volume size set of vehicular tasks.
$\mathcal{D}$	The required task completion delay set for the targeted vehicular tasks.
L_{load}	The fixed length of payload for each targeted transmission in MPVU phase.
$\mathcal{F}$	The allocated fraction for the delay-sensitive services scheduling.
$\mathcal{A}_r$	The vehicular user set with delay-sensitive traffic services requirements.
$\mathcal{A}_d$	The vehicular access set with delay-tolerant traffic services requirements.
$TXOP$	The transmission frame opportunity.

Lemma 1: Given the vehicle i 's connectivity range to one WhiteFi Infostation is $\mathcal{D}_{v_i}$, and the arriving vehicular driving speed follows the normal distribution, the PDF of vehicle's residence time $f_{\mathcal{D}_{v_i}}(\tau)$ within the WhiteFi Infostation coverage is as follows,

$$f_{\mathcal{D}_{v_i}}(\tau) = \frac{\wp \mathcal{D}_{v_i}}{\tau^2 \varsigma \sqrt{2\pi}} e^{-\left(\frac{\mathcal{D}_{v_i}/\tau - \bar{\Phi}}{\varsigma \sqrt{2}}\right)^2}, \quad \tau \in \left[\frac{\mathcal{D}_{v_i}}{\Phi_{\max}}, \frac{\mathcal{D}_{v_i}}{\Phi_{\min}}\right] \quad (4)$$

Proof: The Cumulative Distribution Function (CDF) of vehicle's residence time $F_{\mathcal{D}_{v_i}}(\tau)$ can be derived by combining the CDF of vehicle's speed $\widehat{F}_\Phi$ [31], shown as

$$F_{\mathcal{D}_{v_i}}(\tau) = 1 - \widehat{F}_\Phi\left(\frac{\mathcal{D}_{v_i}}{\tau}\right) = 1 - \frac{\wp}{2} \left[1 + \operatorname{erf}\left(\frac{\mathcal{D}_{v_i}/\tau - \bar{\Phi}}{\varsigma \sqrt{2}}\right)\right] \quad (5)$$

where $\wp = 2 / \left(\operatorname{erf}\left(\frac{\Phi_{\max} - \bar{\Phi}}{\varsigma \sqrt{2}}\right) - \operatorname{erf}\left(\frac{\Phi_{\min} - \bar{\Phi}}{\varsigma \sqrt{2}}\right)\right)$. By setting the derivative of expression $F_{\mathcal{D}_{v_i}}(\tau)$ and combining $\frac{d}{dx} \operatorname{erf}(x) = \frac{2}{\sqrt{\pi}} e^{-x^2}$, we can prove the lemma. ■

We can easily get the expression of mean vehicle's residence time within a given vehicular connectivity range $\mathcal{D}_{v_i}$, based on the PDF of vehicle's residence time $f_{\mathcal{D}_{v_i}}(\tau)$, which can be shown as

$$\begin{aligned} \bar{\Gamma}_{\mathcal{D}_{v_i}} &= \int_{\mathcal{D}_{v_i}/\Phi_{\max}}^{\mathcal{D}_{v_i}/\Phi_{\min}} \tau f_{\mathcal{D}_{v_i}}(\tau) d\tau \\ &= \int_{\mathcal{D}_{v_i}/\Phi_{\max}}^{\mathcal{D}_{v_i}/\Phi_{\min}} \frac{\wp \cdot \mathcal{D}_{v_i}}{\tau \varsigma \sqrt{2\pi}} e^{-\left(\frac{\mathcal{D}_{v_i}/\tau - \bar{\Phi}}{\varsigma \sqrt{2}}\right)^2} d\tau \end{aligned} \quad (6)$$

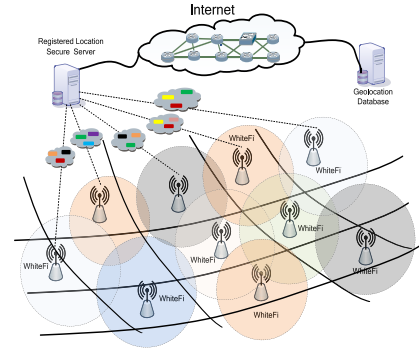


Fig. 5. Multi-radio dynamic white spaces planning for urban WhiteFi Infostations.

IV. OPTIMAL WHITE SPACES PLANNING

A. Problem Formulation

We consider the WhiteFi Infostation is configured with one channel in each radio transmitter, and hence, the M -radio white spaces planning problem is equivalent to a M -channel configuration optimization in essence, which is shown in Fig. 5. We use M -channel configuration and M -radio configuration two terms interchangeably. To be more practical, we study the optimal white spaces planning, which is based on real-world TVWS data collection in Waterloo, shown in Fig. 6. We denote the joint channel-power selection set for WhiteFi Infostation n by $(c_n, p_n(c_n))^M$, $n = \{1, 2, \dots, N\}$. When $M = 1$, it means the single-channel WhiteFi Infostation configuration. We denote the feasible M -channel and joint

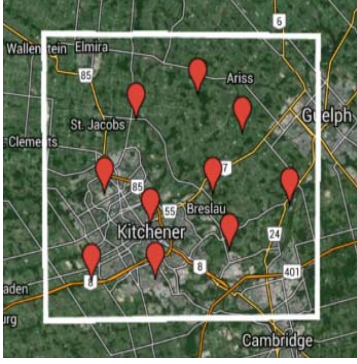


Fig. 6. Real-world TVWS data collection in Waterloo, Ontario, Canada.

channel-power selection set for WhiteFi Infostation n by $\mathcal{J}_n^M$. Easily, we can denote $\mathbb{T}^M = (c_1^M, c_2^M, \dots, c_N^M)$ as the M -channel configuration profile for all WhiteFi Infostations, and denote $\mathbb{P}^M = (p_1^M, p_2^M, \dots, p_N^M)$ as the M -channel transmission power configuration on the selected channels, which forms a joint channel-power selection set for all the N WhiteFi Infostations, denoted by $\Upsilon^M = (\mathbb{T}, \mathbb{P})^M$. For M -channel WhiteFi Infostation deployment, the Shannon capacity of WhiteFi Infostation n can be calculated as,

$$\mathbf{E}_n(\Upsilon^M) = \sum_{m \in M} B_w \log_2 \left(1 + \Re \left(p_m, \varpi_{c_m}^n, \frac{p_i}{r_{i,n}^\phi} \right) \right) \quad (7)$$

where $\Re(\cdot)$ is the cumulative signal-to-noise ratio function, $\Re(\cdot) \triangleq \frac{p_m}{\varpi_{c_m}^n + \sum_{m \in M} \sum_{i \in \mathcal{N} \setminus \{n\}: c_i = c_m} p_i / r_{i,n}^\phi}$, ϕ is a path loss parameter, $r_{i,n}^\phi$ is the distance from WhiteFi Infostation i to WhiteFi Infostation n , $\varpi_{c_m}^n$ is the background noise power including the interference from incumbent primary TV users on the channel c_m , and the accumulated interference from other WhiteFi Infostations that choose the same channel c_m is denoted by $\sum_{m \in M} \sum_{i \in \mathcal{N} \setminus \{n\}: c_i = c_m} p_i / r_{i,n}^\phi$.

Our motivation is to maximize the network-wide throughput, which is the accumulated Shannon capacity of all the N WhiteFi Infostations with M -channel configuration. Basically, the WhiteFi Infostations need to collectively determine the optimal channel selection profile $(\mathbb{T}^M)^*$ with the best power control strategy $(\mathbb{P}^M)^*$, here we can have $(\Upsilon^M)^* = ((\mathbb{T}^M)^*, (\mathbb{P}^M)^*)$, which forms an optimal combination such that the network-wide throughput can be maximized, i.e.,

$$(\Upsilon^M)^* \triangleq \arg \max_{\Upsilon^M \in \mathcal{J} \triangleq \prod_{m=1}^N \mathcal{J}_m^M} \sum_{n \in \mathcal{N}} \mathbf{E}_n(\Upsilon^M) \quad (8)$$

where $\prod_{m=1}^N \mathcal{J}_m^M$ is denoted as the multi-channel and joint channel-power selection profile of all N WhiteFi Infostations over the discrete solution space $\mathcal{J}$.

