Abstract: This paper derives a non-stationary multiple-input multiple-output (MIMO) from the one-ring scattering model. The proposed channel model characterizes vehicular radio propagation channels with considerations of moving base and mobile stations, which makes the angle of arrivals (AOAs) along with the angle of departures (AODs) time-variant. We introduce the methodology of including the time-variant impacts when characterizing non-stationary radio propagation channels through the geometrical channel modelling approach. We analyze the statistical properties of the proposed channel model including the existing one-ring wide-sense stationary channel model as its special case.

Keywords: vehicular communications; mobile fading channels; non-stationary channels; multiple antennas; geometrical channel modeling; one-ring scattering model

I. INTRODUCTION

Recently, vehicular communications have gained extensive attentions as the large demands for highway intelligence, road safety, collision avoidance, and traffic efficiency [1], [2]. Through vehicle-to-anything technologies, a vehicle is entitled to exchange information with other elements in the networks e.g., vehicles and road infrastructure. The traffic accidents and jams reduce significantly by the exchanged warning messages and road information sent to the drivers through vehicular ad hoc networks (VANETs) [3], [4].

With regard to VANETs, the underlying propagation environments of vehicular communications have significant impacts on the reliability, accuracy and efficiency of the transferred information. Therefore, the deep understanding of vehicular radio propagation channels is essential for investigating and designing vehicular communication systems [5]. Moreover, the research on VANETs mainly relies on simulations because of high cost of constructing the real testbed. It is well motivated to mathematically represent the channel characterizations for vehicular communications. For high mobility vehicular communication environments, the main challenge comes from accurately characterizing the fast variations of mobile radio channels when the transmitters and receivers move in relative high speeds.

For this purpose, the authors in [6], [7] characterize vehicular propagation channels...
through measurements campaigns. The channel parameters or statistical properties are concreted from the experimental results, which are very accurate. However, the channel models developed by this approach are restricted to specific environments and invalid in case of environmental changes.

Alternatively, physical channel models have been developed for various vehicular propagation environments through the geometry-based channel modeling approach. The scatterer locations at the base and mobile stations are modeled by a specific geometric pattern, e.g., one ring and two rings. The narrowband MIMO geometrical channel models were proposed in [8] for vehicle-to-vehicle (V2V) communications, which were further extended in [9], [10] to address the frequency selectivity. The channel characterizations are mathematically represented by the main physical channel parameters, e.g., antenna spacings, AODs, and AOAs. The fundamental knowledge of various radio propagation channels can easily be obtained by changing the channel parameters.

Nevertheless, the temporal variations of AODs and AOAs due to the movement of the BS and MS have not been taken into account in all aforementioned geometrical channel models. The underlying channels turn out to be wide-sense stationary. However, the pre-condition of having constant AODs and AOAs is restricted to very short time intervals within a few tens of the wavelength that the BS (or MS) moves [11], [12]. As shown by the empirical investigations [13], if communication vehicles move at relatively high speeds, the AODs and AOAs turn out to be time-variant, which results in a non-stationary propagation scenario.

The authors in [14]–[17] have contributed on modeling nonstationary propagation channels for vehicular communications. Under the one-ring scattering environments, [14] have developed a non-stationary channel model for the single antenna scenario, in which the base station (BS) is fixed and only the mobile station (MS) moves. The AOA and the direction along which the MS moves have been included in the developed channel model. The impacts of other physical channel parameters on the statistical properties are unknown. Papers [15] and [16] have characterized non-stationary Rayleigh and Double Rayleigh channels for mobile-to-mobile communications, respectively. Authors in [14]–[16] have focused on nonstationary single antenna scenarios, meaning only one antenna is installed at the base and mobile station. A MIMO channel model has been developed based on the T-junction scattering pattern in [17] for V2V propagation channels. Both AODs and AOAs are time dependent due to vehicles’ movements, which indicates the underlying channel non-stationary. The T-junction scattering environment is not a typical driving environment that vehicles experience the most, which limits the use of the developed channel model. Moreover, the assumption of the double-bouncing scattering in [17] brings more restrictions to the applicable situations. The two communicating vehicles need to be located in two separate streets and move in a small range close to the junction.

