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RESEARCH ARTICLE

Modeling and performance analysis of dynamic spectrum sharing between DSRC and Wi-Fi systems

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ABSTRACT

The Notice of Proposed Rulemaking 13-22 released by Federal Communications Commission unlocks the Dedicated Short Range Communication (DSRC) spectrum for Wi-Fi availability, which undoubtedly brings unpredictable effects to the new-emerging vehicular applications and services. To efficiently harmonize the spectrum operation between DSRC and Wi-Fi networks, several dynamic spectrum-sharing schemes are already proposed to improve the spectral efficiency over a limited bandwidth situation and as well to satisfy the ever-increasing demand for bandwidth resource. Different from most previous literature that mainly focused on the performance analysis of cellular-network-centric spectrum sharing, we aim to analyze the performance of the mainstream dynamic spectrum-sharing schemes specially designed for the coexistence of DSRC and Wi-Fi networks against various combinations of network parameters through a hybrid network model and performance indicators. We employ the Poisson point process to model a hybrid network where DSRC vehicles and Wi-Fi devices coexist, and introduce the performance indicators of spectrum efficiency and data rate to assess the utility of different spectrum sharing candidates. Through the presented hybrid model and performance indicators, we collect extensive numerical and simulation results to investigate four typical spectrum allocation schemes for DSRC and Wi-Fi coexistence, that is non-sharing scheme, original sharing scheme, and Qualcomm's and Cisco's proposals, respectively. The results show that the dynamic spectrum sharing in the 5.9-GHz band can significantly raise the performance of Wi-Fi network without excessively degrading the DSRC system, and especially the Cisco's proposal prefers to protect the DSRC profit while the Qualcomm's draft favors Wi-Fi exclusively. Copyright © 2016 John Wiley & Sons, Ltd.

KEYWORDS
dynamic spectrum sharing; hybrid network; Wi-Fi; DSRC; performance analysis

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1. INTRODUCTION

The US Congress established the Intelligent Transportation System program in 1991 [1], which has greatly improved road traffic safety and efficiency [2]. In October 1999, the US Federal Communications Commission (FCC) allocated 5.850–5.925 GHz spectrum band especially for Dedicated Short Range Communications (DSRC) based Intelligent Transportation System applications and services [3]. DSRC is a short- to medium-range wireless communication technology that enables direct vehicle-to-vehicle and vehicle-to-infrastructure contact in order to support a variety of safety and entertainment applications. The DSRC spectrums available are divided into seven 10-MHz channels and a 5-MHz guard band at the low end [4]. Two adjacent 10-MHz channels could be combined into a 20-MHz channel. The extensive testbed experimentations of DSRC in 10-MHz channels have been performed in the U.S. to evaluate whether or not DSRC can concurrently support numerous applications. The results showed that the bandwidth is well suited to the delay and Doppler spreads experienced in vehicular environment [5]. However, it remains an open question whether the concern of channel congestion, especially for vehicle-to-vehicle safety communication, might be better addressed by a combined 20-MHz channel, or not [4].

Analogically, Wi-Fi allows an electronic device to exchange data or to connect the Internet using 2.4-GHz UHF and 5-GHz SHF radio waves. Undoubtedly, Wi-Fi obtains a tremendous success that almost 2 billion Wi-Fi chips were shipped in 2013 [6]. IEEE specifications 802.11b and 802.11 g define the regulations in 2.4-GHz band and 802.11a, 802.11n, and 802.11 ac for 5-GHz band. The 2.4-GHz band has become increasingly crowded and overloaded [7] because this unlicensed band is also open for other wireless devices (e.g. cordless phones). More seriously, there are only three non-overlapping channels (Channels 1, 6, and 11) within 2.4-GHz band. So Wi-Fi devices might divert to fully utilize the 5-GHz spectrum that provides an unprecedented experience, for example fast data rate and rare connection loss. The Wi-Fi industry already claims a great deal of interests to the 5-GHz bands, which is generally in accordance to the Unlicensed National Information Infrastructure regulations [8].

In the early 2013, as response to the rapid popularization of Wi-Fi devices, the FCC issued a Notice of Proposed Rulemaking, numbered 13-22, which suggests appending an additional 195-MHz bands in 5 GHz to be allowably operated by the unlicensed Wi-Fi devices [9]. As a result, the FCC and the automotive industry has come to an agree to test sharing the DSRC spectrum, so that Wi-Fi and DSRC devices might share the same space in near future and Wi-Fi's speed and capabilities can be easily boosted. Most previous studies mainly concerned the performance analysis of the cellular-network-centric spectrum sharing such as LTE and Wi-Fi networks. Therefore, it is essential to modeling and analyzing such new-emerging sharing situation.

The nature of the issue is that two different communication systems form a hybrid network and have to dynamically share the allocated spectrum. Qualcomm and Cisco respectively proposed their dynamic spectrum-sharing schemes. Qualcomm [10] proposed to: (i) share the low part of the spectrum but the upper part dedicated to the DSRC operation, and (ii) merge two adjacent 10-MHz channels to 20-MHz channels for DSRC with purposes to facilitate detecting Wi-Fi devices during the on-going DSRC communications. Cisco [7] assigned a high priority to DSRC operations because Wi-Fi devices should abandon channels upon detecting DSRC communications present. Besides the Qualcomm's and Cisco's proposals, we also analyze another two spectrum allocation schemes, that is the non-sharing scheme and the original sharing scheme. In the non-sharing scheme, just as the name implies, Wi-Fi and DSRC systems only conservatively utilize their respective spectrum bands and no channel sharing occurs. As for the original sharing scheme, two systems share the low part of 5850 to 5925-MHz spectrums, which is similar to the Qualcomm's proposal, but a little difference is DSRC exclusively keeps its original 10-MHz channels. In this paper, we propose a hybrid network model and the corresponding assessment metrics to investigate the effects of the aforementioned spectrum-sharing schemes on the concerned performance indicators.

The rest of the paper is organized as follows. Section 2 overviews the related work. Section 3 detailedly provides the system model, the performance metrics, and the candidate dynamic spectrum-sharing schemes. The extensive numerical and simulation results are presented in Section 4. Finally, some conclusions are drawn and the future work is given in Section 5.

2. RELATED WORK

The concept of hybrid network spectrum sharing has attracted much attention from academia and industry. Lin et al. [11] proposed a random spatial Poisson-point-process based network model and a unified performance evaluation framework to analyze device-to-device enhanced cellular networks and to optimize spectrum-sharing parameters. However, the focused ground cellular network refers to the traditional cellular architecture composed of only tower-mounted macro base stations. Irnich et al. [12] discussed various spectrum sharing techniques and their applicability to the relevant range of future spectrum regulatory system of 5G, and pointed out that Wi-Fi coexistence mode, as one of the distributed spectrum sharing techniques, is a particular example of how a MAC behavior of a non-contention-based system may be adapted to allow for smooth horizontal coexistence with Wi-Fi systems. Zhao et al. [13] proposed a cognition-based spectrum-sharing scheme for Long Term Evolution-Advanced (LTE-A) system, which included Auto-Correlation based Advanced Energy spectrum sensing method and spectrum sharing procedure for spectrum sharing between DVB and LTE-A system. However, these studies [12,13] do not consider the spectrum-sharing problem between DSRC and Wi-Fi. Nair et al. [14] adopted the continuous time Markov chain to analyze the dynamic spectrum access in the overlay scenario where a secondary network visits the medium only in the absence of the primary and operates without any restrictions, as well as in the underlay scenario where secondary networks can access the channels in the presence of the primary network as long as they do not cause any harmful interference to the primary network, and moreover they proposed a hybrid spectrum access scheme that can significantly improve the throughput. Li et al. [15] proposed a joint spatial and temporal spectrum-sharing scheme. Lansford et al. [9] discussed the U-NII-4 band sharing between Wi-Fi and DSRC, particularly for the industrial activities that devoted to balancing the demand of the Wi-Fi market and the protection of the DSRC effort. But, the key factors affecting the spectrum sharing are not stated in [15] and [9]. Tian et al. [16] proposed a bio-inspired network selection method that enables multiple terminals to autonomously adapt their wireless access in a dynamic heterogeneous environment where DSRC, WiFi and Cellular networks co-exist. This adaptation has been proven to achieve a high performance in terms of the global QoS satisfaction degree and the fairness index of global network resource allocation, showing the great potential for designing QoS-guaranteed spectrum allocation solutions.