B. Optimal Dynamic TVWS Assignment

The optimization of (8) is a general combinatorial optimization problem, which could be challenging due to the large size of discrete solution space $\mathcal{J}$, even in a centralized processing way. To better solve the problem, we first

investigate the generalized channel-power selection space $\mathbb{J}_n$ of the white spaces networking. We denote the perfect set of available TVWS channels by $\mathcal{S} = \{\mathcal{T}_2, \mathcal{T}_3, \dots, \mathcal{T}_{51}\}$, and we do not distinguish the TVWS device type in the channel-power selection space $\mathbb{J}_n$, and consider the power control range as $(0mW, 4000mW]$ for defining the generalized channel-power selection space. For TVWS channel $c_i = \mathcal{T}_i$ with power transmission p_i , and $\mathcal{T}_i \in \mathcal{S}$, the power transmission range can be divided into $\left\lceil \frac{40-0}{\ell^I} \right\rceil + \left\lceil \frac{100-40}{\ell^{II}} \right\rceil + \left\lceil \frac{4000-100}{\ell^F} \right\rceil$ segments. Hence, we can provide a generalized formulation of available joint channel-power selection matrix $\mathbb{J}_n$ of WhiteFi Infostation n , which is shown as follows,

$$\mathbb{J}_n = \begin{pmatrix} \mathcal{T}_2 & \mathcal{T}_3 & \dots & \mathcal{T}_K \\ p_{12} & \dots & p_{1K} \\ \vdots & \ddots & \vdots \\ p_{I2} & \dots & p_{IK} \end{pmatrix} \quad (9)$$

Where I is the size of divided power transmission sections, and $I = \left\lceil \frac{40-0}{\ell^I} \right\rceil + \left\lceil \frac{100-40}{\ell^{II}} \right\rceil + \left\lceil \frac{4000-100}{\ell^F} \right\rceil$; K is the maximal sequence number of available TVWS channel, here $K = 51$. For the notion p_{ik} , $i = 1, 2, \dots, I$, $k = 2, 3, \dots, K$ in the matrix $\mathbb{J}_n$, we will discuss the detailed cases for the joint channel-power selection strategy of the WhiteFi Infostation n :

- $p_{ij} = 0$: The channel $\mathcal{T}_j$ is not available for WhiteFi Infostation n or WhiteFi Infostation n does not select the channel $\mathcal{T}_j$ for the local configuration optimization.
- $p_{ij} \neq 0$: The channel $\mathcal{T}_j$ is selected. For single-channel configuration scenario, the current joint channel-power selection for WhiteFi Infostation n can be denoted by $(c_n = \mathcal{T}_i, p_n(c_n) = p_{ij})$. If $c_n \subset \mathcal{S}_n^{II}$, then $p_{i,k} \in \mathcal{P}_n^{II}$; If $c_n \subset \mathcal{S}_n^I$, then $p_{i,k} \in \mathcal{P}_n^I$.

We can rewrite (8) as a typical MWC optimization problem, i.e., $\max_{\Upsilon^M \in \mathcal{J}} \sum_{n \in \mathcal{N}} \mathbf{E}_n(\Upsilon^M)$. The MWC optimization problem has the equivalent optimal value as the following problem:

$$\begin{aligned} \text{MWC - EQ: } & \max_{\mathbf{p}_{\Upsilon^M} \geq 0} \sum_{\Upsilon^M \in \mathcal{J}} p_{\Upsilon^M} \sum_{n \in \mathcal{N}} \mathbf{E}_n(\Upsilon^M) \\ & s.t. \sum_{\Upsilon^M \in \mathcal{J}} p_{\Upsilon^M} = 1 \end{aligned} \quad (10)$$

where p_{Υ^M} is the joint channel-power selection probability.

Obviously, when the optimal channel-power profile is selected with the probability 1, the problem of **MWC-EQ** will have the exact solution as that of **MWC**. Based on the conclusion from [32], (10) can be well approximated by using the following convex optimization problem:

$$\begin{aligned} & \max_{\mathbf{p}_{\Upsilon^M} \geq 0} \sum_{\Upsilon^M \in \mathcal{J}} p_{\Upsilon^M} \sum_{n \in \mathcal{N}} \mathbf{E}_n(\Upsilon^M) - \frac{1}{\alpha} \sum_{\Upsilon^M \in \mathcal{J}} p_{\Upsilon^M} \log p_{\Upsilon^M} \\ & s.t. \sum_{\Upsilon^M \in \mathcal{J}} p_{\Upsilon^M} = 1 \end{aligned} \quad (11)$$

where α is a positive constant to control the approximation ratio, and when $\alpha \rightarrow \infty$, the optimization approximation of (11) will become the exact solution of (10).

We can derive a close-form optimization solution of problem (11) by applying the Karush-Kuhn-Tucker (KKT) conditions [33]. Let λ be the Lagrange multiplier associated with the equality constraint and $p_{\gamma^M}^*$ be the optimal solution of problem (11), we can have

$$\sum_{n \in \mathcal{N}} \mathbf{E}_n(\gamma^M) - \frac{1}{\alpha} \log p_{\gamma^M}^*(\mathbf{E}_n) - \frac{1}{\alpha} + \lambda = 0, \quad \forall \gamma^M \in \mathcal{J} \quad (12)$$

$$\sum_{\gamma^M \in \mathcal{J}} p_{\gamma^M}^*(\mathbf{E}_n) = 1 \quad (13)$$

$$\lambda \geq 0 \quad (14)$$

Based on the derived result in [27], we can get the optimal solution $p_{\gamma^M}^*(\mathbf{E}_n)$ in (11) as

$$p_{\gamma^M}^*(\mathbf{E}_n) = \frac{\exp(\alpha \sum_{n \in \mathcal{N}} \mathbf{E}_n(\gamma^M))}{\sum_{\gamma^{M'} \in \mathcal{J}} \exp(\alpha \sum_{n \in \mathcal{N}} \mathbf{E}_n(\gamma^{M'}))} \quad (15)$$

Theorem 1: Given any probability distribution of joint channel-power selection $p_{\gamma^M}^*(\mathbf{E}_n)$ in (15), there exists at least one continuous-time time-reversible ergodic Markov chain whose stationary distribution is $p_{\gamma^M}^*(\mathbf{E}_n)$.

Proof: Reference [32] has proved that (15) can be implemented by modeling as a distributed time-reversible Markov chain, and as the Markov chain converges, the optimal joint channel-power selection $p_{\gamma^M}^*(\mathbf{E}_n)$ can achieve the maximal network-wide throughput of M -radio white spaces planning. Hence, we can prove the theorem. ■

Based on the above theoretical analysis, the proposed Optimal Dynamic TVWS Assignment (ODTA) algorithm can be realized in a distributed Markov chain way, which is described as follows in Algorithm 1.

Theorem 2: The gap between the proposed ODTA algorithm for M -radio and joint channel-power configuration and the optimal solution of MWC optimal problem is bounded by $\frac{1}{\alpha} \log |\mathcal{J}|$.

Proof: It is known from [32] that we can use the differentiable function to approximate the MWC problem, i.e.,

$$\max_{\gamma^M \in \mathcal{J}} \sum_{n \in \mathcal{N}} \mathbf{E}_n(\gamma^M) \approx \frac{1}{\alpha} \log \sum_{\gamma^M \in \mathcal{J}} \exp \left(\alpha \sum_{n \in \mathcal{N}} \mathbf{E}_n(\gamma^M) \right) \quad (16)$$

By applying the Log-Sum-Exp approximation equation in [33], i.e.,

$$\max_{i=1,2,\dots,n} x_i \leq \log \left(\sum_{i=1}^n e^{x_i} \right) \leq \max_{i=1,2,\dots,n} x_i + \log(n)$$

we can have

$$\begin{aligned} \max_{\gamma^M \in \mathcal{J}} \sum_{n \in \mathcal{N}} \mathbf{E}_n(\gamma^M) &\leq \frac{1}{\alpha} \log \sum_{\gamma^M \in \mathcal{J}} \exp \left(\alpha \sum_{n \in \mathcal{N}} \mathbf{E}_n(\gamma^M) \right) \\ &\quad + \frac{1}{\alpha} \log |\mathcal{J}| \end{aligned} \quad (17)$$

Hence, we can prove the theorem. ■

Theorem 3: The computational complexity of ODTA algorithm is $\Theta(NC_K^M(C_I^1)^M \Lambda)$. When the radio number $M = 1$, the computational complexity is $\Theta(NK I \Lambda)$.