Given both the MS and BS in motion, this paper models non-stationary mobile radio channels, which serves vehicular communications. Multiple antenna scenarios are concentrated in this paper, which differs with [14]. The scattering conditions at the MS are characterized by the well-known one-ring geometry model [18], [19], i.e., all scatterers are placed on a circle. However, we remove the assumption made in [18], [19] that the ring’s radius is much smaller than the distance between the mobile and base stations. All the considerations, i.e., non-stationary scenarios, moving BS and MS, and removed assumption, bring a totally new form to the mathematical channel model. We present the methodology of introducing the time-variant influence when modeling non-stationary propagation environments through the geometrical channel modeling approach. The influence of time-dependent AODs and AOAs are investigated. The complex channel gain is formulated as a
function with more physical channel parameters included. Thus, the derived mathematic model enables to characterize non-stationary fading behaviors of given propagation scenarios more precisely. The statistical properties of the derived model are analyzed with emphasis not only on the local ACF but also on the space CCF. It is essential to investigate the space CCF since both theory and simulations indicate that antenna spacings have strong impacts on the vehicular communication system performance. We also demonstrate that our proposed non-stationary one-ring channel model reduces to the wide-sense stationary one existing in [19] when considering the special case of constant AODs and AOAs.

The remaining contents of the paper are organized into five sections. We first review the one-ring geometry scattering model in Section II. Then, the time-dependent AODs and AOAs are studied in this section. Section III presents the mathematical expressions of the geometrical non-stationary one-ring channel model. Section IV addresses the statistical properties including the time ACF and space CCF. Section V shows the numerical results. Last but not least, Section VI gives the concluding remarks.

II. ONE-RING SCATTERING MODEL

This section concisely reviews the one-ring MIMO scattering model, which has been employed in [18], [19] for modeling stationary scenarios. It is depicted in figure 1 that at the BS, $M_T$ transmit antennas are installed with the orientation denoted by the angle $\alpha_T$. The antenna spacing is $\delta_T$. The MS is surrounded with $N$ scatterers $S_{SR}^{(n)}$, which are situated over a circle with radius $R$. At the MS side, there are $M_R$ antennas separated by the antenna spacing $\delta_R$. These antennas are tilted at the angle $\alpha_R$.

At reference time $t = 0$, the MS is located at the $(0,0)$ of the $xy$-plane with a distance $D$ away from the BS. The initial AOA, represented by $\phi_R^{(n)}$, is the orientation of the plane-wave bounced by the $n$th scatterer before arriving at the original MS position $O_R$. The BS is originally situated on $x$-axis. The orientation of the plane-wave originating from the BS and reflected by the $n$th scatterer is depicted by the angle $\phi_T^{(n)}$, namely AOD.

Furthermore, as shown in figure 2, the MS moves at a fixed velocity $v_R$ along with the direction specified by the motion angle $\beta_R$. Suppose that at time $t$, the MS reaches the new position $O_R'$. The values of the AOAs change against time $t$. For convenience, we represent the time-dependent AOAs by

Fig. 1. Geometrical one-ring scattering model with scatterer $S_{SR}^{(n)}$ surrounding the MS.

Fig. 2. Geometrical one-ring scattering model with moving BS and MS; time-variant AODs $\phi_T^{(n)}(t)$ and AOAs $\phi_R^{(n)}(t)$.
\( \phi_s^{(n)}(t) \), which specifies the propagation direction of the plane-wave reaching the new MS’s location \( O_n' \) through the \( n \)th scatterer. The BS moves at a speed \( v_T \) with the angle of motion \( \beta_T \). At time \( t \), the BS moves to the point \( O_n' \).

Similarly, the AOD also depends on time due to the moving BS. We use \( \phi_k^{(n)}(t) \) to represent the angle of departure from the BS located at \( O_n' \) and bounced by the \( n \)th scatterer.

