A Novel Non-WSSUS Statistical Model of Vehicle-Vehicle Radio Channel for the 5-GHz Band

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Abstract. In recent years, with the dramatic development in intelligent transportation systems (ITS), vehicle-vehicle (V2V) radio channel models have drawn much attention. With the analysis of the preceding statistical models of V2V channel, it is obvious that the critical works in developing statistical channel models focus on two aspects, the modeling of the time-variant properties and the modeling of the severe multipath fading. In this paper, we discuss an innovative method to model the fading dispersive channels that do not satisfy the assumption of wide-sense stationary uncorrelated scattering (WSSUS). And the Weibull distribution is integrated to mimic the severe multipath fading of V2V radio channel. Moreover, based on the tapped-delay like (TDL) model, the non-WSSUS channel impulse response (CIR) function has been formulated. There are several statistical properties characterized to evaluate the performance of the proposed model, such as, Power delay profile (PDP), Temporal auto-correlation function (ACF), Local scattering function (LSF) and Power spectrum density (PSD). The simulation results demonstrate that the proposed model has a good performance in the characterization of the non-WSSUS V2V radio channel. Hence, the channel model presented will be beneficial in future V2V communications systems.

Keywords: V2V radio channel models · Non-stationary · Correlated scattering Weibull fading · Statistical model

1 Introduction

V2V radio communication systems have recently drawn great attention for the potential to reduce traffic jams and accident rates [1]. Several attractive benefits of V2V radio communications are the intelligent perception of the road condition, the capacity for probing the dynamic weather and the awareness of the traffic condition, such as the traffic congestion, traffic distribution. For the advantages of V2V radio communication system, a recent standard for V2V communications in the 5-GHz Unlicensed National Information Infrastructure band has been developed, designing for extending the IEEE 802.11a application environment.

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However, the time-frequency selective fading features of such V2V channel are significantly different from the traditional cellular network channel, and thus requires distinct channel models [2]. Consequently, many V2V channel models have been proposed. And there are several statistical modeling works related to V2V radio channel, even though most of V2V channel models are the geometry-based stochastic models (GBSM) [3]. In [4], the authors take the Doppler spectrum shapes into account, reference [5] report the PDP and tap fading statistics. In [6], the authors have measured the features of the typical V2V channel rigorously based on the dedicated short-range communications (DSRC) standard. Furthermore, the implement of Rician or Rayleigh fading under the hypothesis of WSSUS has been presented in [7]. The work in [8] report the analysis of the multipath fading of V2V radio channel in the 5-GHz band. In addition, the description of severe multipath fading by means of taking the Weibull distribution into account.

Due to the complexity and diversity of the radio propagation environments, V2V radio channel tend to be non-WSSUS. According to the modeling of the non-stationarity, the work in [9] presents a basic non-stationary model algorithm named "birth and death" process, the multipath component is considered to be not static, it could appear or disappear after a generally short duration. In [10], the authors discuss that non-WSSUS can be divided into two part, one is the stationarity with respect to time, another is the correlation with respect to the scatterer, and the channel correlation function (CCF) is proposed to describe the non-WSSUS properties.

The remainder of this article is outlined as follows. In the next section, we give a specific description of the channel model. We then evaluate the performance of the channel model by analyzing the simulation results. Finally, conclusions are drawn in the final section.

2 Channel Model

In this section, we first describe the WSSUS CIR models. The modeling of the non-WSSUS is then addressed. Finally, the severe multipath fading is integrated to the presented channel model.