Algorithm 1 ODTA Algorithm

Input: WhiteFi $n \in \mathcal{N} = \{1, 2, \dots, N\}$, M , $\phi, r_n^\phi, \alpha, \varpi_{c_m}^n, r_{i,n}^\phi$.

Output: $(\gamma^M)^* = ((\mathbb{T}^M)^*, (\mathbb{P}^M)^*)$.

1: **Initialization:**

2: Generating the joint channel-power selection matrix $\mathbb{J}_n$,

3: RLSS informs $\mathbb{J}_n$ to WhiteFi Infostation n , $n \in \mathcal{N}$;

4: WhiteFi Infostation n randomly selects a joint channel-power configuration $(c_{n,0}, p_{n,0}(c_{n,0}))^M$ i. e., $(\gamma^M)^* \leftarrow \gamma_0^M = (\mathbb{T}_0^M, \mathbb{P}_0^M)$.

5: **End initialization**

6: **Loop** Iteration i :

7: RLSS randomly select one WhiteFi Infostation n , $n \in \mathcal{N}$, to update the M -radio channel-power configuration;

8: **If** WhiteFi Infostation n is selected, **Do**

9: **Calculating** $\sum_{n \in \mathcal{N}} \mathbf{E}_n(\gamma^M)$;

10: WhiteFi Infostation n selects a channel-power configuration $\gamma_i^M = (c_n, p_n(c_n))^M$ with probability $\frac{\exp(\alpha \sum_{n \in \mathcal{N}} \mathbf{E}_n(\gamma_i^M))}{\sum_{(\gamma_i^M)' \in \mathcal{J}} \exp(\alpha \sum_{n \in \mathcal{N}} \mathbf{E}_n((\gamma_i^M)'))}$, **Then;**

11: $(\gamma^M)^* \leftarrow \gamma_i^M, i = i + 1$,

12: **End if**

13: **End Loop**

14: Return $(\gamma^M)^* = ((\mathbb{T}^M)^*, (\mathbb{P}^M)^*)$.

Proof: The ODTA algorithm is performed with the unit of iteration. In each iteration, RLSS will select one WhiteFi Infostation for the channel and power configuration update. Line 9 involves the summation of the capacities of N WhiteFi Infostations. Since individual WhiteFi Infostation has $C_K^M(C_I^1)^M$ channel-power selection choices. This step has the complexity of $NC_K^M(C_I^1)^M$. Line 10 involves at most $C_K^M(C_I^1)^M$ summation and division operations and hence has a complexity of $C_K^M(C_I^1)^M$. Line 11 has a complexity of $\Theta(1)$. Suppose that the ODTA algorithm takes $\Lambda(\alpha)$ iterations for the algorithm to converge, which is related to the optimization approximation ratio α . Then total computational complexity of ODTA algorithm is $\Theta(NC_K^M(C_I^1)^M \Lambda)$. Easily, when $M = 1$, the computational complexity can be given as $\Theta(NK I \Lambda)$. Hence, we can prove the theorem. ■

V. VEHICULAR ACCESS IN WhiteFi INFOSTATION

The DCF based access scheme cannot well address the increased congestion in the large-coverage Wi-Fi-like TVWS deployments, which is showed in [9]. The PCF based access approach can support the time-bounded services, which will be helpful for the delay-sensitive vehicular media streaming applications. To further reduce the overhead of polling approach in the PCF scheme [34], [35], we introduce the Contention-Free Multi-Polling (CFMP) vehicular access method for the M -stream dynamic vehicular access scheduling among different vehicular services within the coverage of the WhiteFi Infostation.

The CFMP vehicular access scheduling process is controlled by polling from a Point Coordinator (PC) at the WhiteFi

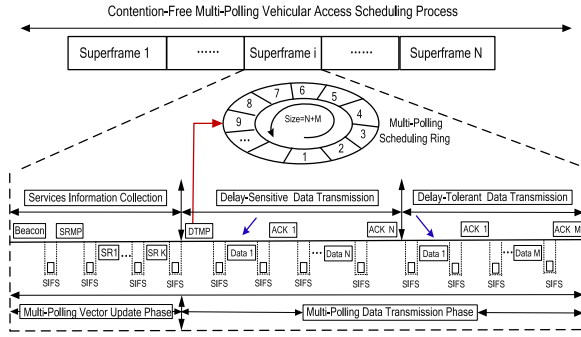


Fig. 7. The vehicular contention-free multi-polling access process associated with one WhiteFi Infostation.

infostation, which is performed with the unit of superframe, and shown in the Fig. 7. We consider that each superframe is with a fixed interval unit, which is composed of Multi-Polling Vector Update (MPVU) phase and Multi-Polling Data Transmission (MPDT) phase. In the MPVU phase, PC will collect the current access status information including the wireless link status and vehicular traffic service information by broadcasting the Status-Request Multi-Polling (SRMP) frame to the vehicles with media streaming requirements, and based on the vehicular access criterions, we employ an optimal multi-polling scheduling ring for implementing the multi-polling data transmission in the MPDT phase. Our main motivation of CFMP vehicular access scheduling is to adapt to the varied wireless channel status, vehicular mobility and most importantly the different vehicular media streaming requirements. For simplification, we only consider the vehicular access scheduling within the coverage of one WhiteFi Infostation and assume that each vehicle randomly associates with one WhiteFi Infostation and keeps connecting until it moves out of the coverage region. We first present the following definitions before making the optimal vehicular access scheduling decisions.

Let T_{sf} be the superframe duration which is composed of one MPVU duration T_{vu} and one MPDT duration T_{dt} , i.e., $T_{sf} = T_{vu} + T_{dt}$. As shown in Fig. 7, we can form a $N + M$ multi-polling transmission ring given a K -user access scheduling requirement, and T_{vu} , T_{dt} can be respectively given as:

$$T_{vu} = T_{bea} + T_{srmp} + K T_{sr} + (K + 1) T_{sifs} \quad (18)$$

$$T_{dt} = T_{dtmp} + \sum_{i=1}^N \left(T_{pre} + T_{hdr} + T_{ack} + 2 T_{sifs} + \frac{L_{load}}{\mathcal{R}_{v_k}} \right) \quad (19)$$

where T_{bea} , T_{srmp} , T_{sr} , T_{pre} , T_{hdr} , T_{ack} , T_{dtmp} are the time durations of beacon frame, Status-Request MultiPoll (SRMP) frame, Status-Response (SR) frame, preamble frame, PHY and MAC header frame, ACK frame and Data Transmission MultiPoll (DTMP) frame respectively. T_{sifs} is the SIFS idle time. $\mathcal{R}_{v_k}$ is an auto-rate function, which maps the given minimum received SINR to the raw bit rate $\mathcal{R}_{v_k}$ provided to the vehicular user k [9]. We define

$SINR_{v_k}$ as the received SINR of vehicular user k , which is a location-aware value related to the distance between the vehicular user k and WhiteFi Infostation n and other interfering WhiteFi Infostations using the same TVWS channel, i.e., $r_{v_k}^\phi$ and $r_{v_k,i}^\phi$. Given an optimal channel-power selection set $(\Upsilon^M)^*$ by ODTA algorithm, $SINR_{v_k}$ can be calculated by

$$SINR_{v_k} = \frac{p_m / r_{v_k,n}^\phi}{\varpi_{c_m}^n + \sum_{m \in M} \sum_{i \in \mathcal{N} / \{n\} : c_i = c_m} \frac{p_i}{r_{v_k,i}^\phi}} \quad (20)$$

where r_n^ϕ is the coverage radius of WhiteFi Infostation n . r_n^ϕ is related to the configured channel frequency f and transmission power p_m , and can be calculated by applying the free-space path loss model. According to the FCC regulations, each TVWS channel can be matched to a unique frequency range $[f(c_i), f(c_i) + 6MHz]$. Based on the aforementioned coverage radius calculation parameters, we can get the coverage $r_n((c_n, p_n(c_n)))$ of the WhiteFi Infostation n with the $(c_n, p_n(c_n))$ channel-power configuration, $n \in \mathcal{N}$, which can be expressed as:

$$P_{rx} = P_{tx}(p_n) - 20 \log_{10}(r_n) - 20 \log_{10}(f(c_n)) - 32.45 \quad (21)$$

where $r_n((c_n, p_n(c_n)))$ is given in km, and the coverage radius of m -radio WhiteFi Infostation configuration can be calculated accordingly by (21) accordingly.