The time-dependent AOA \( \phi_k^{(n)}(t) \) and AOD \( \phi_k^{(n)}(t) \) can be calculated by

\[
\phi_k^{(n)}(t) = \text{atan2}(y_n - D_{k,n} \cos \beta_n, x_n - D_{k,n} \sin \beta_n) \quad (1a)
\]

\[
\phi_k^{(n)}(t) = \text{atan2}(y_n - D_{k,n} \cos \beta_n, x_n) - D_{k,n} \cos \beta_n + D) \quad (1b)
\]

where \( \text{atan2}(y, x) \) is the four-quadrant inverse tangent function, \( D_{k,n} \) denotes the distance that the MS moves during the interval \([0, t]\) and \( D_{k,n} \) represents the distance that the BS moves in this time slot. The symbol \( x_n \) and \( y_n \) are the coordinates of the \( n \)th scatterer.

The AOA \( \phi_k^{(n)}(t) \) and AOD \( \phi_k^{(n)}(t) \) in eq. (1) are nonlinear functions against time \( t \). The AOA and AOD turn out to be linear function by expanding them in Taylor series at \( t = 0 \). If we keep the first two terms, the AOA \( \phi_k^{(n)}(t) \) and AOD \( \phi_k^{(n)}(t) \) can be expressed as

\[
\phi_k^{(n)}(t) = \phi_k^{(n)}(0) + \xi_n \cdot t \quad (2a)
\]

\[
\phi_k^{(n)}(t) = \phi_k^{(n)}(0) + \gamma_n \cdot t \quad (2b)
\]

where

\[
\phi_k^{(0)} = \text{arctan2}(y_n, x_n) \quad (3a)
\]

\[
\phi_k^{(b)} = \text{arctan2}(y_n, x_n + D) \quad (3b)
\]

\[
\xi_n = \frac{\partial \phi_k^{(n)}(t)}{\partial t} \bigg|_{t=0} = \frac{v_T}{R} \sin(\phi_k^{(n)}(0) - \beta_n) \quad (3c)
\]

\[
\gamma_n = \frac{\partial \phi_k^{(n)}(t)}{\partial t} \bigg|_{t=0} = Rv_T \sin(\phi_k^{(n)}(0) - \beta_n) - Dv_T \cos \beta_n \quad (3d)
\]

According to the geometrical relationship, we find that the original AOD \( \phi_k^{(n)}(t) \) in eq.(3d) is related with the AOA \( \phi_k^{(n)}(t) \) by the following equation

\[
\phi_k^{(n)} = \arcsin \frac{R \sin \phi_k^{(n)}}{\sqrt{D^2 + R^2 + 2DR \cos \phi_k^{(n)}}}. \quad (4)
\]

As presented in eq.(2b), the time-variant AODs \( \phi_k^{(n)}(t) \) depend on the constant AODs \( \phi_k^{(n)} \). Therefore, the time-variant AODs \( \phi_k^{(n)}(t) \) can be finally expressed by a function related with \( \phi_k^{(n)} \) instead of \( \phi_k^{(n)}(t) \) if we submit eq. (4) into eq.(3d). To keep simplicity, we present the time-variant AODs by the general term \( \phi_k^{(n)}(t) \) in all formulæ of the paper where the time-variant AODs appear.

### III. Non-Stationary MIMO

#### Channel Model Under One-Ring Scattering Environments

**3.1 Channel impulse response**

This subsection is devoted to the derivation of the mathematical expression for the channel impulse response. Based on the plane-wave propagation principle, the channel impulse response between the antenna \( A_l \) and the antenna \( A_k \) is calculated by

\[
h_k(l) = \sum_{n=1}^{N} E_n \cdot \exp\left(-j \frac{2\pi}{\lambda} D_{nl} \cdot (\phi_k^{(n)}(t) - \beta_k)\right). \quad (5)
\]

In eq.(5), \( E_n = 1/\sqrt{N} \) represents the constant gain. The phase shift \( \theta_n \) follows the uniform distribution in the interval \([0,2\pi)\) [18].

The phase change \( \tilde{k}_r \cdot \tilde{r}_n \) and \( \tilde{k}_r \cdot \tilde{r}_n \) due to the motions of the BS and the MS are given by

\[
\tilde{k}_r \cdot \tilde{r}_n = -2\pi f_{\text{sec}} \cos \left(\phi_k^{(n)}(t) - \beta_k\right) \quad (6a)
\]

\[
\tilde{k}_r \cdot \tilde{r}_n = 2\pi f_{\text{sec}} \cos \left(\phi_k^{(n)}(t) - \beta_k\right) \quad (6b)
\]

The phase change \( k_0 \cdot D_{nl}(t) \) in eq.(5) caused by the total propagation distance can be expressed by

\[
k_0 \cdot D_{nl}(t) = \frac{2\pi}{\lambda} \left[ D_{nl}(t) + D_{nl}(0) \right] \quad (7)
\]

where \( \lambda \) is the wavelength.