Most previous works are based on extensive system level simulations using tools such as NS3 and OPNET, which is usually very time-consuming because of the complicated dynamics of the overlaid hybrid networks, such as LTE and Wi-Fi networks, Wi-Fi, and DSRC networks. Therefore, a mathematical approach would be helpful for more efficient performance evaluation and transparent comparisons of various techniques. Additionally, the challenges in modeling and analyzing the DSRC and Wi-Fi hybrid networks are to capture the multi-path fading effects and random backoff mechanism of DSRC and Wi-Fi nodes, and to identify signal-to-interference-plus-noise-ratio (SINR) that is a function of the network geometry. These issues are addressed in this paper. We aim to study the average behavior over the spatial realizations of DSRC and Wi-Fi hybrid networks whose nodes are placed according to homogeneous Poisson point process (PPP). We derive the expressions of performance metrics regarding SINR. To the best of our knowledge, until to now there is neither any metric to quantify the benefit of the spectrum sharing between DSRC and Wi-Fi, nor comprehensive comparisons among various mainstream spectrum allocation schemes available for the purpose of DSRC and Wi-Fi coexistence. The contributions of the paper are mainly summarized as follows. (i) We propose a hybrid network model composed of DSRC and Wi-Fi communications through adopting the spatial PPP, and investigate its performance w.r.t. spectrum efficiency (bit/s/Hz) and data rate (bit/s). (ii) We formulize four mainstream spectrum allocation schemes, that is the non-sharing scheme, original sharing scheme, Qualcomm's, and Cisco's proposal. (iii) We theoretically analyze the effects of various parameters, for example node density and contention window (CW) size on the concerned performance indicators in every focused spectrum-allocation scheme. We also emphasize the key factors that affect the performance of DSRC and Wi-Fi in the spectrum-sharing environment. (iv) We collect simulation results in the scenario of Jilin University by using OpenStreetMap [17] and SUMO [18], and analyze the gap between the numerical and simulation results.

3. SYSTEM MODEL

Here, we first present the related models, including network model, channel model, power control model, and channel access model. Then, we formulize two metrics, that is spectrum efficiency and data rate, which allow us to quantitatively characterize the spectrum-sharing utility of various schemes. Finally, we introduce four focused spectrum-sharing candidates in detail.

3.1. Network model

In last decade, PPP has become a powerful mathematical tool to investigate the hybrid networks. Particularly, key performance metrics can be derived by modeling the locations of Wi-Fi and DSRC networks entities as a realization of certain spatial random point process. The PPP often appears in limit theorems of random operations applied to non-PPPs. Concretely speaking, if a random operation is applied to a non-PPP, such as randomly and independently moving each point, then as this operation is repeated more and more, the resulting point process will randomly behave more and more like a PPP [19]. We define the PPP in a plane where it plays a role in stochastic geometry and spatial statistics. If a PPP has a constant parameter, then it is called a homogeneous PPP. This parameter, called intensity in this paper, specifies the expected number of points (e.g. access point (AP), Wi-Fi client, DSRC-enabled vehicle, and road side unit (RSU)) per some unit of area. There have been many applications of the homogeneous PPP on the real line (often interpreted as time and space) in an attempt to model seemingly random events occurring. It has been frequently utilized to model seemingly disordered spatial distributions of certain wireless networks, for example LTE networks [20] where it is assumed that the phone transmitters are positioned following a homogeneous PPP. Generally speaking, the LTE base station can cover 500 m–1000 m range in a dense unban scenario. According to 802.11p standard definition, a RSU typically can cover a 1000-m range while a vehicle can transmit message to 300-m distance, which is similar to cellular networks especially as microcell and picocell techniques increasingly polarize in 4G/5G era. Besides applied to analysis in cellular network scenarios, homogeneous PPP can also model traffic [21] and CSMA/CA-based networks such as Wi-Fi [22]. Because of its analytical tractability and practical appeal in situations where transmitters and/or receivers are located or move around randomly over a large area, the homogeneous PPP has been by far the most popular spatial model for modeling the spatial distribution of opportunistic Wi-Fi-like networks [23] and is a feasible tool for analyzing DSRC and Wi-Fi coexistence performance. The homogeneous PPP assumption for APs and RSUs is reasonable because of the unplanned nature of most Wi-Fi APs and DSRC RSU deployments [22]. Both Wi-Fi clients (e.g. handheld devices) and DSRC-enabled vehicles are also assumed to be distributed according to homogeneous PPPs [20]. Observe that the distribution of vehicles is not fixed because vehicles are moving with time. Taking a snapshot of the road at time 0, it is realistic to model the vehicles as a homogenous PPP. It is already proved by [21] that if the vehicles admit a homogenous PPP at time 0, they form again a homogenous PPP at some later time t. Because both Wi-Fi clients and vehicles are assumed as homogeneous PPPs, we can analyze the performance of the mixture of Wi-Fi and DSRC nodes, which are assumed to stay at the origin. This is guaranteed by Slyvniak's theorem [24].

Figure 1 shows the concerned hybrid network composed of DSRC-enabled vehicles and RSUs, Wi-Fi clients, and Wi-Fi APs, where the IEEE 802.11 networks employ infrastructural access. The notation $\{X_i\}$ denotes the spatial location of node i. Wi-Fi APs are placed with density λ_{AP}, that is the area size of a hexagonal cell is $1/\lambda_{AP}$. N_W Wi-Fi nodes are randomly distributed within each cell following homogeneous PPP [25,26] where the number of points in disjointed intervals is independently scattered over a space in Poisson distribution, that is given each random subset of the plane, the total number of the points follows Poisson distribution. The density λ_W of Wi-Fi nodes is equal to $N_W\lambda_{AP}$. DSRC nodes (e.g. a vehicle or a RSU) are also located by PPP with density λ_D. Accordingly, the average

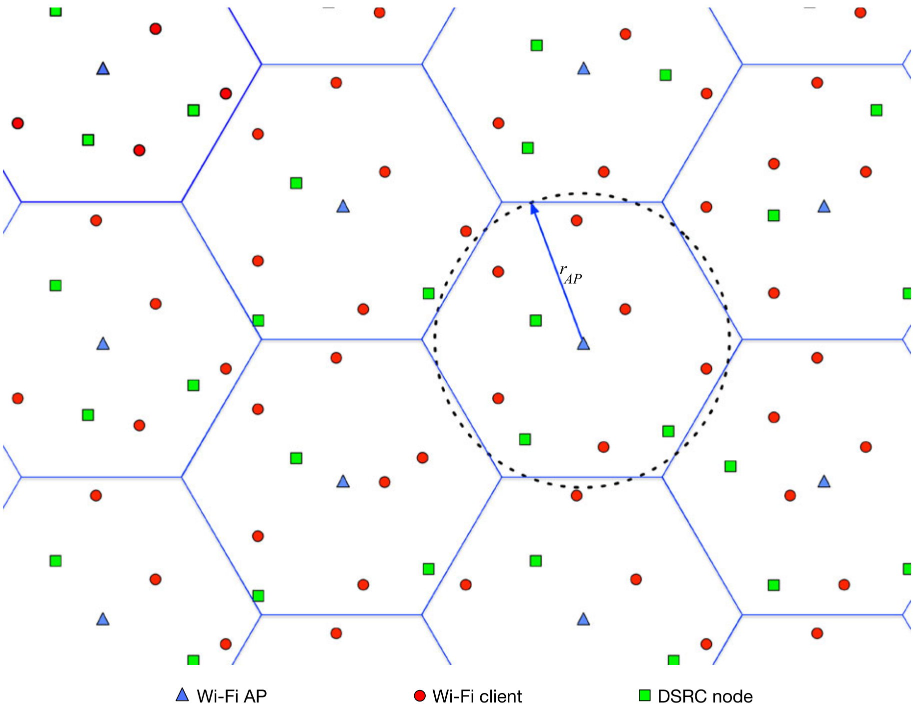

Figure 1. A hybrid network composed of DSRC and Wi-Fi nodes.

area covered by a DSRC node is $1/\lambda_D$. For ease of explanation, we use the transmission radius r_{AP} and r_D of Wi-Fi cells and DSRC nodes to indicate the density. Regarding $\pi r^2 \lambda = 1$, we can deduce $r_{AP} = 1/\sqrt{\pi \lambda_{AP}}$ and $r_D = 1/\sqrt{\pi \lambda_D}$. The spatial location and transmit power of node i are denoted by X_i and P_i, respectively.