We denote $\mathcal{G}_{T_{if}} = \{V_1, V_2, \dots, V_k\}$ as the vehicular access set, and the targeted volume size set of vehicular media streaming is denoted by $O = \{O_{v_1}, O_{v_2}, \dots, O_{v_k}\}$. The required task completion delay set for the targeted vehicular tasks is denoted by $\mathcal{D} = \{d_{v_1}, d_{v_2}, \dots, d_{v_k}\}$. We consider two types of vehicular content distribution services within the coverage of WhiteFi Infostation, i.e., 1) delay-sensitive vehicular media streaming services, such as real-time navigation video reporting for traffic conditions and online media streaming etc.; 2) delay-tolerant vehicular content distribution services, such as large-volume sized media file downloading and location-aware video advertising. For simplification, we assume each vehicle with content distribution requirement only submits one type of vehicular service application for each superframe scheduling when it drives within the coverage range of WhiteFi infostation. If the service requirement O_{v_i} of vehicle i is delay-sensitive, we denote the time constraint for the task completion delay by $[0, d_{v_i}]$; If the service requirement O_{v_i} of vehicular i is delay-tolerant, we consider the time constraint for the service completion delay is the whole sojourn time within the coverage of WhiteFi infostation, which is denoted by $[0, \Gamma^{d_{v_i}}]$, i.e., $d_{v_i} = \Gamma^{d_{v_i}}$.

A. Optimal Vehicular Media Streaming

The optimal vehicular media streaming scheduling is necessary for both the delay-sensitive and delay-tolerant vehicular services in the MPDT phase. After the MPVU phase, the PC forms the updated multi-polling scheduling ring and the MPDT phase starts accordingly. We consider the constant superframe duration T_{sf} and fixed length of payload L_{load} for

each targeted transmission of one scheduled vehicular user in the MPDT phase. Considering the SINR based vehicular transmission rate $\mathcal{R}_{v_k}$, the time duration of transmission window T_{dt,v_k} of each scheduled vehicular user will be different, i.e.,

$$T_{dt,v_k} = T_{dtmp} + T_{pre} + T_{hdr} + T_{ack} + 2T_{sifs} + \frac{L_{load}}{\mathcal{R}_{v_k} (SINR_{v_k})}$$

which means the larger data-rate $\mathcal{R}_{v_k}$ is, the less occupied transmission duration of scheduled user will be allocated in one superframe T_{dt} . Hence, selecting a vehicular user with high data-rate will save transmission time for other vehicular users in a fixed superframe duration. We schedule the two types of traffic services among the M -stream synchronously with the unit of one superframe duration, i.e., $[(p-1)T_{sf}, pT_{sf}]$, $p \in \mathbb{N}^+$. For the paralleled M -stream vehicular services scheduling, and considering the allocated scheduling fraction for the delay-sensitive and delay-tolerant services is $\mathcal{F}$ and $1-\mathcal{F}$ respectively, we can get the transmission time window for the delay-sensitive services and delay-tolerant services in one superframe is $M\mathcal{F}T_{sf}$ and $M(1-\mathcal{F})T_{sf}$ respectively. We consider the allocated scheduling fraction for the two types of traffic services during each superframe is fixed and the two types of traffic services is uncorrelated, hence, we can design different scheduling algorithms for the two types of services, which would not affect the performance of two types of scheduled services. We discuss distinguished scheduling optimizations for the two types of traffic services shown as follows.

Delay-Sensitive Vehicular Traffic Services: During each superframe duration $[(p-1)T_{sf}, pT_{sf}]$, and $p \in \mathbb{N}^+$ in the MPVD phase, the goal of multi-polling vehicular access scheduling principle is to serve the maximal number of vehicular users with delay-sensitive requirements. If vehicular i is selected for the data transmission during p -th polling period, which can be denoted by $\varpi_{v_i,p} = 1$, otherwise, $\varpi_{v_i,p} = 0$. Given the vehicular user set $\mathcal{A}_r$ with delay-sensitive traffic services requirements, the scheduling formulation goal and constraints can be expressed as:

$$\begin{aligned} \max \quad & \sum_{i \in \mathcal{A}_r} \varpi_{v_i,p}, \quad p \in \mathbb{N}^+ \\ \text{s.t.} \quad & d_{v_i} \geq pT_{sf} \\ & \varpi_{v_i,p} \in \{0, 1\} \\ & \sum_{i \in \mathcal{A}_r} (L_{load}/\mathcal{R}_{v_i} (SINR_{v_i})) \varpi_{v_i} \leq M\mathcal{F}T_{sf} \end{aligned} \quad (22)$$

The M -stream multi-user scheduling problem for delay-sensitive vehicular traffic services in (22) is a typical Job-Shop Problem (JSP), which is NP-Hard [36]. To maximize the served number of vehicular users with delay-sensitive traffic requirements, we define the heuristic admission control conditions for the delay-sensitive vehicular traffic services in the vehicular user set $\mathcal{A}_r$ as follows: 1) The Most-Urgent-First-Served (MUFS) rule for the services with one-superframe completion delay, e.g., traffic safety related media content distribution. For those types of messages with the constraint $O_{v_i} \leq L_{load}$, we consider the priority condition to the delay-sensitive parameter, which can be expressed as $v_i > v_k$, iff $d_{v_i} > d_{v_k} \geq pT_{sf}$. 2) The First-Completion-First-Served (FCFS) rule for the services with multi-superframe

Algorithm 2 DSVS Algorithm

Input: $p, \mathcal{F}, T_{sf}, M, \mathcal{G}_{T_{sf}}, O, \mathcal{R}_{v_i} (SINR_{v_i})$.

Output: $\mathbb{M}P_r$.

```

1: Initialize:  $\Omega = 0$ ;  $\mathbb{M}P_r = \emptyset$ ,  $\varpi_{v_i} = 0$ ,  $v_i \in |\mathcal{A}_r|$ .
2:  $[\mathcal{D}^*, \mathbf{I}] = \text{SORT}(\mathcal{D}, 'Ascend')$ ;
3: For  $i = 1; i \leq |\mathcal{A}_r|$  do
4:   If  $\Omega \leq M\mathcal{F}T_{sf}$  do
5:      $\Omega = \Omega + L_{load}/\mathcal{R}_{v_{I(i)}} (SINR_{v_{I(i)}})$ 
6:      $\varpi_{v_{I(i)}} = 1$ ,  $\mathbb{M}P_r \leftarrow \mathbb{M}P_r \cup v_{I(i)}$ ;
7:   End If;
8: End For
9:  $[\left\{ \frac{(O_{v_i} - (p-1)L_{load})}{\mathcal{R}_{v_i} (SINR_{v_i})} \right\}^*, \mathbf{I}]$ 
    $= \text{SORT}\left(\left\{ \frac{(O_{v_i} - \sum_{j=1}^p \varpi_{v_i,j} L_{load})}{\mathcal{R}_{v_i} (SINR_{v_i})} \right\}, 'Ascend')$ ;
10: While  $\Omega \leq M\mathcal{F}T_{sf}$  &&  $\varpi_{v_i} == 0$  do
11:   For  $i = 1; i \leq |\mathcal{A}_r|$  do
12:      $\Omega = \Omega + L_{load}/\mathcal{R}_{v_{I(i)}} (SINR_{v_{I(i)}})$ ,  $\varpi_{v_{I(i)}} = 1$ ,
        $\mathbb{M}P_r \leftarrow \mathbb{M}P_r \cup v_{I(i)}$ ;
13:   End For
14: End While
15: Return  $\mathbb{M}P_r$ .
```

completion delay. The second priority condition is the predicted earliest completed tasks during the p -th superframe scheduling transmission, which is related to the residual volume size of targeted transmission data after the completion of p -th superframe scheduling transmission and the location-aware transmission data rate $\mathcal{R}_{v_k} (SINR_{v_k})$. The FCFS rule can be expressed as $v_i > v_k$, iff

$$\frac{\left(O_{v_i} - \sum_{j=1}^p \varpi_{v_i,j} L_{load}\right)}{\mathcal{R}_{v_i} (SINR_{v_i})} > \frac{\left(O_{v_k} - \sum_{j=1}^p \varpi_{v_k,j} L_{load}\right)}{\mathcal{R}_{v_k} (SINR_{v_k})} \quad (23)$$