As the BS and the MS move, the positions of the antennas vary against time. At time \( t \), the new location of the \( k \)th receive antenna is denoted in figure 2 by \( A_k^{(n)} \). The \( l \)th transmit
antenna reaches \( A_{r, n}^{(k)} \). The time-dependent term \( D_{n}^{(k)}(t) \) in eq. (7) represents the total propagation distance of the \( n \) th plane-wave from \( A_{r, n}^{(k)} \) through \( S_{k}^{(n)} \) to \( A_{r}^{(k)} \). The total propagation distance \( D_{n}^{(k)}(t) \) is composed by two part: the plane-wave travelling distance from the \( n \)th scatterer to \( A_{r}^{(k)} \) denoted by \( D_{n}(t) \) and the distance of the plane-wave emitted from the \( l \)th transmit antenna \( A_{r, l}^{(k)} \) reaching the obstacle \( S_{k}^{(n)} \), denoted by \( D_{n}(t) \).

If we apply the law of cosine to the triangle \( O_{r}^{(k)} S_{k}^{(n)} A_{r}^{(k)} \) and consider the assumption \((M_{r} - 1)\delta_{r} << R\) that usually made in the one-ring scattering model, \( D_{n}(t) \) in eq.(7) is approximated as

\[
D_{n}(t) \approx D_{S, O_{r}}(t) - \frac{(M_{r} - 2k + 1)\delta_{r}}{2} \cos(\phi_{r}^{(n)}(t) - \alpha_{r}),
\]

where \( D_{S, O_{r}}(t) \) is the distance from the \( n \)th scatterer to \( O_{r}^{(k)} \) (see figure 2). The distance \( D_{S, O_{r}}(t) \) is calculated by the law of sine from the triangle \( O_{r}^{(k)} S_{k}^{(n)} O_{r}^{(k)} \) as below

\[
D_{S, O_{r}}(t) = R \cdot \psi_{s}(t),
\]

\[
\psi_{s}(t) = \frac{\sin(\phi_{r}^{(n)} - \beta_{r})}{\sin(\phi_{r}^{(n)} + \xi_{n} \cdot t - \beta_{r})}.
\]

Similarly, applying the law of sine (cosine) to the geometry at the BS, the distance \( D_{n}(t) \) in eq. (7) can be written as

\[
D_{n}(t) = D_{S, O_{r}}(t) - \frac{(M_{r} - 2l + 1)\delta_{r}}{2} \cos(\phi_{r}^{(n)}(t) - \alpha_{r}),
\]

where

\[
D_{S, O_{r}}(t) = D_{S, O_{r}} \cdot \phi_{r}(t)
\]

\[
D_{S, O_{r}} = \sqrt{D^{2} + R^{2} + 2DR\cos(\phi_{r}^{(n)})}
\]

\[
\phi_{r}(t) = \frac{\sin(\phi_{r}^{(n)} - \beta_{r})}{\sin(\phi_{r}^{(n)} + \gamma_{r} \cdot t - \beta_{r})}.
\]

Submitting the equations (6)-(11) into (5), we obtain the mathematic expression of the channel impulse response

\[
h_{n}(t) = \frac{1}{\sqrt{N}} \sum_{n=1}^{N} a_{r, n}(t) \cdot b_{s, n}(t) e^{j \left[ (2\pi f_{r}(t) + \phi_{r}^{(n)}(t) + \theta_{r} + \delta_{r}(t)) \right]},
\]

where

\[
a_{r, n}(t) = e^{j \left[ \pi (M_{r} - 2l + 1) \frac{\delta_{r}}{2} \cos(\phi_{r}^{(n)}(t) - \alpha_{r}) \right]},\]