2.1 WSSUS CIR Models

In nearly all statistical models, the channel is modeled as a TDL model with a time-varying linear filter, and thus the impulse response of the filter is introduced to completely characterize the channel. However, the CIR can be defined as function $h(t,\tau)$, besides, the function is corresponding to the response of the channel at time t to an impulse input at time $t-\tau$. Furthermore, based on the hypothesis of WSSUS and Rayleigh fading distribution, the CIR function in the flat-fading channel can be expressed as

$$h(t,\tau) = \delta(\tau-\tau_0)\cdot\sum_{k=1}^{N}\alpha_k(t)e^{jw_{D,k}(t-\tau_0)-jw_c\cdot\tau_0} \quad (1)$$

where, at time t, $\alpha_k(t)$ represents the k th tap amplitude with respect to the Doppler spectrum, and the argument of the exponential term is the k th tap phase. According to the flat-fading channel, all the multipath component has same time delay τ_0. The δ-function is a Dirac delta, the carrier frequency is $w_c = 2\pi f_c$, and the term $w_{D,k} = 2\pi f_{D,k}$ represents the Doppler shift associated with the k th tap.

According to the practical propagation environments, V2V radio channel have numerous time-varying delay paths, so it will be frequency-selective rather than flat-fading. Besides, it is likely to have a Line-of-Sight (LOS) of V2V radio channel, so the distribution of the multipath fading will satisfy the Rician distribution. Consequently, the CIR function is given by

$$h(t,\tau) = \sum\nolimits_{k=1}^{N} \left\{ \begin{array}{c} \sqrt{\frac{1}{K_k+1}}\alpha_k(t)e^{jw_{D,k}(t-\tau_k)} \\ +\sqrt{\frac{K_k}{K_k+1}}e^{j[w_{D,LOS,k}(t-\tau_k)+\varphi_{LOS,k}]} \end{array} \right\} e^{-jw_c\cdot\tau_k}\delta(\tau-\tau_k) \tag{2}$$

where, K_k represents the Rician factor of the k th tap, however, it will be 0 when the LOS does not exist. And the term $w_{D,LOS,k} = 2\pi f_{D,los,k}$ represents the Doppler shift associated with the k th LOS, $\varphi_{LOS,k}$ represents the initial phase of the k th LOS.

2.2 Models for the Non-WSSUS

It is mentioned above that the non-WSSUS properties has two parts, one is the non-stationarity with respect to time, another is the correlated scatterer. Correspondingly, two algorithms are respectively presented to describe the two parts of the non-WSSUS.

Birth and Death Process. V2V radio propagation environments change frequently and rapidly because of the mobility and low transmitting and receiving antenna heights. With the time-variability of V2V channel, the number of multipath components and their strengths may not be static. In [9], An algorithm named the birth and death process is proposed to generate the time-vary multipath components. We incorporate this birth and death process into our developed channel models using persistence process $z_k(t)$.

For the persistence process, the Markov chain is frequently used to model it. And thus, we developed first-order two-state Markov chains specified by two matrices: the transition (TS) matrix and the steady-state (SS) matrix [11]. These matrices are expressed as follows:

$$TS = \begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix} \quad SS = \begin{bmatrix} S_0 \\ S_1 \end{bmatrix} \tag{3}$$

Here, the element P_{ij} in matrix TS is defined as the probability of converting the state i to state j, and each SS element S_i means that the steady-state probability of state i. Figure 1 shows sample persistence process associated with the third and fifth taps for the Urban-Antenna Inside Car (UIC) setting [9]. It is depicted that the third and fifth taps can appear or disappear after a short duration, so the non-stationarity in time domain can be perfectly modeled. In other words, the non-stationary CIR function is expressed as

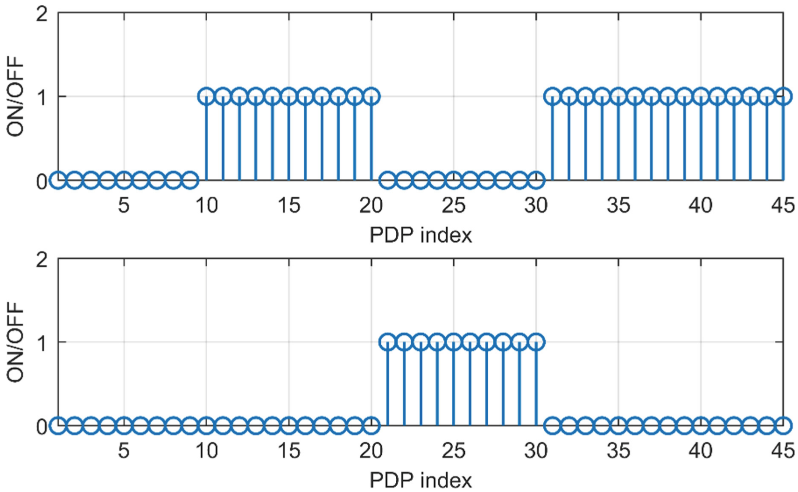

Fig. 1. Sample persistence processes $z_k(t)$ for taps 3 and 5 for the UIC case.