The optimal polling users set $\mathbb{M}P_r$ with delay-sensitive vehicular media streaming services in the scheduling list includes two subsets, i.e., the users with one-superframe service completion delay and residual V potential scheduled users with multi-superframe service completion delay, we can formulate the optimal polling users selection process during each superframe duration $[(p-1)T_{sf}, pT_{sf}]$, $p \in \mathbb{N}^+$, as follows:

$$\begin{aligned} \mathbb{M}P_r \triangleq & \{\mathcal{G}_{T_{sf}} | O_{v_i} \leq L_{load}\} \\ & \cup \left\{ \underset{v_i \in \mathcal{A}_r}{\text{Arg min } V} \left(\frac{(O_{v_i} - \sum_{j=1}^p \varpi_{v_i,j} L_{load})}{\mathcal{R}_{v_i} (SINR_{v_i})} \right) \right\} \end{aligned} \quad (24)$$

Based on the above description, we present the Delay-Sensitive Vehicular Services (DSVS) scheduling in Algorithm 2.

Delay-Tolerant Vehicular Traffic Services: For this type of vehicular traffic services in the MPVD phase, the goal of multi-polling scheduling principle is to guarantee the maximal transmitted data for all the vehicles sojourned within the

coverage of WhiteFi Infostation with certain level scheduling fairness. If vehicle i is selected for the data transmission during the p -th polling period, we let $\varpi_{v_i,p} = 1$, otherwise $\varpi_{v_i,p} = 0$. For the vehicular user set $\mathcal{A}_d$ with delay-tolerant traffic services requirement, the formulation goal and constraints can be expressed as:

$$\begin{aligned} \max \quad & \sum_{p \in \mathbb{N}^+} \sum_{i \in \mathcal{A}_d} \varpi_{v_i,p} \cdot \mathcal{R}_{v_i,p} (SINR_{v_i,p}) \\ \text{s.t.} \quad & \varpi_{v_i} \in \{0, 1\} \\ & \sum_{i \in \mathcal{A}_d} (L_{load} / \mathcal{R}_{v_i} (SINR_{v_i})) \varpi_{v_i} \leq M(1 - \mathcal{F}) T_{sf} \end{aligned} \quad (25)$$

Similarly, the M -stream multi-user scheduling problem for delay-tolerant vehicular traffic services in (25) is a typical job-shop problem, which is NP-Hard [36]. To achieve the optimal goal, we aim at maximizing the transmitted data volume within the coverage of WhiteFi Infostation while considering the access scheduling fairness, and we define the optimal admission control conditions for the delay-tolerant vehicular traffic services in the vehicular user set $\mathcal{A}_d$ as follows: 1) The Larger-Rate-First-Served (LRFS) rule: We give the first priority condition to the vehicular users with the larger physical layer data-rate $\mathcal{R}_{v_i} (SINR_{v_i})$. The LRFS regulation is expressed as $v_i > v_k$, iff $\mathcal{R}_{v_i} (SINR_{v_i}) > \mathcal{R}_{v_k} (SINR_{v_k})$. 2) The Less-Transmitted-First-Served (LTFS) rule: To well balance the different sojourn time length $\Gamma^{D_{v_i}}$ within the coverage of WhiteFi Infostation and the fairness of vehicular data transmission opportunities, we give the second priority condition to the vehicular sojourn time and data transmission opportunity combined parameter, and the LTFS regulation during each superframe duration $[(p-1)T_{sf}, pT_{sf}]$, $p \in \mathbb{N}^+$ can be formulated as $v_i > v_k$, iff

$$\frac{O_{v_i} - \sum_{j=l}^{p-1} (L_{load} \cdot \varpi_{v_i,j})}{O_{v_i} \Gamma^{D_{v_i}}} > \frac{O_{v_k} - \sum_{j=l}^{p-1} (L_{load} \cdot \varpi_{v_k,j})}{O_{v_k} \Gamma^{D_{v_k}}} \quad (26)$$

Hence, we can find the optimal polling users set $\mathbb{M}_d$ with W delay-tolerant traffic services during each superframe period by applying the optimal polling users selection function for delay-tolerant services in the scheduling list, which is a weighted function of physical layer data-rate $\mathcal{R}_{v_i} (SINR_{v_i})$ and the fairness of vehicular transmission opportunity. The optimal polling users selection function for delay-tolerant services can be formulated as:

$$\mathbb{M}_d \triangleq \arg \max_{v_i \in \mathcal{A}_d} W \{ \mathbb{F}(v_i) \} \quad (27)$$

where $\mathbb{F}(\cdot)$ is an additive function of $\mathbb{F}_{SINR}(v_i)$ and $\mathbb{F}_{FAIR}(v_i)$. We define $\gamma + \beta = 1$, and,

$$\mathbb{F}(\cdot) \triangleq \gamma \mathbb{F}_{SINR}(v_i) + \beta \mathbb{F}_{FAIR}(v_i) \quad (28)$$

where

$$\mathbb{F}_{SINR}(v_i) \triangleq \frac{\mathcal{R}_{v_i} (SINR_{v_i})}{\sum_{v_i \in \mathcal{A}_d} \mathcal{R}_{v_i} (SINR_{v_i})} \quad (29)$$

$$\mathbb{F}_{FAIR}(v_i) \triangleq \frac{O_{v_k} - \sum_{j=1}^{p-1} L_{load} \cdot \varpi_{v_i,j}}{O_{v_k} \Gamma^{D_{v_i}}} \quad (30)$$

Algorithm 3 DTVS Algorithm

Input: $p, \mathcal{F}, \gamma, T_{sf}, M, \mathcal{G}_{T_{sf}}, O, \mathcal{R}_{v_i} (SINR_{v_i})$.

Output: $\mathbb{M}_d$.

```

1: Initialize:  $\Omega = 0; \mathbb{M}_d = \emptyset$ .
2: For  $i = 1; i \leq |\mathcal{A}_r|$  do
3:    $\varpi_{v_i} = 0$ 
4: End For
5:  $[\mathbb{F}(\cdot)^*, \mathbb{I}] = \text{SORT}(\mathbb{F}(\cdot), 'Descend')$ ;
6: For  $i = 1; i \leq \mathcal{A}_r$  do
7:   If  $\Omega \leq M(1 - \mathcal{F})T_{sf}$  do
8:      $\Omega = \Omega + L_{load} / \mathcal{R}_{v_{I(i)}} (SINR_{v_{I(i)}})$ 
9:      $\varpi_{v_{I(i)}} = 1, \mathbb{M}_d \leftarrow \mathbb{M}_d \cup v_{I(i)}$ ;
10:   End If;
11: End For
12: Return  $\mathbb{M}_d$ .

