# An Improved Non-Geometrical Stochastic Model for Non-WSSUS Vehicle-to-Vehicle Channels

**Abstract**: A novel non-geometrical stochastic model (NGSM) for non-wide sense stationary uncorrelated scattering (non-WSSUS) vehicle-to-vehicle (V2V) channels is proposed. This model is based on a conventional NGSM and employs a more accurate method to reproduce the realistic characteristics of V2V channels, which successfully extends the existing NGSM to include the line-of-sight (LoS) component. Moreover, the statistical properties of the proposed model in different scenarios, including Doppler power spectral density (PSD), power delay profile (PDP), and the tap correlation coefficient matrix are simulated and compared with those of the existing NGSM. Furthermore, the simulation results demonstrate not only the utility of the proposed model, but also the correctness of our theoretical derivations.

**Keywords**: vehicle-to-vehicle; non-WSSUS channels; non-geometrical stochastic model; LoS component; statistical properties

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## 1 Introduction

Vehicle-to-vehicle (V2V) communication plays a key role in intelligent transportation systems (ITS), which aims at improving the traffic efficiency, minimizing traffic accidents and enabling some new applications [1]. As a newly emerging communication technique, V2V communication faces research challenges and standardization problems, which limit its further development. Therefore, much research attention has been attracted to V2V channel modeling for facilitating the analysis and design of V2V communication systems [2], [3].

As addressed in [4], [5], V2V channel models can be categorized as geometry-based deterministic model (GBDM) [6] and stochastic model, and the latter can be further classified as non-geometrical stochastic model (NGSM) [7], [8] and geometry-based stochastic model (GBSM). The GBDM is characterized by V2V physical channel parameters in a completely deterministic approach, whereas its computational complexities increase with the accuracy requirement. Compared with GBDM, stochastic models have better tradeoff between accuracy and complexity, and thus have been widely used currently in V2V channel modeling. The authors in [9] – [15] proposed several GBSMs, which used the simplified ray tracing principle and equivalent scatterer concept to simulate propagation environment. Though the GBSM can be easily adapted to diverse scenarios, it is more complex than the NGSM. The NGSM determines physical parameters of the V2V channel in a completely stochastic manner without presuming any underlying geometry. In the literature [7], [8], two conventional wideband NGSMs were proposed and are both based on the tapped delay line (TDL) structure.

The wideband NGSM developed in [7] is a conventional channel model standardized by IEEE 802. 11p. The NGSM in [7] includes the line-of-sight (LoS) component and has variable types of Doppler spectra for different delays. Specifically, due to the short distance of V2V communication, it often includes the LoS component, especially for the scenario with low vehicular traffic density (VTD). In order to identify the presence of LoS component, the model employs the Ricean fading. Moreover, in the NGSM [7], each tap contains several unresolvable

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subpaths, and subpaths with different delays have different types of Doppler spectra, e. g. , flat shape, round shape, classic 3 dB shape, and classic 6 dB shape. However, for simplicity, the NGSM [7] is based on the wide sense stationary uncorrelated scattering (WSSUS) assumption and only employs the Ricean fading, which cannot mimic the severe fading in V2V channels.

In the wideband NGSM [8], two characteristics of the V2V channels not considered in [4] are taken into account, i. e. , non-stationarity and severe fading. Due to unpredictable traffic and changes in the size, location, as well as velocity of scatterers, the number of multipath components and strengths alter frequently, resulting in the non-stationarity in both time and frequency domains for V2V channels. The NGSM [8] employs the first-order two-state Markov chains and generates correlated stochastic variables to describe the non-stationarity in both time and frequency domains, respectively. Moreover, in V2V channels, the fading of multipath component is often worse than Rayleigh fading due to severer delay dispersion and Doppler dispersion. Hence, the model also describes the severe fading by means of the Weibull distribution, in which the tap amplitudes follow the Weibull distribution, with the fading parameter determining fading severity. However, since the NGSM [8] considers both non-stationarity and severe fading, it is difficult to further identify the existence of LoS component and possess variable types of Doppler spectra for different delays.

Based on the measurement data presented in above two conventional NGSMs, we can summarize four important and unique characteristics that exist in V2V channels, i. e. , non-stationarity, severe fading, the existence of LoS component, and variable types of Doppler spectra for different delays. However, both NGSMs implement only half of the above four characteristics. Therefore, neither of the two conventional NGSMs can meet the requirements. Motivated by this, a new NGSM is desirable to be developed for non-WSSUS V2V channels.

To fill the aforementioned gap and accurately describe the characteristics of the V2V channel, we propose an improved model based on the NGSM [8] for non-WSSUS V2V channels. The proposed model not only considers the non-stationarity but also describes the severe fading in V2V channels, keeping the advantages of the NGSM [8]. Moreover, to mimic the V2V channel non-stationarity in frequency domain, channel models should generate correlated taps, which consist of the amplitude part and phase part. Since the amplitude and phase of taps are independent, the distribution of amplitude and phase should be properly modeled respectively. Specifically, the tap amplitude statistics can be modeled as Weibull distribution to mimic the severe fading. For simplicity, most papers defined a uniformly distributed phase over the interval as shown in [8] and [16]. However, the uniformly distributed phase leads to the corresponding channel taps having no ability to include the LoS component. To include the LoS component, the authors in [17] proposed a Laplace distributed phase. However, the Laplace distributed phase cannot mimic the scenarios without the LoS component. To further fill the gap, we propose a non-uniformly distributed phase, which is properly combined with the fading parameter used in the severe fading modeling. By changing value of the fading parameter, the proposed model can flexibly mimic different V2V scenarios with and without LoS components. The main contributions of this paper can be summarized as follows.

1) For the first time, we prove that it is inappropriate to impose a uniformly distributed tap phase, which causes the absence of LoS component.