3.2. Channel model

Because wireless signal is propagated over a specific channel, we need to generalize a channel model for figuring out various spectrum-sharing schemes. The channel model aims to universally capture a group of channels whatever is occupied by DSRC or Wi-Fi nodes, and to accurately reflect the overlap among channels.

Wi-Fi nodes are permitted to share the spectrum with DSRC nodes in 5.9-GHz band. We assume that DSRC nodes occupy n_D channels while Wi-Fi nodes possess n_W channels in any spectrum allocation scheme. We use $CH_D = \{ch_{D,1}, ch_{D,2}, \ldots, ch_{D,}n_{D,}\}$ and $CH_W = \{ch_{W,1}, ch_{W,2}, \ldots, ch_{W,}n_{W,}\}$ to denote DSRC and Wi-Fi channel sets, respectively.

A node selects a channel for subsequent transmission from the candidate channel set with a probability called channel-selective factor. The channel-selective factors of DSRC channel $ch_{D,i}$ and Wi-Fi channel $ch_{W,i}$ are denoted by $k_{D,i}$ and $k_{W,i}$, respectively, where $\sum_{i=1}^{n_D} k_{D,i} = 1$ and $\sum_{i=1}^{n_W} k_{W,i} = 1$.

A channel may overlap to another channel, especially in the Wi-Fi situation. For IEEE 802.11 ac as an example in Figure 2, a 20-MHz channel such as Channel 36 overlaps to three other channels, that is 40-MHz, 80-MHz, and 160-MHz bandwidth, which implies that the Wi-Fi and DSRC

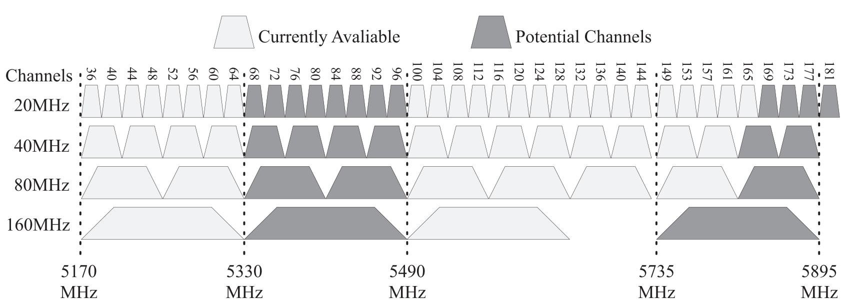

Figure 2. Wi-Fi channels in 5-GHz band.

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channels could overlap with each other. We define the sets $CH_{ID}(ch)$ and $CH_{IW}(ch)$ to respectively represent the DSRC and Wi-Fi channel sets that overlap to the given channel ch. $B(ch)$ indicates the bandwidth of channel ch, and $f_o(ch_i, ch_j)$ is the proportion of ch_i overlapping to ch_j, as expressed by:

$$f_o\left(ch_i, ch_j\right) = \frac{B\left(ch_i \cap ch_j\right)}{B\left(ch_j\right)}. \tag{1}$$

The coexistence of Wi-Fi and DSRC nodes mainly fit to the urban scenario where pedestrian can freely access the Wi-Fi hot points while vehicles can communicate with other vehicles and/or RSUs via DSRC. In urban scenario, a Line Of Sight (LOS) between the transmitter and receiver is always blocked by static (e.g. buildings) and mobile barriers (e.g. vehicles), so non-LOS communication situations are more common in our concerned unban scenario that urges to deploy the coexistence of Wi-Fi and DSRC nodes. Conversely, LOS is commonly available in highway scenario that however does not greatly need the coexistence of Wi-Fi and DSRC because pedestrian theoretically should not appear on highway and DSRC communication dominates the information exchange between vehicles. Therefore, we reasonably adopt Rayleigh fading model for signal propagation in our concerned hybrid scenario where there is no dominant propagation along a LOS between the transmitter and receiver.

3.3. Power control model

The utility of the dynamic spectrum sharing is closely dependent on the transmit power, because the high transmit power leads to a long transmission distance at the cost of serious interference to neighbor nodes. Thus we need to model the power control through considering transmission range and node density.

We employ Signal Noise Ratio (SNR) to adjust the transmit power. SNR is expressed by:

$$SNR = \frac{P_r}{N} = \frac{P_t \cdot TR^{-\alpha}}{\widehat{N} B}. \tag{2}$$

where TR is the communication radius, that is $TR = TR_D$ for DSRC nodes and $TR = TR_W$ for Wi-Fi nodes. P_t is the transmit power, and P_r is the received power at the edge of the coverage region. Parameter α is the large-scale path-loss exponent. N is the noise power and equals the product of the power spectral density of the additive white Gaussian noise $\widehat{N}$ and the bandwidth B. The required transmit power that makes the received signal strength over the antenna sensitivity can be calculated by (2) regarding the experienced SNR.

Obviously, the transceiver's distance cannot exceed the coverage radius. We assume that the effective transceiver distance L_0 follows a Rayleigh distribution with probability density function (PDF) given by:

$$f_{L_0}(x) = 2\pi\lambda x e^{-\lambda\pi x^2}, \quad x \geq 0. \tag{3}$$

where λ is the node density, that is λ_D for DSRC nodes and λ_W for Wi-Fi nodes. Because the minimum link length L between two communicating nodes should be larger than threshold $L_{threshold}$, we set $L_{threshold} = 1$ m. The PDF of L is expressed by:

$$f_L(x) = \frac{f_{L_0}(x)}{\int_1^{\infty} f_{L_0}(x)\mathrm{d}x} = \frac{2\pi\lambda x e^{-\lambda\pi x^2}}{e^{-\lambda\pi}}, \quad x \geq 1. \tag{4}$$

The probability of L larger than TR is calculated by:

$$P(L > TR) = \int_{TR}^{\infty} f_L(x)dx = e^{-\lambda\pi\left(TR^2 - 1\right)}. \tag{5}$$

L_{AP} indicates the distance between a Wi-Fi client and its attached AP, and the corresponding PDF is given by:

$$f_{L_{AP}}(x) = 2\pi\lambda_{WA} x, \ 0 \leq x \leq 1/\sqrt{\pi\lambda_{WA}}. \tag{6}$$

The probability of L falling between $L_{threshold}$ and r_{AP} is expressed by:

$$P\left(1 \leq L \leq 1/\sqrt{\pi\lambda_{WA}}\right) = \int_1^{1/\sqrt{\pi\lambda_{WA}}} f_{L_{AP}}(x)dx = \pi\lambda_{WA}. \tag{7}$$

3.4. Channel access model

For medium access control, we consider the carrier sense multiple access with collision avoidance (CSMA/CA) method. As soon as a CSMA/CA device observes an idle channel, it needs to follow a random back-off period before transmission. This back-off period is chosen randomly from a set of possible values called CW. We assume that a DSRC (or Wi-Fi) node can visit the channel with probability τ_D (or τ_W) during each time slot. Broadcasting is the primary means of information dissemination over DSRC nodes. The CW size CW_D of each broadcasting station stays constant. τ_D is given by CW_D [27]:

$$\tau_D = \frac{2}{1 + CW_D}. \tag{8}$$

In the Wi-Fi system, we mainly focus on the unicast and τ_W is expressed by [28]:

$$\tau_W = \frac{2}{1 + CW_{W\min} + sCW_{W\min}/2}. \tag{9}$$

where CW_{Wmin} and CW_{Wmax} indicate the minimum and maximum CW, respectively. $CW_{Wmax} = 1024$ and $CW_{Wmax} = 2^s CW_{Wmin}$, where s is the maximum back-off stage. One note is that this corresponds to an infinite number of transmission attempts.

3.5. Performance metric

We now formulize the spectrum efficiency and data rate to identify the spectrum-sharing utility.

3.5.1. Spectrum efficiency

T_D and T_W respectively denote the spectrum efficiency of DSRC and Wi-Fi nodes, as expressed by:

$$\begin{cases} T_D = \tau_D \sum_{i=1}^{n_D} \rho k_{D,i} T_D\left(ch_{D,i}\right) \\ T_W = \tau_W \sum_{i=1}^{n_W} \rho k_{W,i} T_W\left(ch_{W,i}\right) \end{cases}. \quad (10)$$

where ρ is the discount factor, and the channel access probability τ_D and τ_W are defined by (8) and (9).