```

Based on the above description, we give the Delay-Tolerant Vehicular Services (DTVS) scheduling as in Algorithm 3:

Remark 1: The allocated scheduling duration fraction $\mathcal{F}$ can both affect on the serviced vehicular users number with delay-sensitive requirements and the mean throughput for the vehicular access in WhiteFi Infostations. In order to avoid this situation, we can define the adaptive fraction controlling regulation which is initialized by $|\mathcal{A}_r|/|\mathcal{A}_d|$. If the multi-polling access scheduling approach is experiencing increasing missed deadlines of delay-sensitive vehicular users, we can increase one transmission frame opportunity for the delay-sensitive vehicular user, i.e., $\mathcal{F} = \mathcal{F} + TXOP$; if it is experiencing growing wasted transmission time, we can decrease one transmission frame opportunity for the delay-sensitive vehicular user, i.e., $\mathcal{F} = \mathcal{F} - TXOP$, where we have $TXOP$ as,

$$TXOP = T_{sifs} + T_{bea} + \left(T_{pre} + T_{hdr} + T_{ack} + 2T_{sifs} + \frac{L_{load}}{\min_{v_i \in \mathcal{A}_r} \{ \mathcal{R}_{v_i} \}} \right) \quad (31)$$

Remark 1 points out that the allocated scheduling duration fraction $\mathcal{F}$ can affect on the performance of proposed CFMP vehicular access approach, e.g., serviced vehicular users number with delay-sensitive requirements and the mean vehicular access throughput. The allocated scheduling duration fraction $\mathcal{F}$ needs to dynamically change according to the delay requirements distribution of arriving services. Therefore, an adaptive fraction controlling regulation is a necessity in the proposed CFMP vehicular access scheduling approach.

VI. SIMULATION RESULTS

We evaluate the performance of both proposed optimal white spaces planning and the vehicular media streaming approach within the coverage of WhiteFi Infostation using Matlab, and based on the YouTube statistic result of mobile Internet video data analysis in [37], Table II lists the setting of simulation parameters.

TABLE II
SETTING OF DETAILED SIMULATION PARAMETERS

Parameters	Value	Parameters	Value
$\mathcal{N}$	10	M	1/2/3
i	100 ms	B_w	6 MHz
T_{sf}	32 ms	L_{load}	8 kb
T_{sifs}	10 μ s	T_{bea}	14 μ s
T_{srmp}	10 μ s	K	500
OV_i in $\mathcal{A}_r$	[8, 24] kb	p	200
OV_j in $\mathcal{A}_d$	[64, 5000] kb	d_{v_i} in $\mathcal{A}_r$	[8, 128] μ s

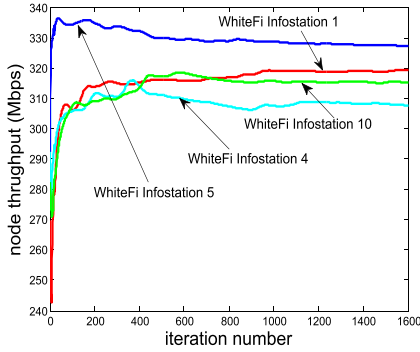


Fig. 8. The average node throughput of WhiteFi Infostation with $\alpha = 0.5$ and $M = 2$.

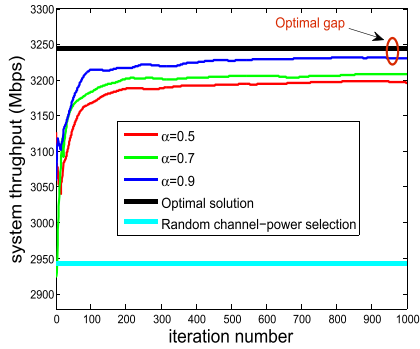


Fig. 9. The dynamics of average system throughput considering 10 WhiteFi Infostations.

A. Simulation Results of White Spaces Planning

As shown in Fig. 6, we utilize the real-world TVWS collection data to make the optimal white spaces planning, which is collected from 10 locations randomly distributed in the 40 km $\times$ 40 km region of Waterloo city, Canada. From November 24, 2014 to December 7, 2014, we inquiry the white spaces Geolocation database in the 10 locations using the database pilot hosted by Spectrum Bridge [28].

Fig. 8 presents the dynamics of average node throughput of WhiteFi Infostations with the approximation ratio value $\alpha = 0.5$ and the radio configuration number $M = 2$. In addition, Fig. 8 shows that the ODTA algorithm can be converged for the optimal white spaces planning after limited number of iterations. From Fig. 9, we can see that the convergence time of proposed ODTA algorithm is increased as the approximation ratio α increases. Specially, the ODTA algorithm can achieve about 10% performance gain over the random radio

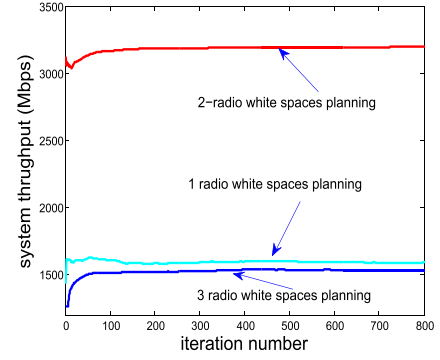


Fig. 10. The average system throughput with different radio configurations.

channel-power selection approach, and the gap between the ODTA algorithm with $\alpha = 0.9$ and the optimal traversal solution is only about 0.3%, which indicates very little performance loss by the proposed Markov approximation in the optimal white space planning. Furthermore, Fig. 10 shows the average system throughput with different radio configurations. It can be seen that only the 2-radio configuration in the white spaces planning reaches the maximal average system throughput, which indicates that the increased radio number can both improve the average system throughput and increase the mutual WhiteFi Infostations interferences, and the radio configuration number can play a crucial role in the optimization of the average system throughput of white space networking. For the investigated white spaces planning scenario in Fig. 6, the best radio configuration number can be set to 2.

B. Simulation Results of Vehicular Media Streaming

The dynamics of wireless channel conditions due to the vehicular mobility can have significant impacts on the vehicular media streaming. The investigated vehicular mobility model and Eq. (6) can efficiently track the realtime vehicular locations and sojourned time durations within the coverage of WhiteFi Infostation. To conduct more valid performance evaluation of the proposed scheduling approaches, we utilize the real-world urban taxis traces collected in Shanghai, China, [38]. From the real urban taxis traces, we can abstract the varying vehicular locations and realtime residual sojourn time within the coverage of WhiteFi Infostations. Those collected data does not loss the generality for the evaluation on how the proposed scheduling scheme can adapt to vehicular mobility.

We randomly select 500 taxis traces for the performance evaluation of vehicular media streaming scheduling. From Fig. 11, we can get the simulated vehicular content distribution scenario with 3 taxis' traces during 24-hour observations within the coverage of WhiteFi Infostation. Based on different taxi traces, we can track the 500 taxis' locations and residual sojourned time realtime for each vehicular media streaming scheduling during each superframe period in the contention-free multi-polling access scheduling process. Shown in the Table II, for delay-sensitive vehicular services, we consider that the volume size of vehicular media streaming follows a random distribution from 8kb to 24kb and the required task

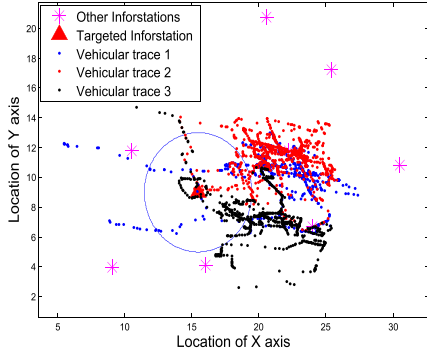


Fig. 11. The simulated vehicular content distribution scenario with 3 taxi traces.

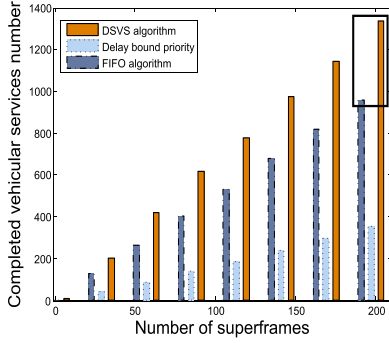


Fig. 12. The typical approaches comparison for the delay-sensitive services scheduling.

completion delay follows a random distribution from $8 \mu s$ to $128 \mu s$; for delay-tolerant vehicular services, we consider that the volume size of vehicular media streaming follows a random distribution from 64 kb to 5000 kb.

1) *Performance of Delay-Sensitive Vehicular Services:* Fig. 12 shows the simulation results of the proposed scheduling approach for the vehicular delay-sensitive services with the scheduling duration fraction $\mathcal{F} = 0.5$ and radio configuration number $M = 2$. Specially, we compare the first-in-first-out (FIFO) algorithm, delay-bound-priority algorithm and DSVS algorithm in terms of the completed vehicular services number. After running of 200 simulation superframes, we can see from Fig. 12 that the DSVS algorithm can significantly outperform both the FIFO and delay-bound-priority algorithm, which achieves about 39.27% performance gain over the delay-bound-priority algorithm.