2) We propose an improved NGSM with the non-uniformly distributed phase for non-WSSUS V2V channels, which extends the NGSM [8] to identify the presence of the LoS component. Therefore, the proposed model has the ability to mimic the aforementioned first three unique characteristics of V2V channels. The simulation results demonstrate that the LoS component is successfully added into Doppler power spectral density (PSD).

3) The effectiveness and accuracy of the proposed V2V channel model are validated by extensive simulations.

The rest of this paper has the following structure. In Section 2, we describe the constriction steps of the NGSM in [8] and propose an improved NGSM. The simulation results of the proposed model for different scenarios, including Doppler PSDs, power delay profile (PDP), and the tap correlation coefficient matrix are provided and analyzed in Section 3 in comparison with the NGSM [8]. Finally, conclusions are drawn in Section 4.

## 2 Channel Models for Non-WSSUS V2V Channels

In this section, we first review the constriction steps of the NGSM in [8] and prove that imposing a uniformly distributed tap phase is inappropriate. Then, an improved NGSM with non-uniformly distributed tap phase is proposed.

### 2.1 Conventional NGSM with Uniform Phase Distribution

The constriction steps of existing NGSM [8] include three parts: non-WSS modeling, non-US modeling, and severe fading modeling. In this section, we will briefly describe the constriction steps of the model and prove that it is too restrictive to impose a uniform phase distribution in the NGSM [8].

### 2.1.1 Non-WSS Modeling

Due to unpredictable traffic and changes in the size, location, and velocity of scatterers, the number of multipath components and strengths alter frequently. Based on the literature [18], the NGSM in [8] represents the non-WSS characteristic by employing the “birth and death” process with persistence process $Z_k(t) = \{0, 1\}$ in V2V channel model, where tap “off” means below 25-dB threshold from the main tap.

Such thresholding methods [19] - [21] are widely used in the literature to limit the number of taps to those that have the non-negligible energy [8].

In addition, the state transition process of the on/off process can be described by first-order two-state Markov chains, and the transition (*TS*) matrix and the steady-state (*SS*) matrix [8] can be given by

$$TS = \begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix} \qquad SS = \begin{bmatrix} P_0 \\ P_1 \end{bmatrix}, \tag{1}$$

where each element $P_{ij}$ in matrix *TS* is defined as the probability of going from state $i$ to state$j$, and each *SS* element $P_j$ gives the "steady-state probability" associated with the $j$th state.

Then, the channel impluse repulse (CIR) of the NGSM in [8] can be expressed as

$$h(t,\tau) = \sum_{k=1}^{N} z_k(t) c_k(t) \delta(\tau - \tau_k) \times \exp\left\{ j2\pi \left[ f_{D,k}\left(t - \tau_k\right) - f_c \cdot \tau_k \right] \right\}, \tag{2}$$

where $Z_k(t) = \{0, 1\}$ is a persistence process used to account for the finite "lifetime" of the propagation paths. $h(t,\tau)$ denotes the channel output at time $t$ due to an impulse input at time $t - \tau$. $c_k(t)$ represents the $k$-th received amplitude, the exponential term represents the $k$-th received phase, and the $k$-th echo path has a time-varying propagation delay $\tau_k$. The $\delta$ function is a Dirac delta (impulse), and $f_c$ is the carrier frequency in Hz. The term $f_{D,K}$ represents the Doppler shift, which is associated with the $k$-th received multipath echo.

### 2.1.2 Non-US Modeling

Non-US characteristic reflects the impacts of correlation on different paths/taps, which represents the delay domain characteristics. To accurately represent correlated scattering (non-US) characteristic, the model generates complex Gaussian stochastic variables. As shown in **Fig. 1**, the correlated complex Gaussian stochastic variables can be generated with any desired correlation coefficients.

The process to generate correlated complex Gaussian stochastic variables with correlation $\rho^G$ from pairs of uncorrelated Gaussian stochastic variables is as follows: 1) Generate uncorrelated complex Gaussian stochastic variables $V$ through the independent Gaussian stochastic variables; 2) using Cholesky decomposition of the correlation matrix $LL^H = \rho^G$ to determine the coloring matrix $V$, where $L^H$ is the Hermitian transpose of $L$; 3) Generate correlated complex Gaussian stochastic variables by means of $W = LV$.

### 2.1.3 Severe Fading Modeling

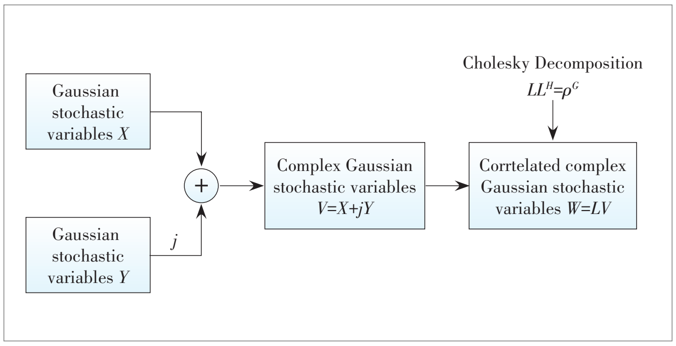
In V2V channels, due to more severe delay dispersion, Doppler dispersion, and non-stationarity characteristics, the fading of multipath component is often worse than Rayleigh fading. As addressed in [22], overall, the best fit for the largest number of taps is obtained by means of the Weibull distribution. Therefore, in the NGSM [8], the tap amplitude statistics are modeled as the flexible Weibull distribution, which can be written as

$$p_W(x) = \frac{\beta}{a^\beta} x^{\beta - 1} \exp\left[ -\left( \frac{x}{a} \right)^\beta \right], \tag{3}$$

where $\alpha = \sqrt{E\left(x^2\right)/\Gamma\left[\left(2/\beta\right) + 1\right]}$ denotes a scale parameter and $\beta$ is a fading parameter to represent fading severity. When $\beta = 2$, the Weibull distribution can be transformed to the well-known Rayleigh distribution, and as $\beta$ increases, the situation in which the signal becomes more deterministic. When $\beta$ is large enough, it means that the LoS component will exist in the V2V communications. However, when $\beta < 2$, the severe fading will exist in the V2V channel.