$$h(t,\tau) = \sum_{k=1}^{N} h'(t,\tau) \cdot z_k(t,\tau_k) \cdot \delta(\tau - \tau_k) \tag{4}$$

Here, $h'(t,\tau)$ represents the CIR of the WSSUS channel. The term $z_k(t,\tau_k)$ represents the k th tap persistence process.

Correlated Scatter Model. According to the non-WSSUS channel, the CCF can be computed as:

$$R_h(t,\tau;\Delta t,\Delta\tau) = E\{h(t,\tau+\Delta\tau)h^*(t-\Delta t,\tau)\} \tag{5}$$

Here, $\Delta t, \Delta\tau$ denote time lag and delay lag, respectively. $E\{\cdot\}$ denotes mathematical expectation, i.e., ensemble averaging, and it is reflected by the non-stationarity with respect to time and correlated with respect to delay.

In the former subsection, the birth and death process is introduced to model the non-stationarity with respect to time. Hence, we pay attention to the correlation with respect to delay. The delay-correlated matrix $\boldsymbol{L}$ is introduced to model it.

$$h(t,\tau) = \sum_{k=1}^{N} h''_{US}(t,\tau) \cdot L_k(\tau,\tau_k) = \boldsymbol{H}''_{US}(t,\tau) \cdot \boldsymbol{L} \tag{6}$$

where, $h''_{US}(t,\tau)$ represents the CIR of the US channel. The term $L_k(\tau,\tau_k)$ represents the delay-correlated vector with respect to the k th multipath component. Furthermore, the correlated with respect of delay is corresponding to the correlation of $\boldsymbol{L}$. However, the

Doppler spectrum of the different taps is likely to be different, so the correlation matrix of the spectrum shaping filter output will be a diagonal matrix.

$$\boldsymbol{D} = E\left[\boldsymbol{ff}^{\boldsymbol{H}}\right] \tag{7}$$

Here, $\boldsymbol{f}$ denotes the output vector of the spectrum shaping filter, and it can be generated by the transition of the complex white Gaussian noise through the spectrum shaping filter. The term $\boldsymbol{D}$ represents the correlation matrix of $\boldsymbol{f}$. Hence, the correlation of the channel is given by

$$\boldsymbol{\rho} = E\left\{(\boldsymbol{Lf})\cdot(\boldsymbol{Lf})^{\boldsymbol{H}}\right\} = E\left\{\boldsymbol{Lff}^{\boldsymbol{H}}\boldsymbol{L}^{\boldsymbol{H}}\right\} = \boldsymbol{L}\left\{E\left\{\boldsymbol{ff}^{\boldsymbol{H}}\right\}\right\}\boldsymbol{L}^{\boldsymbol{H}} = \boldsymbol{LDL}^{\boldsymbol{H}} \tag{8}$$

However, the tap cross-correlation matrix $\boldsymbol{\rho}$ can be measured by varying antenna locations and collecting data at different times of the day and under different traffic conditions [9]. As a consequence, the cholesky decomposition can be used to resolve the measured $\boldsymbol{\rho}$, and the $\boldsymbol{L}$ will be turned out.

$$\boldsymbol{\rho} = \boldsymbol{TT}^{\boldsymbol{H}} = \boldsymbol{TD}^{-1/2}\cdot\boldsymbol{D}\cdot\boldsymbol{D}^{-1/2}\boldsymbol{T}^{\boldsymbol{H}} = \boldsymbol{LDL}^{\boldsymbol{H}} \tag{9}$$

Note that $\boldsymbol{T}$ denotes the results of the cholesky decomposition of $\boldsymbol{\rho}$. Above all, $\boldsymbol{L}$ is chosen to be

$$\boldsymbol{L} = \boldsymbol{TD}^{-1/2} \tag{10}$$

Besides, if all of the taps have the same Doppler spectrum, then we have $\boldsymbol{D} = 1$ and $\boldsymbol{L} = \boldsymbol{T}$.