The discount factor ρ equals 1 in the four focused spectrum allocation schemes except for the Cisco's proposal where the value of ρ depends on the concrete situation. As Cisco proposed, DSRC nodes can access the medium superiorly over Wi-Fi nodes. Wi-Fi nodes should release the channel upon detecting the communication present within the overlapped DSRC channels. If a Wi-Fi node selects a channel without overlapping to any DSRC channel, that is without causing interference to the DSRC nodes, then $\rho = 1$ and $I_D = 0$. Otherwise, Wi-Fi nodes can receive data with the probability P_{no_D} $(CH_{ID}(ch))$ that no DSRC communications occur in the overlapped channels within the coverage region. The potential interfering DSRC nodes that select channels CH_{ID} (ch) are identified by PPP with the density $\lambda_D \sum_{ch_{D,i} \in CH_{ID}(ch)} k_{D,i}$. The shortest distance between the receiver Wi-Fi node and the interfering DSRC node is denoted by $L(ch)$, then ρ is calculated by:

$$\rho = \mathrm{P}_{no_D}(CH_{ID}(ch)) = \mathrm{P}(L(ch) > TR_D). \quad (11)$$

One note is that T_D and T_W indicate the spectrum efficiency for all the available channels. For a given channel ch, the spectrum efficiency is given by:

$$T_{D(W)}(ch) = \mathrm{E}[\log(1 + SINR(ch))]. \quad (12)$$

where the SINR is:

$$SINR = \frac{W}{I + N} = \frac{P_t L^{-\alpha} G}{I_D + I_W + N}. \quad (13)$$

where W is the received power and G is the channel-fading factor following the distribution $exp(1)$. N and I denote the noise power and interference power, respectively. I_D and I_W are the interference power emitted from DSRC and Wi-Fi nodes over another, respectively. So the spectrum efficiency of channel ch, that is (12) is reformatted by:

$$E[\log(1 + SINR)] = \int_0^{\infty} \frac{e^{-Nx/P_t \cdot E(L^{-\alpha})}}{1 + x} L_I(x/P_t \cdot E(L^{-\alpha}))dx. \quad (14)$$

For DSRC nodes, the expectation of $L^{-\alpha}$ is expressed by:

$$E(L^{-\alpha}) = \frac{\int_1^{TR_D} f_{L_0}(x)x^{-\alpha}dx}{P(1 \le L_0 < TR_D)} = \frac{\int_1^{TR_D} 2\pi\lambda_D x^{1-\alpha} e^{-\pi\lambda_D x^2}dx}{P(1 \le L_0 < TR_D)} \quad (15)$$
$$= \frac{\int_1^{TR_D} 2\pi\lambda_D x^{1-\alpha} e^{-\pi\lambda_D x^2}dx}{e^{-\pi\lambda_D} - e^{-\pi\lambda_D TR_D^2}}.$$

For Wi-Fi nodes:

$$E(L^{-\alpha}) = \frac{\int_1^{1/\sqrt{\pi\lambda_{WA}}} f_{L_{AP}}(x)x^{-\alpha}dx}{P\left(1 \le L_{AP} < 1/\sqrt{\pi\lambda_{WA}}\right)} = \frac{\int_1^{1/\sqrt{\pi\lambda_{WA}}} 2\pi\lambda_{WA} x^{1-\alpha}dx}{P\left(1 \le L_{AP} < 1/\sqrt{\pi\lambda_{WA}}\right)} \quad (16)$$
$$= \frac{\left(1/\sqrt{\pi\lambda_{WA}}\right)^{2-\alpha} - 1}{(2-\alpha)(1 - \pi\lambda_{WA})}$$

where $f_{L0}(x)$ and $f_{LAP}(x)$ are defined by (3) and (6), respectively.

Using the Laplace transform, the interference L_{ID} from DSRC nodes is expressed by:

$$L_{ID}(s) = \exp\left(-s \sum_{ch_{D,i} \in CH_{ID}(ch)} f_o\left(ch, ch_{D,i}\right) \sum_{X_{i \in k_{D,i}\tau_D \Phi_D}} P_{D,i} \|X_i\|^{-\alpha} G_i\right)$$
$$= \exp\left(-\frac{\pi\tau_D\lambda_D}{\mathrm{sinc}(2/\alpha)} s^{2/\alpha} \sum_{i=1}^{n_D} f_o\left(ch, ch_{D,i}\right) k_{D,i} P_{D,i}^{2/\alpha}\right). \quad (17)$$

And the interference L_{IW} from Wi-Fi nodes is expressed by:

$$L_{IW}(s) = \exp\left(-s \sum_{ch_{W,i} \in CH_{IW}(ch)} f_o\left(ch, ch_{W,i}\right) \sum_{X_{i \in k_{W,i}\tau_W \Phi_W}} P_{W,i} \|X_i\|^{-\alpha} G_i\right)$$
$$= \exp\left(-\frac{\pi N_W \tau_W \lambda_{WA}}{\mathrm{sinc}(2/\alpha)} s^{2/\alpha} \sum_{i=1}^{n_W} f_o\left(ch, ch_{W,i}\right) k_{W,i} P_{W,i}^{2/\alpha}\right). \quad (18)$$

Substituting (15)–(18) into (14), we can get the spectrum efficiency of channel ch of DSRC and Wi-Fi nodes, respectively.

3.5.2. Data rate

The data rate R is expressed by:

$$R = T B_t \quad (19)$$

where B_t is the bandwidth amount of all the available channels. The data rate calculation is much simpler than the spectrum efficiency and it equals the product of spectrum efficiency and bandwidth, which infers that the bandwidth brings positive effect to the data rate. In the Wi-Fi system, the bandwidth amount B_t occupied by the sharing scheme is higher than the non-sharing scheme, while in the DSRC system every sharing scheme has the same bandwidth, that is 75 MHz.

3.6. Candidate proposals

We mainly focus on four mainstream spectrum allocation schemes, that is the non-sharing, original sharing, and Qualcomm's and Cisco's proposals.

Figure 2 illustrates the Wi-Fi channels in 5-GHz band. The potential available channels are situated between 5330–5490 MHz and 5735–5815 MHz. In the non-sharing scheme, the potential channels (marked in deep gray in Figure 2) cannot be accessed by Wi-Fi and DSRC systems.

Figure 3 shows the original sharing proposal, where there are four 20-MHz channels, two 40-MHz channels, one 80-MHz channel and one 160-MHz channel that overlaps to the DSRC spectrum. DSRC keeps the original seven 10-MHz channels situated in 5855–5925 MHz, within which the 5855 to 5905-MHz spectrums are shared with the Wi-Fi system.

Figure 4 shows the Qualcomm's proposal, where the four 10-MHz channels at the low part of DSRC spectrums are merged into two 20-MHz channels, that is Channel 173 (5855–5875 MHz) and Channel 177 (5875–5895 MHz) are shared together by Wi-Fi and DSRC systems. Channel 181 (5895–5915 MHz) in the Wi-Fi system is removed, and the other three 10-MHz channels are dedicated for DSRC operations. Additionally, the channel used for DSRC safety purpose is migrated from the band 5855–5865 MHz to the upper band 5905–5915 MHz that is a non-overlap segment.

The Cisco's allocation scheme behaves like the original scheme. However, the DSRC system can prioritarily visit the available channels over the Wi-Fi system. Wi-Fi devices should keep silent upon detecting the DSRC signal.

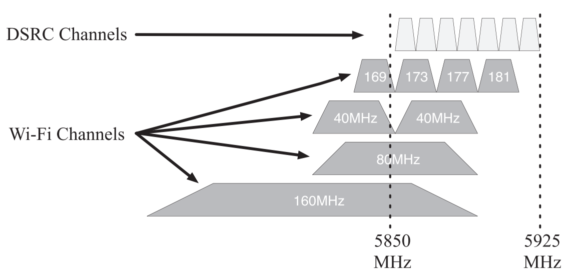

Figure 3. The original sharing proposal.

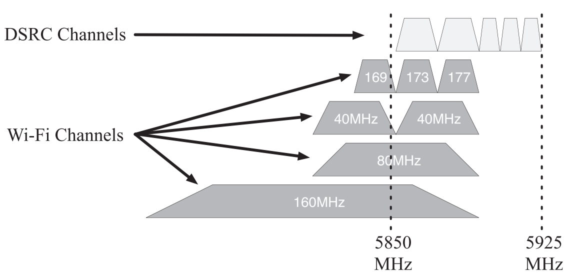

Figure 4. The Qualcomm's sharing proposal.