As can be seen from the above analysis, severe fading modeling can be implemented by the Weibull stochastic process, whereas Weibull stochastic process can be obtained by a complex Gaussian stochastic process [23]. Specifically, the detail construction steps of the NGSM in [8] is shown in **Fig. 2**. As can be readily observed from the figure, the time correlated domain of the model is implemented by means of the linear convolution for the Gaussian stochastic process. In order to maintain the type of Doppler spectra, the NGSM in [8] employs the separation of amplitude and phase, in which only the amplitude is transformed with complex exponentiation $2/\beta$. Whereas, the phase is not be transformed, which is directly separated from the complex Gaussian stochastic variables.

The phase is gained directly from the complex Gaussian stochastic process and if we do not consider the time correlation, the phase will follow a uniform distribution over $[-\pi, \pi]$. Consequently, the tap amplitude follows the Weibull distribution and the tap phase follows the uniform distribution. Thus, the stochastic variables can be expressed as



▲ **Figure 1. Generating correlated complex Gaussian stochastic variables.**

$$\tilde{W}_k = \left|\tilde{W}_k\right| e^{j\tilde{\phi}_k} = \left|\tilde{V}_k\right|^{2/\beta_k} e^{j\tilde{\phi}_k},\ \tilde{\phi}_k \in [-\pi, \pi], \tag{4}$$

where the number of taps is assumed to be $K$ and $\tilde{\phi}_K$is the tap phase of the NGSM [8].

Due to the phase $\tilde{\phi}_K$ with a uniformly distributed over $[-\pi, \pi]$, the mean of the NGSM [8] can be calculated as

$$E(\tilde{W}_k) = \frac{1}{2\pi}\int_{-\pi}^{\pi}\left|\tilde{V}_k\right|^{2/\beta_k} e^{j\tilde{\varphi}_k} d\varphi_k = 0. \tag{5}$$

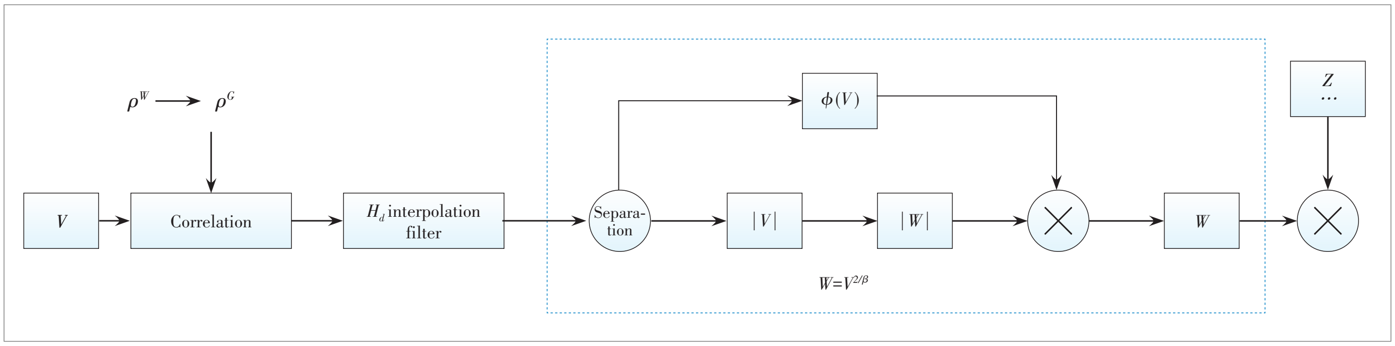
The uniformly distributed tap phase denotes zero-mean in-phase and quadrature components, which causes the absence of LoS component in NGSM [8]. However, based on the aforementioned analysis, the existence of LoS component is one of the important and unique characteristics of V2V channels. Consequently, we can conclude that it is inappropriate to impose a uniformly distributed tap phase. To fill up the aforementioned gaps and accurately describe the characteristics of the V2V channel, an improved model with a non-uniform phase distribution is described thereafter.

### 2.2 Improved NGSM with Non-Uniform Phase Distribution

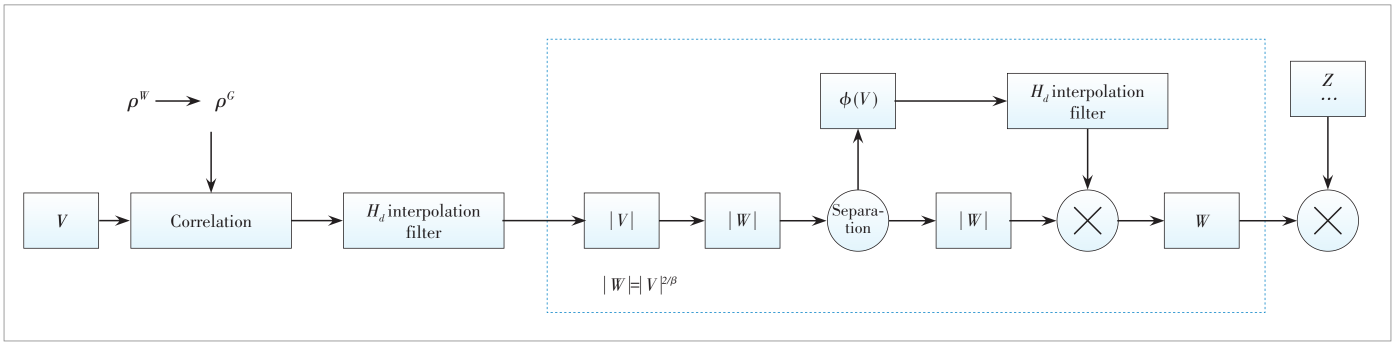
In this section, an improved NGSM with non-uniformly distributed tap phase is proposed, which is based on the existing NGSM [8]. The process to develop the improved model also consists of three parts: non-WSS modeling, non-US modeling, and severe fading modeling. However, the proposed model employs a more accurate method to represent the characteristics of V2V channels, which extends the NGSM [8] to have the ability to include the LoS component.