2.3 Non-WSSUS CIR Model with Severe Multipath Fading

Due to the severe delay disperse and the severe Doppler disperse in V2V channel, the multipath fading is likely to be severer than the Rayleigh fading. Furthermore, with the non-stationarity of V2V radio channel, the number of taps might be enormous and variable. The Weibull distribution [12] is used to model the severe multipath fading.

The Weibull model has two parameters, so it offers substantial flexibility. It can be given by

$$p_w(x) = \frac{\beta}{a^{\beta}}x^{\beta-1}exp\left[-\left(\frac{x}{a}\right)^{\beta}\right] \tag{11}$$

where β is the Weibull shape factor that is corresponding to the fading severity, $a = \sqrt{E(x^2)/\Gamma[(2/\beta)+1]}$ is a scale parameter, and Γ is the Gamma function. However, the Weibull distribution can be equal to the Rayleigh distribution when β equals 2. With the smaller β, the multipath fading will be severer.

Weibull distribution can be generated by Rayleigh distribution [13], we assume that W is a Weibull-distributed random variable, and there must be a Rayleigh-distributed random variable R that is submitted to the term $W = R^{2/\beta}$. Above all, the CIR function of the non-WSSUS V2V channel model is given by

$$h(t,\tau) = \sum\nolimits_{m=1}^{N} \left\{ \sum\nolimits_{k=1}^{N} \left\{ \begin{array}{c} \alpha_k(t) e^{jw_{D,k}(t-\tau_k)} e^{-jw_c \cdot \tau_k} \\ \times z_k(t,\tau_k) \end{array} \right\}^{\frac{2}{\beta_k}} \delta(\tau - \tau_k) \right\} \cdot L_m(\tau, \tau_m) \quad (12)$$

Here, τ_m denotes the m th multipath component, and the term $L_m(\tau, \tau_m)$ represents the m th row of the delay-correlated matrix $\boldsymbol{L}$. Similarly, β_k denotes the Weibull shape factor of the k th multipath component. Furthermore, the proposed channel model is depicted in Fig. 2 followed.

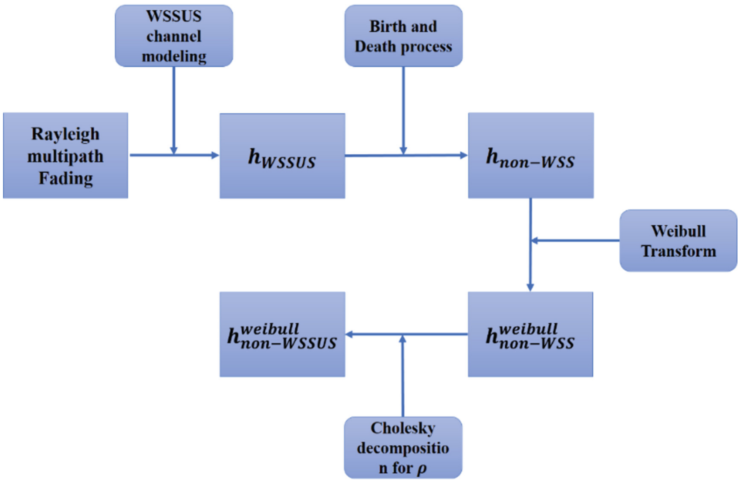

Fig. 2. Model structure for the proposed non-WSSUS V2V channel model.

3 Simulation Results and Analysis

In this section, we investigate the proposed V2V channel model in detail for several statistical properties based on the UIC scenario in [14]. And the following main parameters were chosen for the simulations: the carrier frequency f_c is set as 5.12 GHz, and the bandwidth for the simulations is equal to 10 MHz, the Doppler spectrum of all taps is considered as a same shape, such as, the U-shape. The following Table 1 gives the other parameters were chosen for our simulations.