\[
b_{s, n}(t) = e^{j \left[ \pi (M_{r} - 2k + 1) \frac{\delta_{r}}{2} \cos(\phi_{r}^{(n)}(t) - \alpha_{r}) \right]},\]

\[
f_{r, n}(t) = f_{r, s} \cdot \cos(\phi_{r}^{(n)}(t) - \beta_{r}),\]

\[
f_{r, n}(t) = f_{r, s} \cdot \cos(\phi_{r}^{(n)}(t) - \beta_{r}),\]

\[
\theta_{r}(t) = \frac{2\pi}{\lambda} \left( \sqrt{D^{2} + R^{2} + 2DR\cos(\phi_{r}^{(n)})} \right) \cdot \psi_{s}(t) + R \cdot \psi_{s}(t).\]

### 3.2 Special case with constant AOAs and AODs

In this subsection, we discuss a wide-sense scenario that has been widely investigated in literature [18], [19], where the BS is fixed and the MS moves. The AOAs and AODs are constant.

For constant AOAs, \( \phi_{r}^{(n)}(t) \) in eq.(2a) equals to \( \phi_{r}^{(n)} \) and \( \xi_{n} = 0 \). Similarly, if the AODs are constant, \( \psi_{s}(t) \) in eq.(2b) equals to \( \phi_{r}^{(n)} \) and \( \gamma_{r} = 0 \). For this special case, the time-variant terms \( \psi_{s}(t) \) and \( \phi_{r}(t) \) reduce to constant 1. Since the BS is fixed, the Doppler frequency \( f_{r}(t) \) in eq.(13c) reduces to 0. Moreover, the instantaneous Doppler frequency \( f_{r}(t) \) in eq.(13d) is simplified to time independent Doppler frequency \( f_{r} = f_{r, s} \cdot \cos(\phi_{r}^{(n)} - \beta_{r}) \). In addition, if we consider the assumption made in [18], [19] that ring’s radius \( R \) is much smaller than the distance \( D \) between the base and mobile stations. The AODs are related with the AOAs in a simpler form. The expression in eq. (4) reduces to \( \phi_{r}^{(n)} = R/D \cdot \sin(\phi_{r}^{(n)}) \), which has been used to develop wise-sense stationary channel models in [18], [19]. Following all the simplifications, the channel impulse response in (12) reduces to the time-invariant channel impulse response presented in [18], [19] for the wide-sense stationary one-ring MIMO channel model. Since it is out of the main focus of the paper, the mathematical equations for wise-sense scenarios will not be duplicated here.
IV. STATISTICAL CHARACTERIZATION

4.1 Time-variant ACF

The following equation defines the temporal ACF of the channel model

\[ r_{nn}(\tau, t) = E\left\{ h_{nn}\left( t + \frac{\tau}{2}\right) h_{nn}^\ast\left( t - \frac{\tau}{2}\right) \right\} \]  

where \( E \{ \} \) calculates the expectation and \( (\cdot)^\ast \) takes the complex conjugation. After submitting eq. (12) into eq. (14) and carrying out mathematical calculations, we finally obtain the expression of the ACF as below

\[ r_{nn}(\tau, t) = \frac{1}{N^2} \sum_{n=1}^{N} e^{-\frac{j2\pi}{\lambda_{n}} \left[ \frac{1}{2} (R_{t} + R_{n}) \cos \phi_{Rn}^\ast - R_{n} \cos \phi_{Rn} \right]} \]  

(16)

where \( \text{sinc}\{\} \) denotes the sinc function given by \( \text{sinc}(x) = \sin(x)/x \). In the equations above, \( f_{\tau}(t) \) and \( f_{\kappa}(t) \) are the derivatives of the Doppler frequencies \( f_{\tau}(t) \) and \( f_{\kappa}(t) \) with respect to time \( t \). We have

\[ f_{\tau}(t) = -f_{\tau_{m}} \cdot \lambda_{m} \cdot \sin(\phi_{Rm}^\ast + \gamma_{m} t - \beta_{R}) \]  

(16a)

\[ f_{\kappa}(t) = -f_{\kappa_{m}} \cdot \lambda_{m} \cdot \sin(\phi_{Rm}^\ast + \xi_{m} t - \beta_{R}) \]  