As can be seen from the above analysis, LoS component cannot be included in the NGSM [8]. This is because the tap phase is directly gained from the separation from Gaussian stochastic process and follows a uniform distribution in the interval $[-\pi, \pi]$, which causes the absence of the LoS component. Thus, the uniformly distributed tap phase must be changed. Specifically, in the Weibull stochastic process, the amplitude and the phase of complex Gaussian stochastic variables are both transformed with complex exponentiation $2/\beta$, and then the complex Gaussian stochastic variables are separated into the amplitude part and the phase part since the amplitude and phase of the complex stochastic variables are independent on each other. As a result of the above transformation, $\beta$ affects equivalently the amplitude part and the phase part. Consequently, the tap amplitude follows the Weibull distribution and the tap phase follows non-uniform distribution. Above all, the constriction steps of the improved mode are shown in **Fig. 3**.

With $\beta$ being increased, the resulting tap phase concentrates within a smaller phase range, as expected. Consequently, an impulse at zero occurs as $\beta \to \infty$. Also, when $\beta = 2$, a uni-



▲**Figure 2. The constriction steps of the NGSM [8] (*V* is an independent and identical complex Gaussian stochastic variable, and *Z* is a post-operation such as a persistence process).**



▲**Figure 3. The constriction steps of the improved model (*V* is an independent and identical complex Gaussian stochastic variable, and *Z* is a post-operation such as a persistence process).**

formly distributed phase occurs, and the stochastic variables of the improved model can be expressed as

$$\widetilde{W'}_k = \tilde{V}_k^{\,2/\beta_k} = \left(\left|\tilde{V}_k\right| \cdot e^{j\tilde{\phi}_k}\right)^{2/\beta_k} = \left|\tilde{V}_k\right|^{2/\beta_k} e^{j\tilde{\phi}'_k},$$
$$\tilde{\phi}_k \in [-\pi,\pi], \tilde{\phi}'_k \in [-2\pi/\beta, 2\pi/\beta], \tag{6}$$

where the number of taps is assumed to be $K$ and $\left|\tilde{V}_K\right|$is the tap amplitude, which follows the Weibull distribution. $\tilde{\phi}'_k$ is the tap phase of the improved model and follows the non-uniform distribution, which is a linear function of the uniformly distributed phase. Specifically, the tap phase of the improved model can be given by

$$\tilde{\phi}'_k = \tilde{\phi}_k \cdot 2/\beta_k. \tag{7}$$

Similarly, the mean of the improved model can be calculated as

$$E(\tilde{W}'_k) = \frac{1}{2\pi} \int_{-2\pi/\beta_k}^{2\pi/\beta_k} \left|\tilde{V}_k\right|^{2/\beta_k} e^{j\widetilde{\Phi'}_k} d\tilde{\phi}'_k \Big|_{\beta > 2} = \frac{\left|\tilde{V}_k\right|^{2/\beta_k}}{\pi} (1 -$$
$$\cos\frac{4\pi}{\beta_k}) e^{j\frac{4\pi}{\beta_k}} \Big|_{\beta_k > 2} \neq 0. \tag{8}$$

Equation (8) shows that as $\beta$ increases, the tap phase concentrates within a smaller range, resulting in $E\left(\tilde{W}'_K\right) \neq 0$. Furthermore, on comparing (5) and (8), we can conclude that the improved model with non-uniformly tap phase no longer denotes zero-mean in-phase and quadrature components, the Doppler PSD will show a dominant frequency component, which is able to describe the existence of LoS component [24]. Thus, the results demonstrate the advantage of our proposed method.

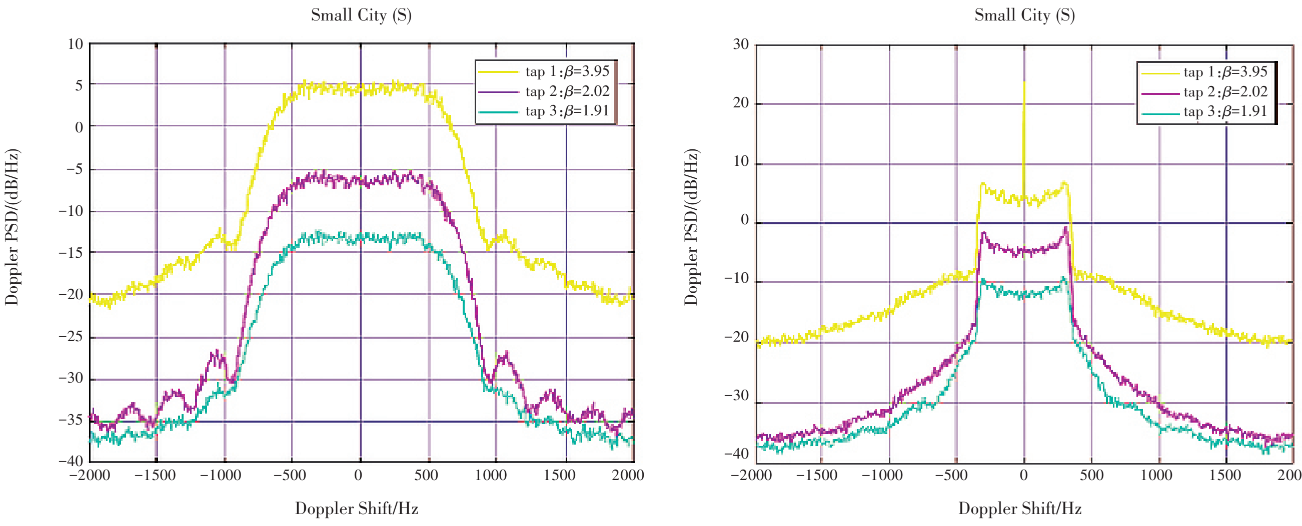
Further analysis shows that each tap of V2V channels exhibits serious Doppler spread due to the high mobility of vehicles, and the phase distribution ranged from $[-\pi, \pi]$ is not enough to represent the serious Doppler environment adequately. The non-uniformly distributed tap phase that derived from the conventional definition of the fading parameter $\beta$ is more accurately used to describe the characteristics of V2V channels. Equation (8) allows further observations: the $E\left(\tilde{W}'\right)$ and $\beta$ is positively correlated, which means that with $\beta$ being increased, the signal becomes more deterministic and the LoS component is also larger [24].