Here, Energy is the measured mean-power of the taps. Weibull shape factor reflects the fading severity of the taps. And P_{00} and P_{11} are the Markov TS matrix diagonal elements, similarly, S_1 means that the steady-state probability of the 'birth' state. However, NA represents that the state of the tap does not exist. Furthermore, the tap cross-correlation matrix for simulations is given behind (Table 2).

Table 1. Channel parameters for the UIC scenario.

Tap Index	Energy	Weibull Shape Factor	$P_{00,k}$	$P_{11,k}$	S_1
1	0.756	2.49	NA	1.0000	1.0000
2	0.120	1.75	0.0769	0.9640	0.9625
3	0.051	1.68	0.3103	0.8993	0.8732
4	0.034	1.72	0.3280	0.8521	0.8199
5	0.019	1.65	0.5217	0.7963	0.7017
6	0.012	1.6	0.6429	0.7393	0.5764
7	0.006	1.69	0.6734	0.6686	0.4971

Table 2. Tap cross-correlation matrix $\boldsymbol{\rho}$ for the UIC scenario.

Tap index	1	2	3	4	5	6	7
1	1	0.1989	0.0555	0.0481	0.0977	0.1074	0.3504
2	0.1989	1	0.1477	0.1495	0.0974	0.2329	0.1999
3	0.0555	0.1477	1	0.2298	0.0106	0.1368	0.1496
4	0.0481	0.1495	0.2298	1	0.2189	0.2088	0.1143
5	0.0977	0.0974	0.0106	0.2189	1	0.1600	0
6	0.1074	0.2329	0.1368	0.2088	0.1600	1	0.2600
7	0.3504	0.1999	0.1496	0.1143	0	0.2600	1

3.1 PDP Simulation Results

Figure 3 shows the three-dimensional (3D) short-time average PDPs simulation results of the non-WSSUS V2V channel model. We notice that the short-time average changes with time t.

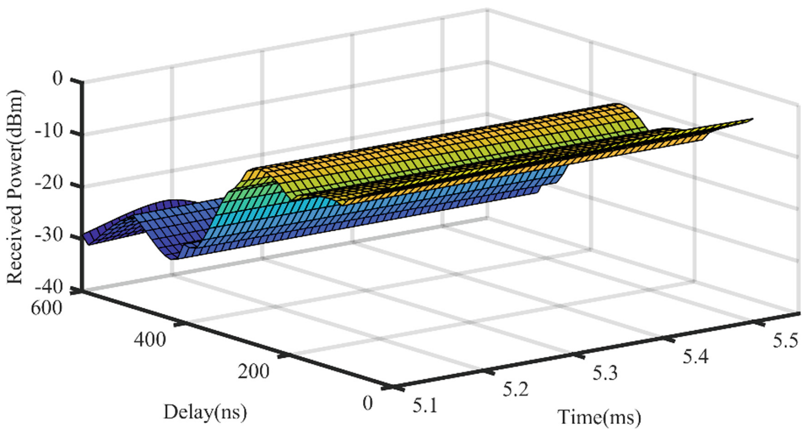

Fig. 3. Three-dimensional (3D) short-time averages PDPs of the non-WSSUS V2V channel model.

To emphasize these changes, five short-time PDPs, each over a duration of 20 μs, from 5.1 to 5.5 ms are depicted in Fig. 4. According to the varying time instants, it is obviously that the proposed channel models have the capacity for modeling the non-stationary delay disperse. In other words, the simulation results demonstrate the non-stationarity of V2V radio channel over the time period of 0.5 ms.