4. RESULTS

Here, we first perform numerical analysis to investigate the effects of various combinations of parameters on the spectrum efficiency and data rate in the four spectrum-sharing schemes. Then, we select a real map as a simulation scenario to investigate the performance of the four dynamic spectrum-sharing schemes. The parameters used in theoretical and simulation results are listed in Table I.

4.1. Numerical results

We investigate the effects of various combinations of parameters on the spectrum efficiency T_D and T_W and data rate R_D and R_W, for example SNR, r_D, r_{AP}, N_W, CW_D, and CW_{Wmin}.

4.1.1. Effects of *SNR*

Figure 5 provides the effects of SNR on the spectrum efficiency T_D and T_W of DSRC and Wi-Fi systems, respectively. The spectrum efficiency T_D of DSRC increases

Table I. Parameters in theoretical and simulation results.

Symbol	*Meaning*	*Value*
λ_D	Density of DSRC nodes	$\frac{1}{\pi 10^2} m^{-2}$
λ_W	Density of Wi-Fi APs	$\frac{1}{\pi 20^2} \mathrm{m}^{-2}$
N_W	Total number of Wi-Fi clients in each Wi-Fi cell	10
α	Path-loss exponent	3.5
TR_D	DSRC maximal communication range	300 m
TR_W	Wi-Fi maximal communication range	50 m
CW_D	DSRC contention window	16
CW_{Wmin}	Contention window minimum in Wi-Fi	16
s	Back-off stage	6
n_W	Number of Wi-Fi channels	Non-sharing: 45 Origin sharing: 68 Qualcomm: 67 Cisco: 68
n_D	Number of DSRC channels	Non-sharing: 7 Origin sharing: 7 Qualcomm: 5 Cisco: 7
B_{tW}	Bandwidth sum of Wi-Fi	Non-sharing: 1780 MHz Origin sharing: 2820 MHz Qualcomm: 2800 MHz Cisco: 2820 MHz
B_{tD}	Bandwidth sum of DSRC	70 MHz
$k_{D,\ i}$	Channel selective factor of channel $ch_{D,i}$ in DSRC	$1/n_D$
$k_{W,\ i}$	Channel selective factor of channel $ch_{W,i}$ in Wi-Fi	$1/n_W$
σ	Time slot	13 μs

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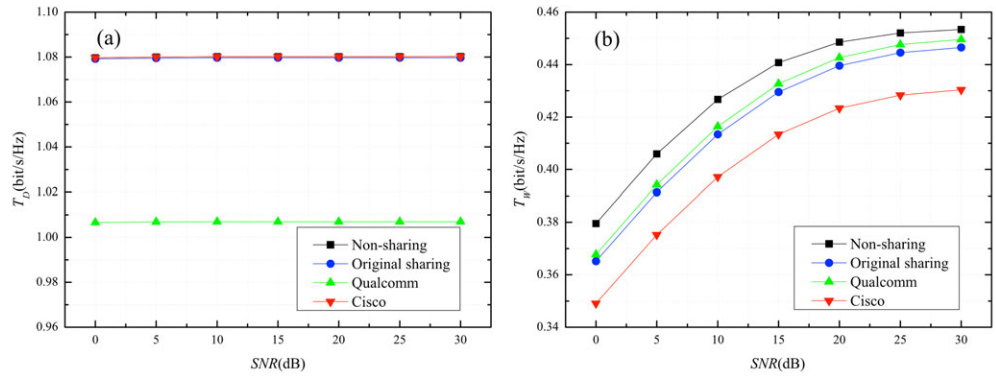

Figure 5. Spectrum efficiency against *SNR* in (a) DSRC and (b) Wi-Fi systems.

quite slowly as *SNR* increases, which is because the interference power is also enhanced significantly. Contrastively, the spectrum efficiency T_W of Wi-Fi is improved remarkably. This is because the Wi-Fi coverage radius is generally much shorter than DSRC (i.e. 50 m < 300 m in this paper), which leads to a stronger effect of the received power than the interference power. Concretely speaking, improving *SNR* is generally to enhance the transmit power P_D and P_W. Because of $P_D > P_W$ and according to (17) and (18), the interference L_{ID} from DSRC nodes to Wi-Fi nodes is stronger than the reverse case, so according to (14) Wi-Fi's spectrum efficiency is more sensitive to the transmit power change (i.e. *SNR* fluctuation) than that of DSRC.

As for the spectrum efficiency T_D of DSRC, the non-sharing, original sharing and Cisco's proposals achieve the same level of about 1.08 bits/s/Hz while the Qualcomm's proposal falls behind by nearly 0.073 bits/s/Hz. The Qualcomm's proposal only has five channels, and thus the channel interference becomes more deteriorative compared to the others. So the spectrum efficiency of the Qualcomm's proposal in DSRC is the lowest of all the four schemes.

At the aspect of the spectrum efficiency T_W of Wi-Fi, the non-sharing scheme behaves best because no DSRC interference exists. The spectrum efficiency of the Cisco's proposal is worse than the others because a high-priority medium access is granted to DSRC nodes. The Qualcomm's proposal contributes a little better than the original scheme.

Figure 6 shows the effects of *SNR* on the data rate R_D and R_W of DSRC and Wi-Fi systems, where the bandwidth amount of channels in DSRC is equal to 75 MHz for all the proposals. From (19), one can know that the changing tendency of the data rate of DSRC should keep accordance with the behavior of spectrum efficiency. For the Wi-Fi system, the data rate increases as the *SNR* is improved. The original sharing scheme and the Qualcomm's proposal take the lead ahead of them. The Cisco's proposal falls behind by 100 Mbits/s and followed by the non-sharing scheme with gap 350–450 Mbits/s, which is because the bandwidth amounts of channels in the spectrum-sharing schemes are much higher than the non-sharing scheme.

4.1.2. Effects of r_D

Figure 7 gives the effects of r_D on the spectrum efficiency T_D and T_W, where increasing r_D (i.e. reducing λ_D) can significantly improve the spectrum efficiency T_D of DSRC. Concretely speaking, the spectrum efficiency quickly climbs up to the peak value ($r_D = 110$ for the Qualcomm's proposal and $r_D = 90$ for the others), and then starts to decrease slowly. This is because the decreased node density of DSRC leads to a mitigated interference.

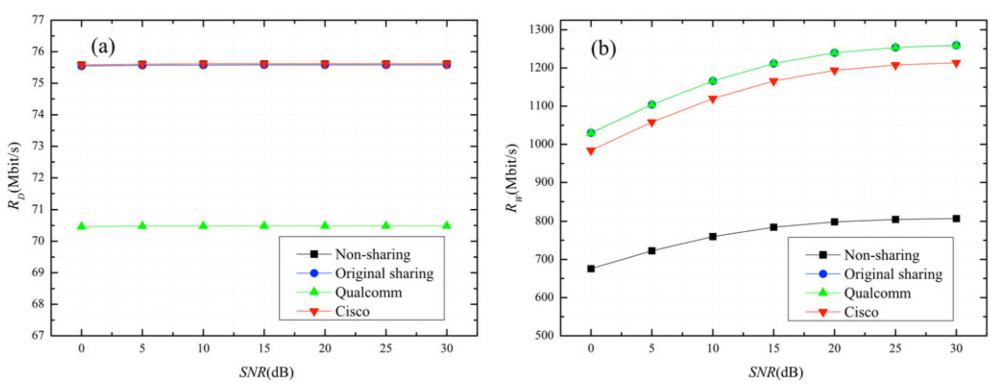

Figure 6. Date rate against *SNR* in (a) DSRC and (b) Wi-Fi systems.