It is also worth noting that the transformation of phase does not influence the amplitude of complex Gaussian stochastic variables, so that this improvement does not have impact on the type of Doppler spectra and the tap correlation coefficient matrix.

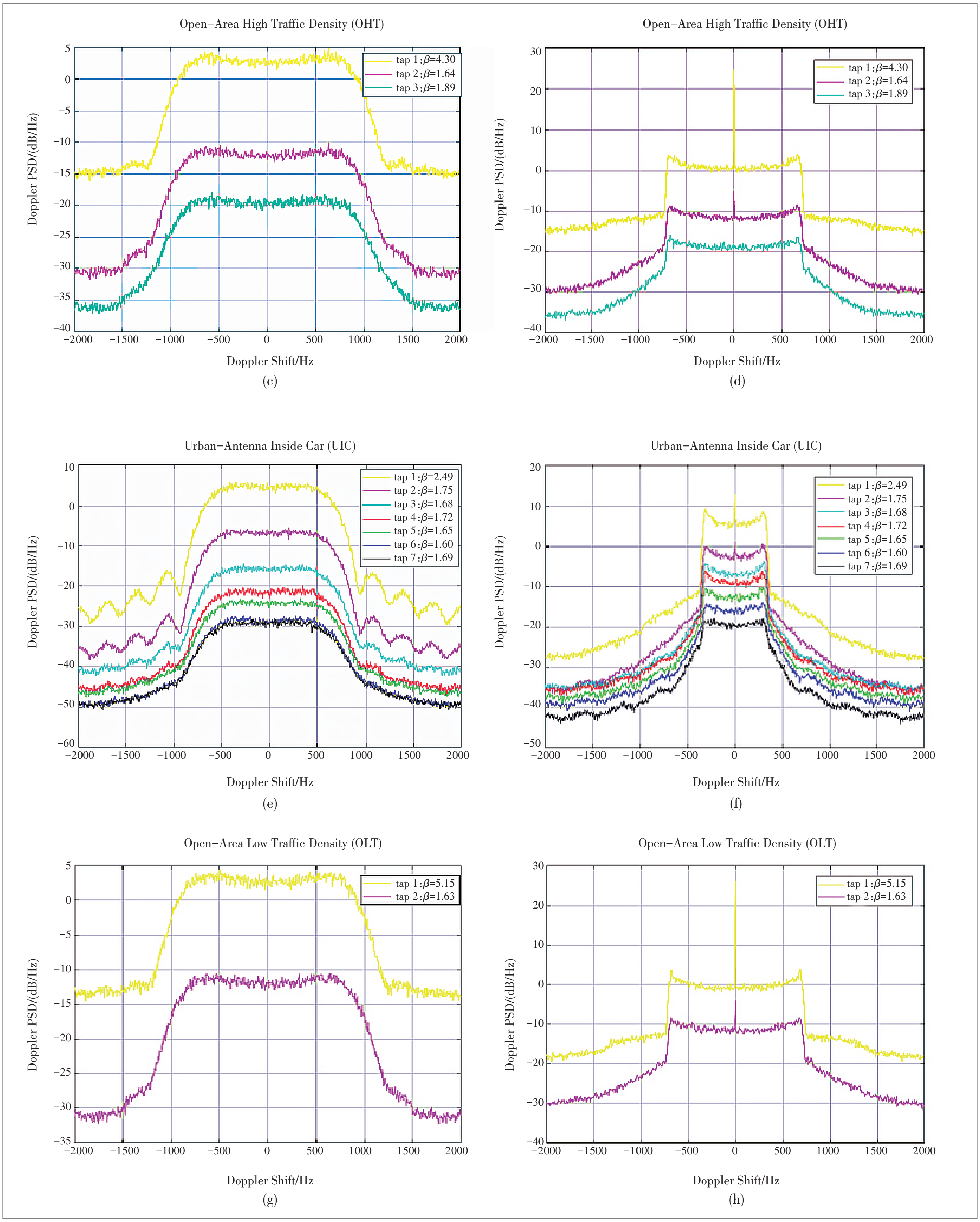
## 3 Simulation Results and Analysis

In this section, the statistical properties of the proposed model in different scenarios, including Doppler PSD, PDP, and the tap correlation coefficient matrix are simulated and compared with those of the NGSM in [8]. To better compare the performance of the two models, the following key parameters are utilized to obtain the simulation results, which are the same as those in [8]. Specifically, the key parameters can be set as the carrier frequency $f_c$ = 5.12 GHz, the bandwidth $BW$ = 10 MHz, and the duration of each "birth and death" process state (i. e., the coherence time of the channel) $T_c$ = 0.0005 ~ 0.001 s. Moreover, all the simulation scenarios are also the same as those in [8], including Small City (S), Urban-Antenna Outside Car (UOC), Urban-Antenna Inside Car (UIC), Open-Area High Traffic Density (OHT), and Open-Area Low Traffic Density (OLT).