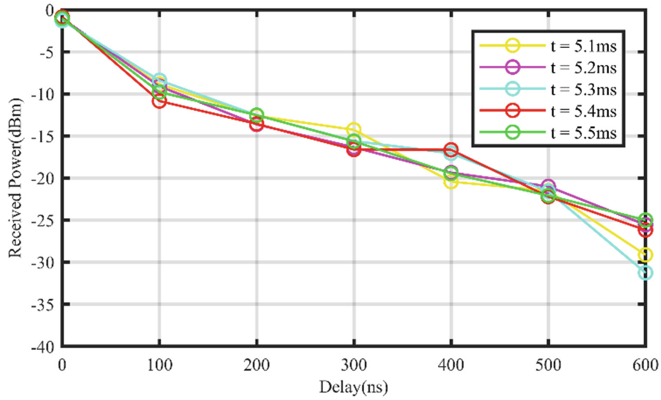

Fig. 4. Five short-time averages PDPs from 5.1 ms to 5.5 ms.

Figure 5 shows the comparison between the long-time PDP simulation results and the measured results for the UIC scenario. It is depicted in Fig. 5 that the simulation results have an approximate agreement with the measured results. However, the measured mean-power results are measured in a short duration, so the channel condition is considered as stationary. Due to the non-stationary properties, the simulation results have a little difference from the measured results. In other words, it is demonstrated that the proposed V2V channel model can perfectly mimic the delay disperse with the non-stationarity.

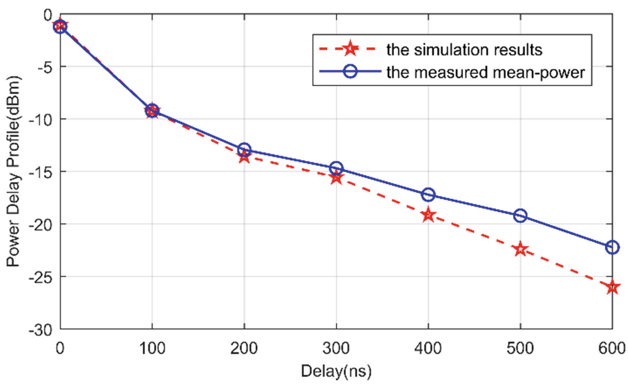

Fig. 5. Comparison between the PDP simulation results and the measured mean-power results for the UIC scenario.

3.2 Correlation Function Simulation Results

ACF simulation results. Figure 6 shows the absolute value of the time-variant ACF of different taps of the proposed V2V channel model at different time instants. And it is noticed that the absolute value of the ACF of different taps is different, besides, the simulation results of different time instants is different. The ACF is varying with time and delay, so the non-WSSUS properties are depicted in Fig. 6. The proposed model has an outstanding performance of modeling the non-WSSUS.

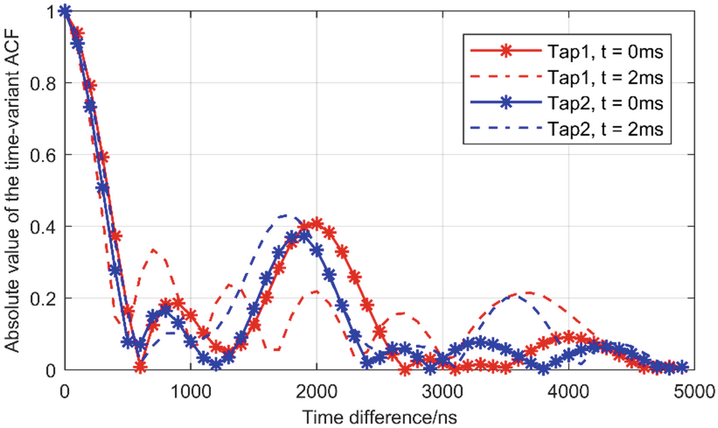

Fig. 6. Absolute value of the time-variant ACF of different taps of the proposed V2V channel model at different time instants for UIC scenario.

LSF simulation results. The absolute value of the time-variant LSF at different time instances is depicted in Fig. 7 above. It is obvious that the power of the effective scatterer varies with time instances. The simulation results show that the time-variant non-stationary properties of the scatterer are mimicked perfectly. Therefore, the proposed channel model is proved to be valuable.