To further investigate the relationship between the configurable parameters and the DSVS algorithm performance in terms of the number of completed vehicular services, Fig. 13 shows that the DSVS algorithm performance is closely related to both the scheduling duration fraction $\mathcal{F}$ and radio configuration number M . For instance, as the radio configuration number M increases from 1 to 3, the performance of completed vehicular services can be improved by maximal 54.7% performance gain. However, due to the minimal delay guarantee constraint of DSVS algorithm and number of vehicular services applications, as scheduling duration fraction $\mathcal{F}$ increases from 0.3 to 0.7, the maximal performance gain is

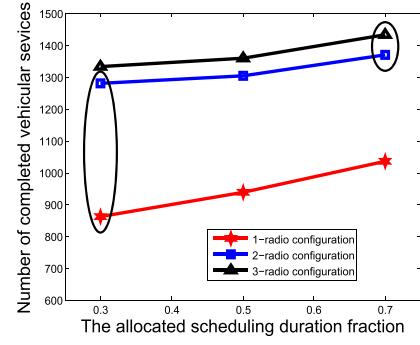


Fig. 13. The configurable scheduling parameters vs DSVS algorithm performance.

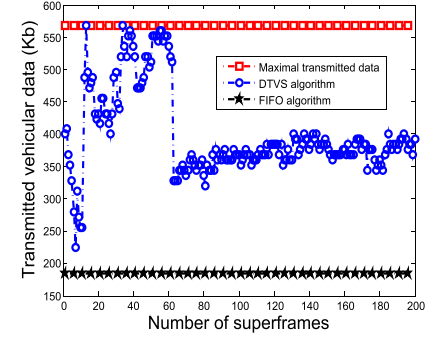


Fig. 14. The typical approaches comparison for the delay-tolerant services scheduling.

about 20.33%, which means that the allocated scheduling duration fraction $\mathcal{F}$ has small influence on the performance of completed vehicular services.

2) *Performance of Delay-Tolerant Vehicular Services:* Figs. 14-15 present the performance evaluation results of DTVS algorithm in terms of the transmitted vehicular data and number of total served vehicles, respectively. Specifically, Fig. 14 presents the comparison results of scheduling approaches, i.e., FIFO algorithm and our proposed DTVS algorithm for the delay-tolerant services scheduling. From Fig. 14, we can see that by setting the weighted data-rate parameter $\gamma = 0.33$ and vehicular access fairness parameter $\beta = 0.67$, the transmitted vehicular data by DTVS algorithm can be adaptive to the vehicular mobility in terms of the physical layer data-rate and vehicular sojourn time within the coverage of WhiteFi Infostation. We consider the delay-tolerant vehicular service requirements are with large data transmission volume sizes, and once vehicular users are selected for the content distribution by the FIFO algorithm, they occupy the transmission channel until they move out of the coverage of WhiteFi Infostation or the targeted transmission tasks are completed, without considering the level of physical layer data-rate in the FIFO scheduling. In Fig. 15, the DTVS algorithm can serve all the vehicles once within the duration of first 19 superframes, which shows the fairness of DTVS algorithm for the vehicular access scheduling of vehicles driving within the coverage of WhiteFi Infostation.

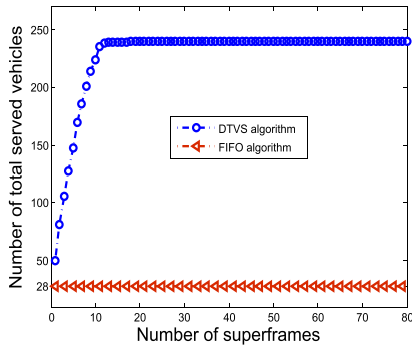


Fig. 15. The scheduling approaches comparison in terms of scheduling fairness.

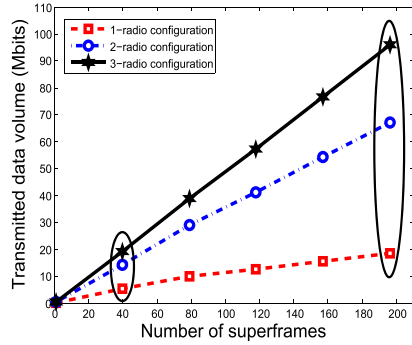


Fig. 16. The configurable radio number vs DTVS algorithm performance.

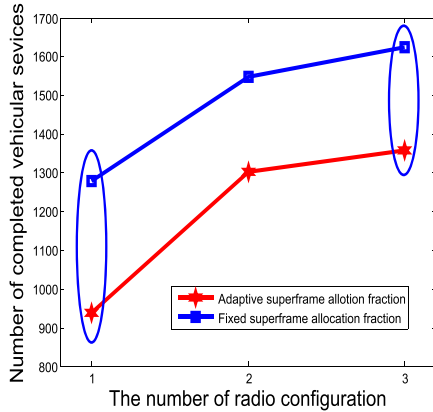


Fig. 17. The effect of adaptive scheduling fraction for delay-tolerant services on DTVS algorithm.

Fig. 16 shows the relation between the configurable radio number and DTVS algorithm performance in terms of the transmitted vehicular data volume. With the increase of configurable radio number, the WhiteFi Infostation can transmit more vehicular data volume. From Fig. 16, as the radio configuration number M increases from 1 to 3, the performance of transmitted vehicular data volume can be improved with the performance gain of 418.25%.

Fig. 17 further shows the effect of adaptive scheduling fraction $\mathcal{F}$ on the DTVS algorithm. We can see that by applying an adaptive scheduling fraction, the maximum number of completed vehicular delay-sensitive services can be increased by 36.32%.

VII. CONCLUSIONS

In this paper, we have proposed a generalized TVWS planning based on the empirical observations of TVWS channel features in real-world Geolocation database. We have jointly considered multi-radio configuration and the channel-power tradeoff in WhiteFi Infostations to enhance the TVWS channel utilization. To solve the NP-hard problem of TVWS planning, we have proposed a distributed Markov approximation solution. More practically, we have presented a contention-free multi-polling access scheduling scheme to support both the deadline-driven and delay-tolerant vehicular media streaming applications. Our simulation results have well verified the effectiveness of the proposed TVWS planning optimization and contention-free multi-polling access scheduling for the two considered VANET applications. In the future, we will consider the vehicular access demands driven TVWS planning by utilizing the vehicular mobility predication.