**Fig. 4** provides the comparison between the Doppler PSD of



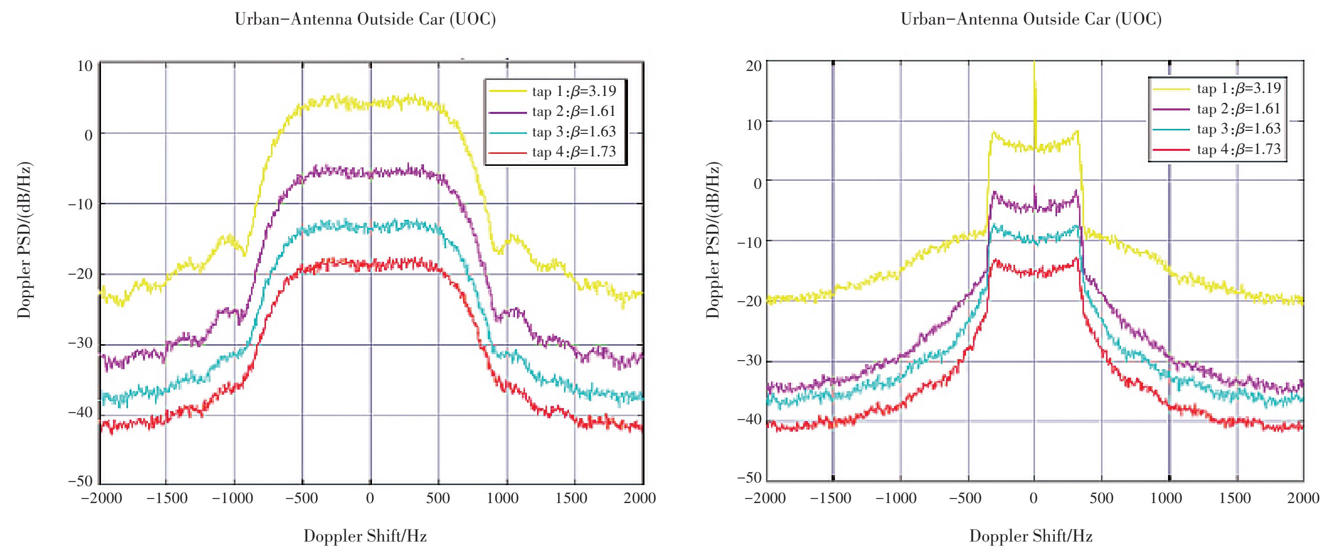
(a) (b)


Open−Area High Traffic Density (OHT)
Doppler PSD/(dB/Hz)
5
0
−5
−10
−15
−20
−25
−30
−35
−40
−2000
−1500
−1000
−500
0
500
1000
1500
2000
Doppler Shift/Hz
tap 1:β=4.30
tap 2:β=1.64
tap 3:β=1.89
Open−Area High Traffic Density (OHT)
Doppler PSD/(dB/Hz)
30
20
10
0
−10
−20
−30
−40
−2000
−1500
−1000
−500
0
500
1000
1500
2000
Doppler Shift/Hz
tap 1:β=4.30
tap 2:β=1.64
tap 3:β=1.89
Urban−Antenna Inside Car (UIC)
Doppler PSD/(dB/Hz)
10
0
−10
−20
−30
−40
−50
−60
−2000
−1500
−1000
−500
0
500
1000
1500
2000
Doppler Shift/Hz
tap 1:β=2.49
tap 2:β=1.75
tap 3:β=1.68
tap 4:β=1.72
tap 5:β=1.65
tap 6:β=1.60
tap 7:β=1.69
Urban−Antenna Inside Car (UIC)
Doppler PSD/(dB/Hz)
20
10
0
−10
−20
−30
−40
−50
−2000
−1500
−1000
−500
0
500
1000
1500
2000
Doppler Shift/Hz
tap 1:β=2.49
tap 2:β=1.75
tap 3:β=1.68
tap 4:β=1.72
tap 5:β=1.65
tap 6:β=1.60
tap 7:β=1.69
Open−Area Low Traffic Density (OLT)
Doppler PSD/(dB/Hz)
5
0
−5
−10
−15
−20
−25
−30
−35
−2000
−1500
−1000
−500
0
500
1000
1500
2000
Doppler Shift/Hz
tap 1:β=5.15
tap 2:β=1.63
Open−Area Low Traffic Density (OLT)
Doppler PSD/(dB/Hz)
30
20
10
0
−10
−20
−30
−40
−2000
−1500
−1000
−500
0
500
1000
1500
2000
Doppler Shift/Hz
tap 1:β=5.15
tap 2:β=1.63

(c) (d)

(e) (f)

(g) (h)



(i) PSD: power spectral density (j)

**▲Figure 4. The Doppler PSD of different models for different scenarios. (a) Doppler PSD of the model in [8] for S scenario; (b) Doppler PSD of the improved model for S scenario; (c) Doppler PSD of the model in [8] for OHT scenario; (d) Doppler PSD of the improved model for OHT scenario; (e) Doppler PSD of the model in [8] for UIC scenario; (f) Doppler PSD of the improved model for UIC scenario; (g) Doppler PSD of the model in [8] for OLT scenario; (h) Doppler PSD of the improved model for OLT scenario; (i) Doppler PSD of the model in [8] for UOC scenario; (j) Doppler PSD of the improved model for UOC scenario.**

the model in [8] and the improved model. Due to the similar Doppler PSD for each scenario, for simplicity, we select scenario S to analyze the simulation results. As can be readily observed from Fig. 4a, for scenario S, the maximum Doppler shift $f_{D,\max}$ is about 500 Hz and the type of Doppler PSD is "classic 3dB". Specially, we notice that Doppler PSD of the NGSM [8] shows no dominant LoS component. In Fig. 4b, we show the simulation results of the improved model for scenario S. It is obvious that maximum Doppler shift $f_{D,\max}$ is still 500 Hz and the Doppler PSD is also "classic 3 dB". As expected, Doppler PSD of the improved model has a strong narrow peak in the middle, which is characteristic to communications in presence of LoS component [25]–[27]. Moreover, the energy of taps with fading parameter $\beta < 2$ is obviously lower than that of other taps, which is consistent with the model in [8]. This is because in the improved model, we also employ $\beta < 2$ to describe the severe fading in V2V channels. The excellent agreement between the theoretical and measured Doppler PSD confirms the utility of the improved model. Therefore, the simulation results demonstrate that the improved model also has the ability to mimic the severe fading, keeping the advantages of the model in [8].