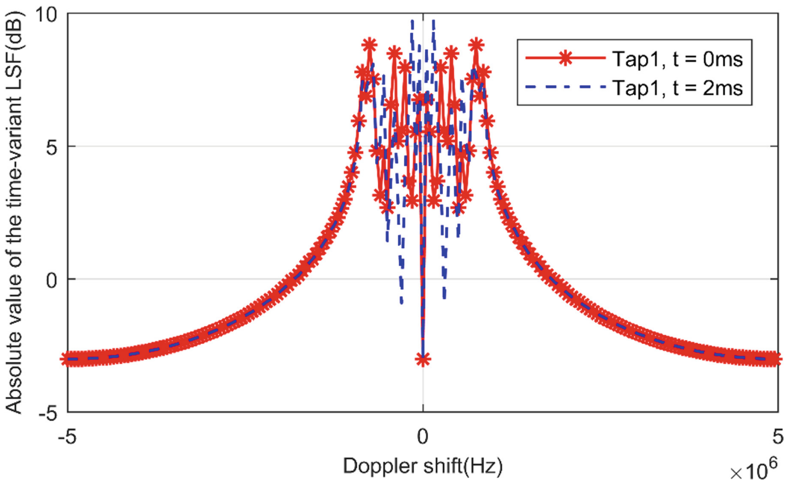

Fig. 7. Absolute value of the time-variant LSF of the first tap of the proposed V2V channel model at different time instants for UIC scenario.

3.3 PSD Simulation Results

Figure 8 shows that The PSD of the taps for the UIC scenario. We can easily notice that the PSD of the taps is similar to the U-shape. Due to the impact of the correlated scatterer, the interaction between each tap will be contributing. As a result, the PSD of the taps may not fit the standard U-shape, in other words, the spectrum distortion exists. However, the non-stationarity with respect to time also affects the PSD spectrum. It is obvious that the PSD of the taps is fluctuant rather than smooth. Furthermore, the simulation results turn out that the modeling of the Doppler disperse with the non-WSSUS is practical.

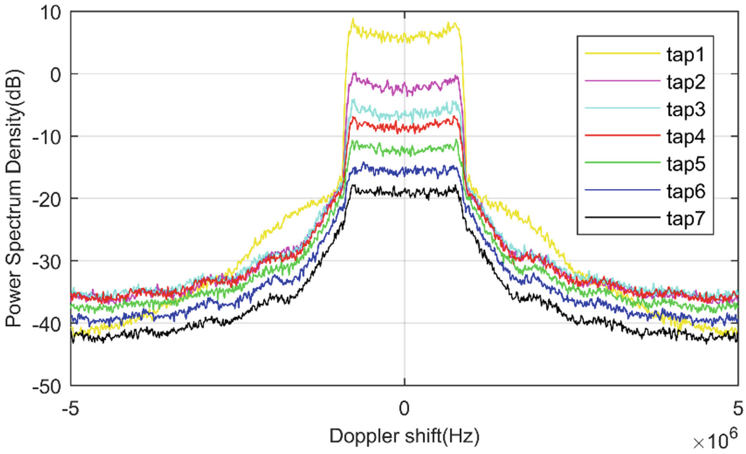

Fig. 8. The PSD simulation results of the taps for UIC scenario.

4 Conclusion

In this paper, we have proposed a novel non-WSSUS statistical model of V2V channel for the 5-GHz band. Several practical statistical models are integrated into the proposed model. Besides, the persistence process and delay-correlated matrix is adapted to characterize the non-WSSUS properties. Moreover, several statistical properties of the proposed model have been investigated. The PDP and PSD simulation results show that the proposed model describes the delay disperse and the Doppler disperse perfectly. According to the time-variant ACF and LSF behaviors, it is demonstrated that the proposed channel model could vividly mimic the non-WSSUS properties of V2V radio channel.

In conclusion, the novel model proposed in this paper can characterize the fluctuant and flexible V2V channel. As a result, the research of the V2V channel will be available for the future ITS construction. Our future work will further adapt the proposed model to more complex and practical scenario, such as the massive-MIMO scenario.

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