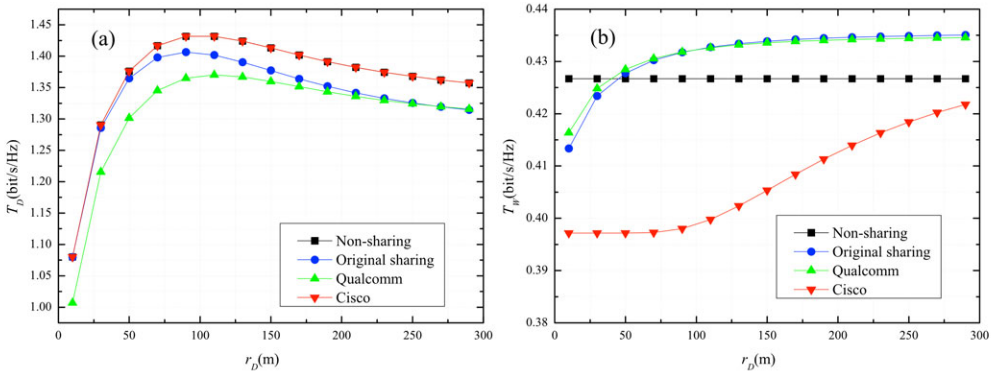

Figure 7. Spectrum efficiency against *rD* in (a) DSRC and (b) Wi-Fi systems.

However, the further decrease of the density enlarges the transceiver distance, which undoubtedly worsens the received power. The Cisco's proposal and the non-sharing scheme behave similarly and followed by the original sharing and Qualcomm's proposal.

In the Wi-Fi system, the spectrum efficiency keeps constant in the non-sharing scheme because of no DSRC interference, while the other sharing schemes perform better because of the alleviated DSRC interference. Concretely speaking, the non-sharing scheme occupies the top position at the initial, but is surpassed by the original sharing and Qualcomm's schemes at $r_D = 50$. The Cisco proposal's is also improved as r_D increases.

Figure 8 displays the effects of r_D on the data rate. In the DSRC system, all the schemes quickly climb up to the peak value at about $r_D = 90$ m, after which the spectrum efficiencies decrease gradually. In the Wi-Fi system, the sharing schemes perform much better than the non-sharing scheme w.r.t. the data rate because the bandwidth amount plays an important role in controlling data rate. In 7(b) and 8(b), only the non-sharing scheme keeps constant spectrum efficiency and date rate in Wi-Fi network, which is because the non-sharing scheme avoids the interference from DSRC to Wi-Fi and thus changing transmission radius r_D does not take any effect according to (17).

4.1.3. Effects of r_{AP}

As shown in Figure 9(a) and Figure 10(a), the concerned metrics in the DSRC system are insensitive to r_{AP}, that is the density of AP, and the Qualcomm's proposal does not behave similarly as the other three schemes. This is because only a few Wi-Fi channels cause interference to DSRC nodes.

The performance indicators in the Wi-Fi system display different results from the DSRC's, as shown in Figure 9(b) and Figure 10(b). Both the spectrum efficiency T_W and data rate R_W increase as r_{AP} increases, and especially, the increment happens to decrease beyond $r_{AP} = 30$ m because of the reduced interference emitted from Wi-Fi itself. As for the spectrum efficiency, the non-sharing scheme ranks the first, followed by the Qualcomm's, original sharing and Cisco's proposals. At the aspect of data rate, the ordered sequence is the original, Qualcomm's, Cisco's and non-sharing schemes, which emphasize again that the bandwidth is the key point affecting the data rate.

4.1.4. Effects of N_W

As shown in Figure 11(a) and Figure 12(a), the concerned metrics in the DSRC system are also insensitive to N_W and especially the original and Qualcomm's proposals decrease very slowly. The gap between the

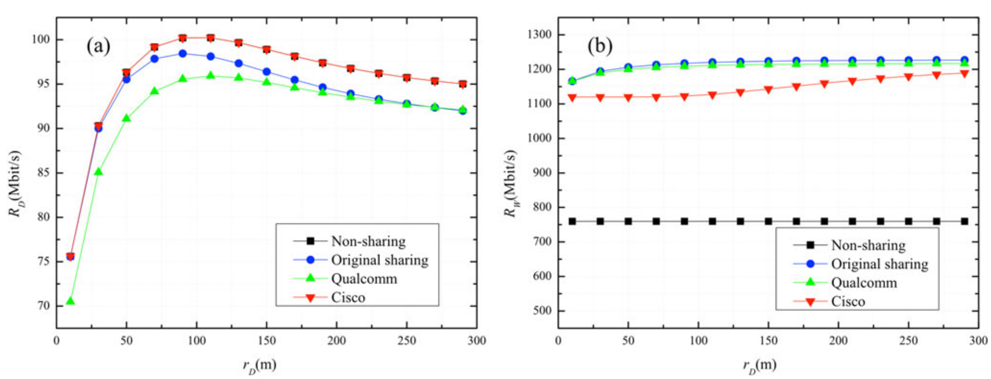

Figure 8. Date rate against *rD* in (a) DSRC and (b) Wi-Fi systems.

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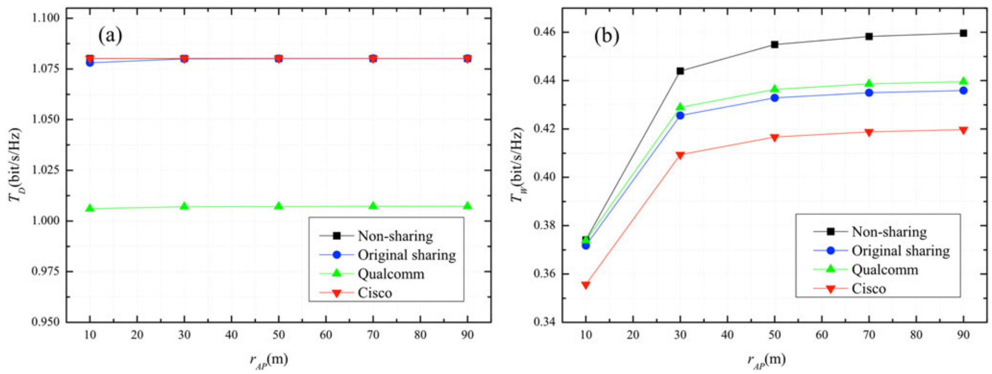

Figure 9. Spectrum efficiency against *rAP* in (a) DSRC and (b) Wi-Fi systems.

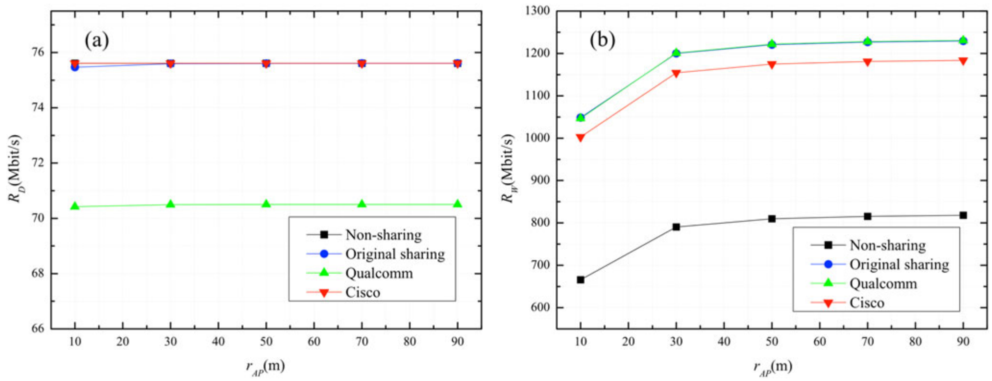

Figure 10. Date rate against *rAP* in (a) DSRC and (b) Wi-Fi systems.

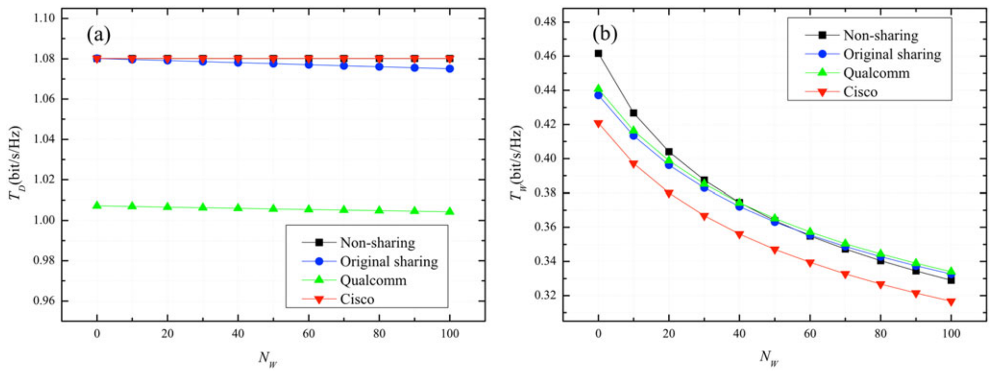

Figure 11. Spectrum efficiency against *NW* in (a) DSRC and (b) Wi-Fi systems.