To further validate the utility of the proposed model, we compare our model with measurement data and model in [7] as shown in **Fig. 5**. It is clear that Doppler PSD of the model in [7] has a dominant narrow peak in the middle to identify the presence of LoS component, which is consistent with that of the improved model. Therefore, we can conclude that on the basis of maintaining the merits of the model in [8], the improved model can mimic the existence of LoS component and better mimic the characteristics of V2V channels.

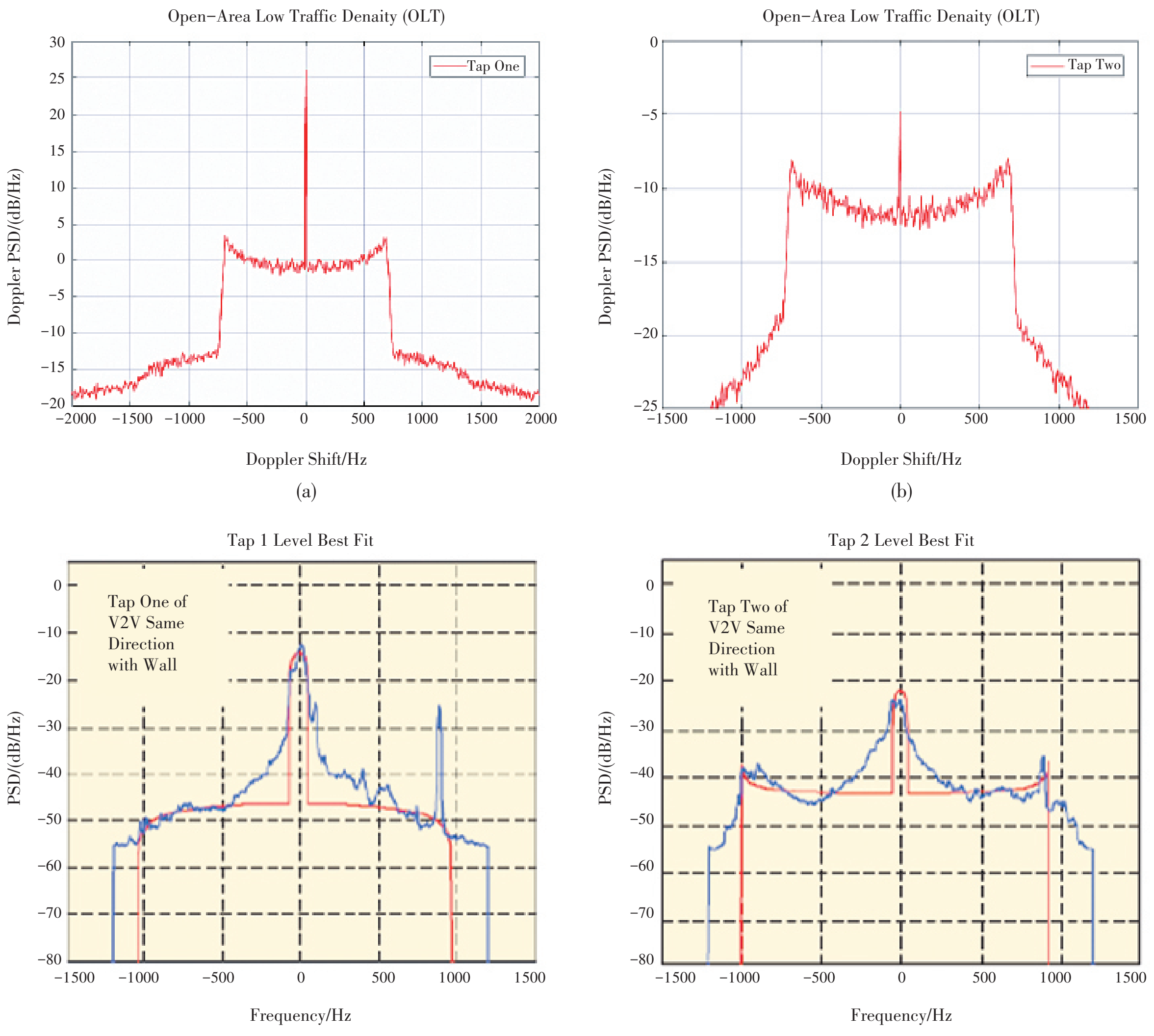
In **Table 1**, we show the tap correlation coefficient matrix of the NGSM in [8] and the improved model for scenario UIC, respectively. The tap correlation coefficient matrix is defined as

$$\rho = \left[r_{i,j}\right] = \frac{\mathrm{cov}\left(\alpha_i,\alpha_j\right)}{\sqrt{\mathrm{var}\left(\alpha_i\right)\mathrm{var}\left(\alpha_j\right)}}$$

where $\left[r_{i,j}\right]$ is the coefficient between tap $i$ and $j$, var(·) denotes variance and cov(·) denotes covariance. Since the correlation coefficient matrix is symmetric about the diagonal, we only need to specify the upper or lower triangular part; for brevity, the lower triangular part corresponds to correlations between taps for the improved model, whereas the upper triangular part corresponds to corre-

**▼Table 1. Correlation matrices of the non-geometrical stochastic model (NGSM) in [8] and improved model for scenario UIC (lower/upper triangular part: improved model/ NGSM in [8])**

| $i$, $j$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| 1 | 1.0000 | 0.1989 | 0.0555 | 0.0481 | 0.0977 | 0.1074 | 0.3504 |
| 2 | 0.1965 | 1.0000 | 0.1477 | 0.1495 | 0.0974 | 0.2329 | 0.1999 |
| 3 | 0.0573 | 0.1411 | 1.0000 | 0.2298 | 0.0106 | 0.1368 | 0.1496 |
| 4 | 0.0474 | 0.1350 | 0.2342 | 1.0000 | 0.2189 | 0.2088 | 0.1143 |
| 5 | 0.1066 | 0.0976 | 0.0152 | 0.2092 | 1.0000 | 0.1600 | 0.0000 |
| 6 | 0.1159 | 0.2363 | 0.1512 | 0.1977 | 0.1524 | 1.0000 | 0.2600 |
| 7 | 0.3249 | 0.1938 | 0.1442 | 0.1211 | 0.0012 | 0.2600 | 1.0000 |