REFERENCES

- [1] H. Hartenstein and K. P. Laberteaux, "A tutorial survey on vehicular ad hoc networks," *IEEE Commun. Mag.*, vol. 46, no. 6, pp. 164–171, Jun. 2008.
- [2] T. H. Luan, X. Shen, F. Bai, and L. Sun, "Feel bored? Join Verse! Engineering vehicular proximity social networks," *IEEE Trans. Veh. Technol.*, vol. 64, no. 3, pp. 1120–1131, Mar. 2015.
- [3] G. Araniti, C. Campolo, M. Condoluci, A. Iera, and A. Molinaro, "LTE for vehicular networking: A survey," *IEEE Commun. Mag.*, vol. 51, no. 5, pp. 148–157, May 2013.
- [4] D. Zhang and C. K. Yeo, "Enabling efficient WiFi-based vehicular content distribution," *IEEE Trans. Parallel Distrib. Syst.*, vol. 24, no. 3, pp. 479–492, Mar. 2013.
- [5] H. Zhou *et al.*, "Chaincluster: Engineering a cooperative content distribution framework for highway vehicular communications," *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 6, pp. 2644–2657, Dec. 2014.
- [6] N. Lu, N. Zhang, N. Cheng, X. Shen, J. W. Mark, and F. Bai, "Vehicles meet infrastructure: Toward capacity–cost tradeoffs for vehicular access networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 14, no. 3, pp. 1266–1277, Sep. 2013.
- [7] A. B. Flores, R. E. Guerra, E. W. Knightly, P. Ecclesine, and S. Pandey, "IEEE 802.11af: A standard for TV white space spectrum sharing," *IEEE Commun. Mag.*, vol. 51, no. 10, pp. 92–100, Oct. 2013.
- [8] M. Madhavan, H. Ganapathy, M. Chetlur, and S. Kalyanaraman, "Adapting cellular networks to whitespaces spectrum," *IEEE/ACM Trans. Netw.*, vol. 23, no. 2, pp. 383–397, Apr. 2014.
- [9] A. Achtzehn, L. Simić, M. Petrova, and P. Mähönen, "Feasibility of secondary networks: Analysis methodology and quantitative study of cellular and Wi-Fi-like TVWS deployments," *IEEE Trans. Mobile Comput.*, vol. 14, no. 2, pp. 373–386, Feb. 2015.
- [10] M. Wang *et al.*, "Asymptotic throughput capacity analysis of VANETs exploiting mobility diversity," *IEEE Trans. Veh. Technol.*, vol. 64, no. 9, pp. 4187–4202, Sep. 2015.
- [11] P. Bahl, R. Chandra, T. Moscibroda, R. Murty, and M. Welsh, "White space networking with Wi-Fi like connectivity," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 39, no. 4, pp. 27–38, 2009.
- [12] S. Deb, V. Srinivasan, and R. Maheshwari, "Dynamic spectrum access in DTV whitespaces: Design rules, architecture and algorithms," in *Proc. ACM MobiCom*, 2009, pp. 1–12.
- [13] L. Yu, C. Liu, W. Zhu, S. Hua, and W. Wang, "Bandwidth efficient and rate-adaptive video delivery in TV white space," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 24, no. 9, pp. 1605–1619, Sep. 2014.
- [14] R. Murty, R. Chandra, T. Moscibroda, and P. Bahl, "SenseLess: A database-driven white spaces network," *IEEE Trans. Mobile Comput.*, vol. 11, no. 2, pp. 189–203, Feb. 2012.
- [15] B. Gao, J.-M. Park, and Y. Yang, "Supporting mobile users in database-driven opportunistic spectrum access," in *Proc. ACM MobiHoc*, 2014, pp. 215–224.
- [16] X. Chen and J. Huang, "Database-assisted distributed spectrum sharing," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 11, pp. 2349–2361, Nov. 2013.

- [17] P. Ameigeiras, D. M. Gutierrez-Estevez, and J. Navarro-Ortiz, "Dynamic deployment of small cells in TV white spaces," *IEEE Trans. Veh. Technol.*, vol. 64, no. 9, pp. 4063–4073, Sep. 2014.
- [18] R. H. Frenkiel, B. R. Badrinath, J. Borres, and R. D. Yates, "The infostations challenge: Balancing cost and ubiquity in delivering wireless data," *IEEE Pers. Commun.*, vol. 7, no. 2, pp. 66–71, Apr. 2000.
- [19] C.-H. Lee, C.-M. Huang, C.-C. Yang, and H.-Y. Lin, "The K-hop cooperative video streaming protocol using H.264/SVC over the hybrid vehicular networks," *IEEE Trans. Mobile Comput.*, vol. 13, no. 6, pp. 1338–1351, Jun. 2014.
- [20] C. Xu, F. Zhao, J. Guan, H. Zhang, and G.-M. Muntean, "QoE-driven user-centric VoD services in urban multihomed P2P-based vehicular networks," *IEEE Trans. Veh. Technol.*, vol. 62, no. 5, pp. 2273–2289, Jun. 2013.
- [21] H. Liang and W. Zhuang, "Efficient on-demand data service delivery to high-speed trains in cellular/infostation integrated networks," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 4, pp. 780–791, May 2012.
- [22] Q. Li, Y. Andreopoulos, and M. van der Schaar, "Streaming-viability analysis and packet scheduling for video over in-vehicle wireless networks," *IEEE Trans. Veh. Technol.*, vol. 56, no. 6, pp. 3533–3549, Nov. 2007.
- [23] F. Soldo, C. Casetti, C.-F. Chiasserini, and P. A. Chaparro, "Video streaming distribution in VANETs," *IEEE Trans. Parallel Distrib. Syst.*, vol. 22, no. 7, pp. 1085–1091, Jul. 2011.
- [24] M. Asefi, J. W. Mark, and X. Shen, "A mobility-aware and quality-driven retransmission limit adaptation scheme for video streaming over VANETs," *IEEE Trans. Wireless Commun.*, vol. 11, no. 5, pp. 1817–1827, May 2012.
- [25] J. Chen, B. Liu, H. Zhou, L. Gui, N. Liu, and Y. Wu, "Providing vehicular infotainment service using VHF/UHF TV bands via spatial spectrum reuse," *IEEE Trans. Broadcast.*, vol. 61, no. 2, pp. 279–289, Jun. 2015.
- [26] J.-H. Lim, W. Kim, K. Naito, J.-H. Yun, D. Cabric, and M. Gerla, "Interplay between TVWS and DSRC: Optimal strategy for safety message dissemination in VANET," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 11, pp. 2117–2133, Nov. 2014.
- [27] A. Chatterjee, S. Deb, K. Nagaraj, and V. Srinivasan, "Low delay MAC scheduling for frequency-agile multi-radio wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 11, pp. 2262–2275, Nov. 2013.
- [28] SpectrumBridge, Inc., Lake Mary, FL, USA. *ShowMyWhiteSpace—Locate TV White Space Channels*, accessed on Dec. 15, 2014. [Online]. Available: <http://www.spectrumbridge.com>
- [29] Telcordia, Piscataway, NJ, USA. *Telcordia Whitespaces Database*, accessed on Dec. 15, 2014. <https://prism.telcordia.com/tvws/home>
- [30] J. Harri, F. Filali, and C. Bonnet, "Mobility models for vehicular ad hoc networks: A survey and taxonomy," *IEEE Commun. Surveys Tuts.*, vol. 11, no. 4, pp. 19–41, Dec. 2009.
- [31] M. J. Khabbaz, W. F. Fawaz, and C. M. Assi, "A simple free-flow traffic model for vehicular intermittently connected networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 3, pp. 1312–1326, Sep. 2012.
- [32] M. Chen, S. C. Liew, Z. Shao, and C. Kai, "Markov approximation for combinatorial network optimization," *IEEE Trans. Inf. Theory*, vol. 59, no. 10, pp. 6301–6327, Oct. 2013.
- [33] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge, U.K.: Cambridge Univ. Press, 2009.
- [34] *IEEE Standard for Information Technology—Telecommunications and Information Exchange Between Systems—Local and Metropolitan Area Networks—Specific Requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, IEEE Standard 802.11-2007 (Revision IEEE Standard 802.11-1999), Jun. 2007, pp. 1–1076.
- [35] B.-S. Kim, S. W. Kim, Y. Fang, and T. F. Wong, "Two-step multipolling MAC protocol for wireless LANs," *IEEE J. Sel. Areas Commun.*, vol. 23, no. 6, pp. 1276–1286, Jun. 2005.
- [36] N. Zribi, I. Kacem, A. El Kamel, and P. Borne, "Assignment and scheduling in flexible job-shops by hierarchical optimization," *IEEE Trans. Syst., Man, Cybern. C, Appl. Rev.*, vol. 37, no. 4, pp. 652–661, Jul. 2007.
- [37] X. Cheng, J. Liu, and C. Dale, "Understanding the characteristics of Internet short video sharing: A YouTube-based measurement study," *IEEE Trans. Multimedia*, vol. 15, no. 5, pp. 1184–1194, Aug. 2013.
- [38] H. Zhu, M. Li, Y. Zhu, and L. M. Ni, "HERO: Online real-time vehicle tracking," *IEEE Trans. Parallel Distrib. Syst.*, vol. 20, no. 5, pp. 740–752, May 2009.
- [39] M. Xing, J. He, and L. Cai, "Maximum-utility scheduling for multimedia transmission in drive-thru Internet," *IEEE Trans. Veh. Technol.*, vol. 65, no. 4, pp. 2649–2658, Apr. 2016.



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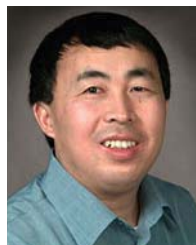


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