Qualcomm's proposal and the other three schemes is around 0.07 bits/s/Hz w.r.t. the spectrum efficiency.

As shown in Figure 11(b) and Figure 12(b), as for the spectrum efficiency, the non-sharing scheme is more sensitive to N_W because it occupies the highest position of T_W at the low value of N_W and then is surpassed by the original and Qualcomm's proposals after $N_W = 50$. At the aspect of data rate, the original sharing scheme behaves similarly as the Qualcomm's while the Cisco's and non-sharing proposals fall behind by 50 Mbit/s and 400 Mbit/s, respectively.

4.1.5. Effects of CW_D

Figures 13 and 14 show the effects of CW_D on the spectrum efficiency and data rate in the DSRC and Wi-Fi systems, respectively, where two systems display the distinctive trends against CW_D. Concretely speaking, in the DSRC system, the performance indicators decrease as CW_D increases because of the reduced probability of DSRC nodes accessing the medium. Especially, the Qualcomm's proposal behaves a bit less than the others. For Wi-Fi nodes at the aspect of

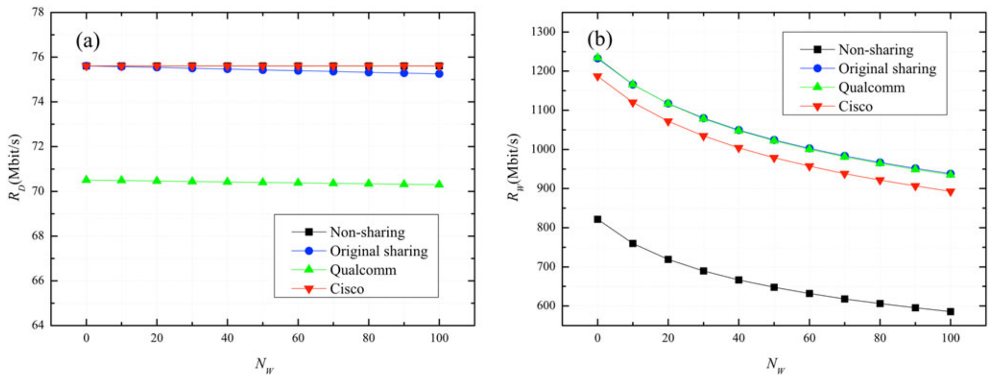

Figure 12. Date rate against *NW* in (a) DSRC and (b) Wi-Fi systems.

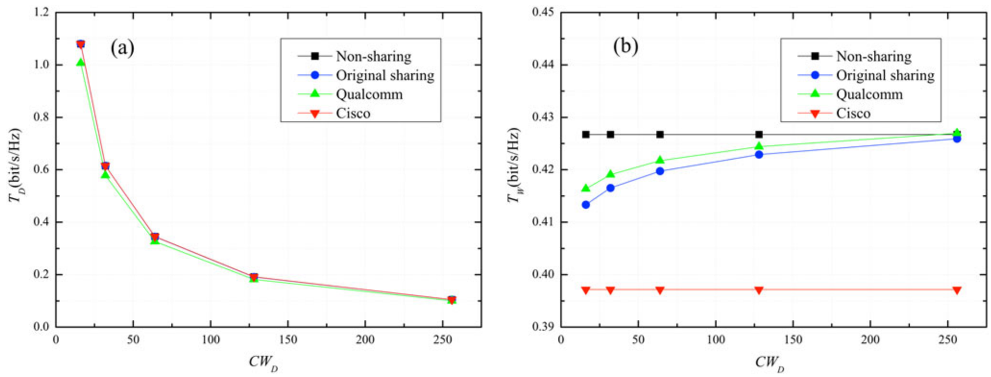

Figure 13. Spectrum efficiency against *CWD* in (a) DSRC and (b) Wi-Fi systems.

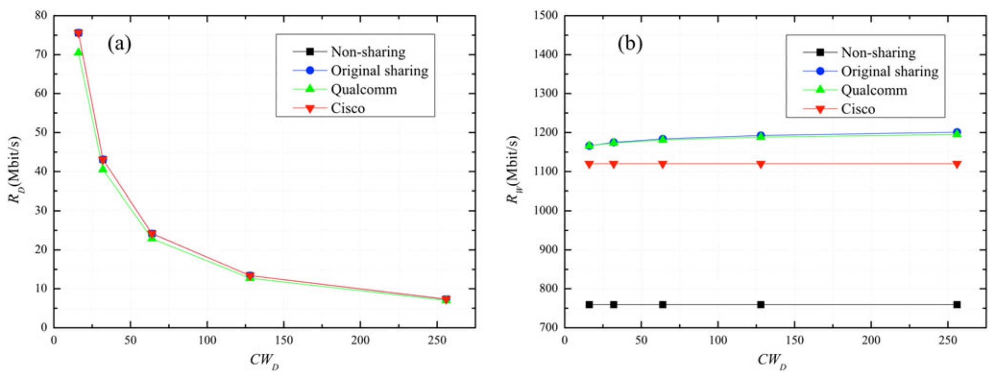

Figure 14. Date rate against *CWD* in (a) DSRC and (b) Wi-Fi systems.

spectrum efficiency, the non-sharing and Cisco's proposals hold fixed value and specially the former leads ahead the latter by 0.03 bit/s/Hz. The other two schemes stay in the middle and increase gradually as CW_D increases. As for the data rate, the Cisco's and the non-sharing schemes stay constant against CW_D while the original and Qualcomm's proposals take the ahead, which is because the DSRC interference becomes weak.

4.1.6. Effects of CW_{Wmin}

Figures 15 and 16 provide the effects of CW_{Wmin} on the focused metrics, where CW_{Wmin} brings different effects on DSRC and Wi-Fi. The performance indicators of DSRC are insensitive to CW_{Wmin} and the Qualcomm's proposal lags behind the others because of few available channels. In the Wi-Fi system, both the spectrum efficiency and data rate drop dramatically because the probability of nodes accessing the medium is significantly reduced as CW_{Wmin} increases.

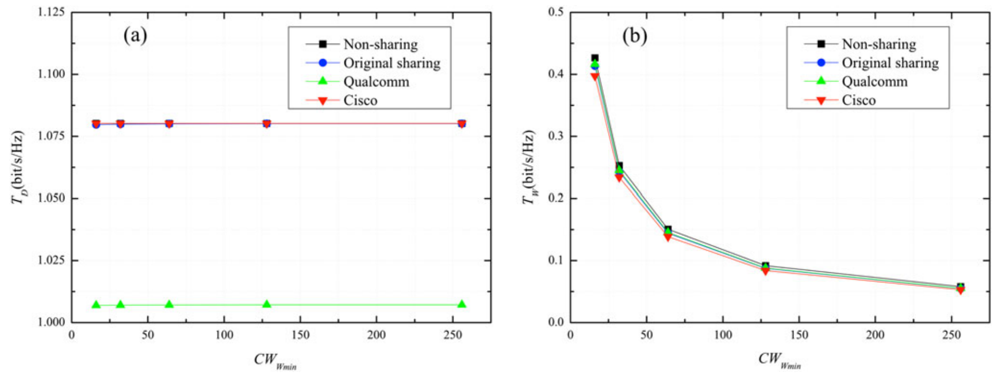

Figure 15. Spectrum efficiency against *CWWmin* in (a) DSRC and (b) Wi-Fi systems.

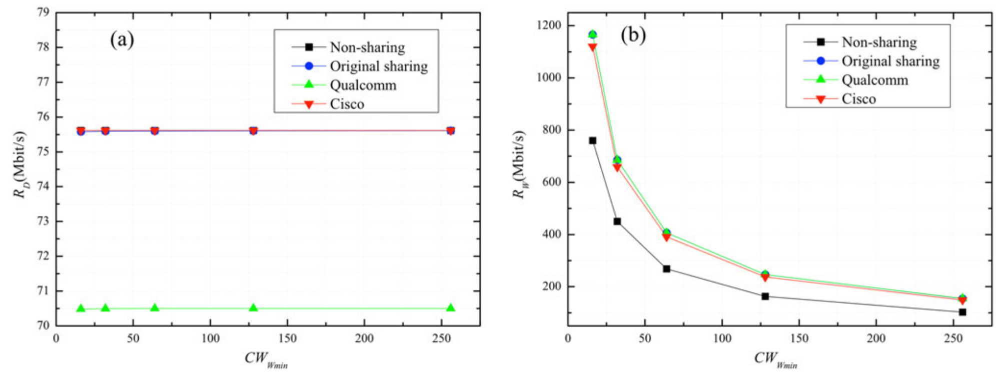

Figure 16. Date rate against *CWWmin* in (a) DSRC and (b) Wi-Fi systems.