(a) (b)

(c) (d)

PSD: power spectral density V2V: vehicle-to-vehicle

▲**Figure 5. The Doppler PSD of different models. (a) (b) Doppler PSD of the improved model; (c) (d) Doppler PSD of the model in [7].**

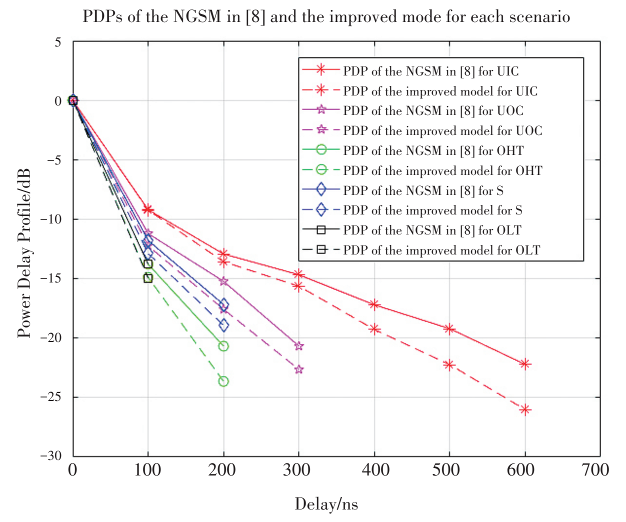
lations between taps for the NGSM in [8]. Through comparison between the corresponding parameters under scenario UIC, we can observe that the corresponding parameters of the improved model only fluctuate with a few correlation coefficient values, but most of them remain consistent. This is because the change of phase distribution does not influence the amplitude of complex Gaussian stochastic process, so this improvement does not have impact on the tap correlation coefficient matrix. The excellent agreement between the simulation results and measured data confirms the utility of the improved model. Therefore, the improved model also has the ability to implement the non-stationarity in frequency domain, maintaining the advantages of the NGSM [8].

**Fig. 6** shows a comparison between the PDP of the NGSM in [8] and the improved model in each scenario: UIC, UOC, OHT, S, and OLT [8]. As can be seen from the figure, both in the NGSM [8] and the improved model, the spread delay in UIC scenario is more severe than others. This is because in the UIC scenario, antenna is inside the vehicles, resulting in more obstacles in channel propagation. We can also notice that in OLT scenario, the scattering and reflection caused by moving vehicles are less than other scenarios with short spread delay, and the energies are concentrated in the first tap, which is also confirmed in the literature [27]. Furthermore, it is obvious that PDP of two models for each scenario has some difference. The cause for this difference is the presence of the dominant LoS component in the improved model. Comparatively speaking, the LoS component is successfully added in the improved model and the energy is more centered in the first path. In this way, the proportion of energy in other paths has a visible decline and the fading is more obvious, which means multipath effect is more apparent as well. Therefore, the comparison of

PDP also validates that the improved model properly includes the LoS component.

As can be seen from the above analysis, we compare the NGSM in [8] with the improved model, and the results can be shown in **Table 2**.

Table 2. shows the comparison results between the NGSM in [8] and the improved model. We can readily observe that both models are based on the assumption of non-WSSUS and describe the severe fading by means of Weibull distribution. In addition, the improved model remains the tap correlation coefficient matrices of the NGSM [8] fortunately, realizing the correlated scattering between each tap. Moreover, from the simulation results of the PDP, it is also obvious that both models implement delay dispersion well. However, compared with the NGSM [8], the improved model includes a dominant LoS component into the Doppler PSD and thus has the ability to describe the presence of LoS component. Consequently, we can conclude that the improved model fills the aforementioned gap and is more accurate to describe the characteristics of V2V channels.



NGSM: non-geometrical stochastic model
PDP: power delay profile
OHT: open-area high traffic density
OLT: open-area low traffice density
S: small city
UIC: urban-antenna inside car
UOC: urban-antenna outside car

**▲Figure 6. PDP of the NGSM in [8] and the improved model for each scenario.**

**▼Table 2. Comparison of the NGSM in [8] and the improved model**

| NGSM in [8] | Improved model |
|---|---|
| non-WSSUS | non-WSSUS |
| severe fading (achieved) | severe fading (achieved) |
| good implementation of delay dispersion | good implementation of delay dispersion |
| the number of taps determined based on the RMS of delay time | the number of taps determined based on the RMS of delay time |
| no description of LoS component | a good description of the LoS component |

LoS: line-of-sight
NGSM: non-geometrical stochastic model
RMS: root-mean-square
WSSUS: wide sense stationary uncorrelated scattering

**Note:** By comparing with the model in [8] as shown in Table 1 and Fig. 4, it is clear that the proposed model can properly mimic the non-stationarity and severe fading. While comparing with the model in [7] as shown in Fig. 5, one can see that the proposed model can mimic the existence of LoS component.

## 4 Conclusions

In this paper, a novel NGSM for non-WSSUS V2V channels has been proposed, which is based on a conventional NGSM in [8]. The proposed NGSM employs a method of generating non-uniformly distributed phase in the Weibull distribution, which extends the NGSM [8] to include the LoS component. It also has been demonstrated by the simulation results that compared with the NGSM [8], the proposed model has added a dominant LoS component into Doppler PSD and thus has explicitly identified the presence of LoS component. Furthermore, the comparison of the PDP has shown that the energy is more centered in the first path in the proposed model. Therefore, it has been verified by the simulation results that the proposed model is more accurate to describe the characteristics of V2V channels.

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