The ranking list of T_W is the non-sharing, Qualcomm's, original, and Cisco's proposals with tiny gaps while the non-sharing scheme is far behind the others in terms of R_W.

4.2. Simulation results

University campus is a typical hybrid network scenario where Wi-Fi APs and clients are ubiquitously present and DSRC-enabled vehicles always travel everywhere. So we select the campus of Jilin University where the authors work as the simulation scenario to investigate the spectrum efficiency and data rate of the four spectrum-sharing schemes. We downloaded the map data of Jilin University from OpenStreetMap, which is a collaborative project to create a free editable map of the world, and imported the map to the traffic simulation tool SUMO, as shown in Figure 17. The campus roads are bidirectional with one lane in each direction. We constantly inject vehicle flows, which follow the Waypoint mobility and share the same traffic parameters. The vehicles' speed ranges from 20 to 60 km/h, which is typical for campus scenario. We set the radius $r_{AP} = 100$ m and Wi-Fi clients are PPP distributed over the map. Other parameter values follow Table I. The results correspond to an average over the time of 10 simulations.

Because of the limit of page, we only provide the effects of *SNR* on the concerned metrics in the four spectrum-sharing schemes, as shown in Figures 18 and 19. The spectrum efficiency and data rate in the DSRC system increase linearly as *SNR* increases, which is somehow different from the numerical results. This is because the densities of APs and DSRC nodes are low in the simulation scenario, which makes the signal increment much higher than the interference increment, so the negative effect of interference on performance metrics of simulation results is a little different from that of numerical results. This point could also be understood that there is no known closed-form interference distribution with PPP distributed transmitters [20]. We now attempt to give some analysis about the gap between the numerical and simulation results from the viewpoint of PPP modeling. PPPs have some appealing features that especially display invariance to a number of key operations. For examples [29], the superposition of two or more independent PPPs is again a PPP, the independent or location-dependent thinning of a PPP is again a PPP, and the point process obtained by displacing point independently of everything else according to some Markov kernel that defines the distribution of the displaced position of the point yields anther PPP. These features could be used to characterize the simulation and even real

Figure 17. The SUMO snapshot of the campus of Jilin University.

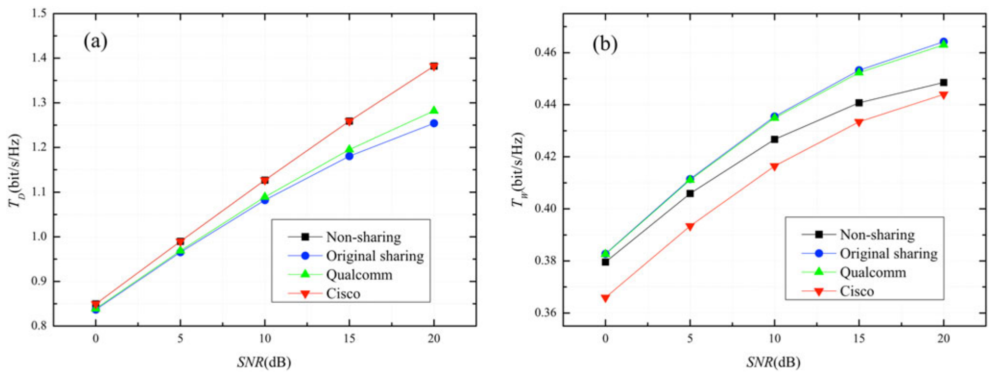

Figure 18. Spectrum efficiency against *SNR* in (a) DSRC and (b) Wi-Fi systems.

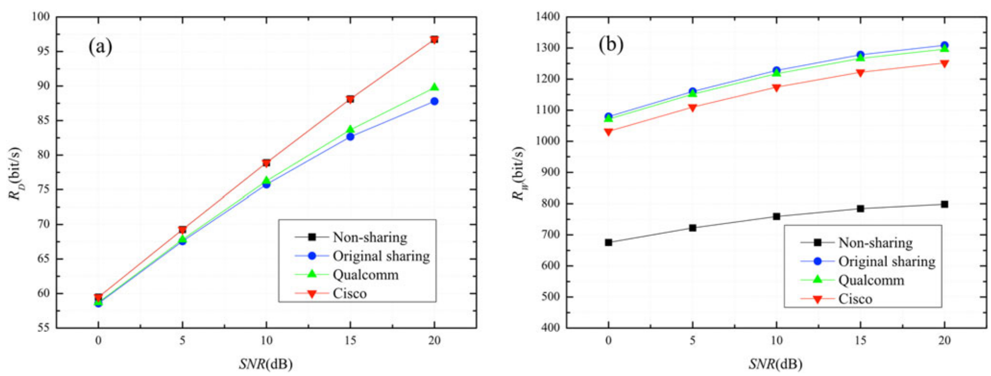

Figure 19. Date rate against *SNR* in (a) DSRC and (b) Wi-Fi systems.

spatial distribution. Roughly speaking, the intensity of the resulting PPP can be derived in closed form from that of the initial PPP and the involved transformations (e.g. superposition, thinning, and displacing). However, because of the lack of closed-form interference distribution with PPP distributed transmitters, the total interference power is not yet completely accurately captured by numerical results.

In the case of DSRC system, the Cisco's proposal performs similarly as the non-sharing scheme because Wi-Fi nodes yield more access opportunities than DSRC nodes. The Qualcomm's proposal behaves a little better than the original sharing scheme, which is because the total number of Wi-Fi channels in the Qualcomm's proposal is less than that in the original sharing scheme, and the Wi-Fi interference caused by the Qualcomm's proposal is weak.

In the Wi-Fi system, the original sharing and Qualcomm's proposals are better than the non-sharing scheme w.r.t. the spectrum efficiency, which is because the DSRC interference is alleviated by the low vehicle density in this situation.

The simulations support the results uncovered by Section 4.1 that the DSRC node density significantly affects the network performance of the hybrid networks. This implies that the mitigation of interference is a key point to improve the performance of DSRC and Wi-Fi hybrid networks. There exists a correlation between the interference from Wi-Fi APs and that from the DSRC nodes. From the simulation results, it can be observed that with low Wi-Fi AP intensity, DSRC is not much affected by additional Wi-Fi network. So, to mitigate the interference, we may attempt to set different energy detection thresholds to Wi-Fi and DSRC nodes for improvement of coexistence performance, which equivalently corresponds to decrease the interferer intensity. Both the numerical and simulation results show that the spectrum efficiency of DSRC is much higher than that of Wi-Fi in hybrid networks. This imbalanced performance means some fair coexistence methods shall be realized by DSRC nodes to guarantee a reasonable performance for Wi-Fi network.

5. CONCLUSIONS

In this paper, we proposed a framework to study the dynamic spectrum sharing between Wi-Fi and DSRC in 5-GHz band through using a hybrid network and analytic performance metrics. We comprehensively investigated four mainstream spectrum allocation schemes, that is the non-sharing, original sharing, Qualcomm's, and Cisco's proposals. Broadly speaking, the spectrum-sharing schemes enable the significant improvement in the data rate of Wi-Fi, with an acceptable degradation of the DSRC performance. Concretely speaking, the Cisco's proposal prefers to guarantee the DSRC system profit while the Qualcomm's proposal favors the Wi-Fi performance. The Cisco's proposal behaves better than the original sharing scheme in the DSRC system while the Qualcomm's proposal surpasses the original sharing scheme in the Wi-Fi system. We also performed a simulation in Jilin University scenario. The results show that the *SNR*, CW size, and especially the DSRC node density are the key factors affecting the performance of the hybrid networks. The densities of Wi-Fi clients and APs impose a stronger effect on Wi-Fi than on DSRC. In practical application, Wi-Fi and DSRC nodes may attempt to find an optimum transmission probability that builds a trade-off between spatial reuse and success probability in DSRC and Wi-Fi hybrid networks. Moreover, Wi-Fi and DSRC participants also find the optimum SINR threshold that maximizes the spectral efficiency. These points are also our future work.

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