(16b)

As observed from eq. (15), the ACF of the underlying channel model is a function of time separation \( \tau \) as expected. Besides, the ACF also depends on time \( t \). For the special case discussed in Subsection III-B, the BS is fixed and the AOA s \( \phi_{Rm}^\ast \) are constant, i.e., \( \xi_{m} = 0 \), the time-dependent ACF reduces to

\[ r_{nn}(\tau) = \frac{1}{N^2} \sum_{n=1}^{N} e^{-\frac{j2\pi}{\lambda_{n}} f_{\tau_{m}} \tau} \]  

(17)

which is the ACF for the wide-sense stationary case [19]. In this scenario, the ACF becomes independent on time \( t \) and close to the shape of the 0th Bessel function.

4.2 Time-variant CCF

The space cross correlation function of the channel model is defined as

\[ \rho_{h_{h_{h_{h}}}}(\delta_{\tau}, \delta_{k}, t) = E\left\{ h_{h_{h}}(t) \cdot h_{h}^\ast(\cdot) \right\} \]  

(18)

After submitting eq. (12) into eq. (18), we obtain the time-variant space CCF given by

\[ \rho_{h_{h_{h}}}(\delta_{\tau}, \delta_{k}, t) = \frac{1}{N} \sum_{n=1}^{N} e^{j\pi (\delta_{\tau} + \phi_{Rn}^\ast - \gamma_{n} t - \beta_{R})} \]  

(19)

The three-dimensional (3D) time-variant CCF in eq. (19) will reduce to a two-dimensional (2D) CCF for the situation described in Subsection III-B, which is time-invariant and only related with the antenna spacings at both stations. The expression of 2D CCF is aligned with the 2D CCF presented in [19] for the wide-sense MIMO one-ring model if we follow the assumption \( R \ll D \) made in [19]. We can derive the 2D spatial correlation function at the BS (or MS) from the 3D CCF in eq. (19) by setting \( k' = k \) (or \( l' = l \)). Analytical expressions are presented as below

\[ \rho_{h_{h_{h}}}(\delta_{\tau}, t) = \frac{1}{N} \sum_{n=1}^{N} e^{j\pi (\delta_{\tau} + \phi_{Rn}^\ast - \gamma_{n} t - \beta_{R})} \]  

(20a)

\[ \rho_{h_{h_{h}}}(\delta_{k}, t) = \frac{1}{N} \sum_{n=1}^{N} e^{j\pi (\delta_{k} + \phi_{Rn}^\ast + \xi_{n} t - \beta_{R})} \]  

(20b)

V. NUMERICAL RESULTS

This section illustrates the analytical findings through several numerical examples.

For this purpose, we assume a propagation environment that the MS is surrounded with \( N = 20 \) scatterers placed on a circle with radius \( R = 200m \). The distance \( D \) between two stations is \( 2000m \). The MS moves at speed \( v_{R} = 110km/h \) along with the motion angle \( \beta_{R} = 60\degree \). The BS moves at the velocity \( v_{T} = 120km/h \) in the direction of \( \beta_{T} = 120\degree \). The maximum Doppler frequency \( f_{\text{max}} \) is set to 91Hz and \( f_{\text{min}} = 100Hz \). The BS has \( M_{R} = 2 \) transmit antennas with the tilt angle \( \alpha_{R} = 30\degree \), whereas the MS has \( M_{g} = 2 \) receive antennas with the tilt angle \( \alpha_{g} = 60\degree \). The initial AOA s \( \phi_{R}^{\ast} = \phi_{g}^{\ast} \) are determined by certain pa-
Subsection III-B. The time-dependent ACF in eq. (15) follows the 0th order Bessel function and independent on time \( t \), which indicates that the channel becomes wide-sense stationary.

Figure 3 depicts the time-variant ACF \( r_{hh}(\tau, t) \) of the proposed non-stationary model. We can see from this figure that at \( t = 0 \), the ACF follows the shape of the 0th order Bessel function. However, as time \( t \) proceeds, the ACF differs more and more. This is clearly shown through figure 4, where 3 snapshots of the \( r_{hh}(\tau, t) \) at time \( t = 0s, t = 1s \), and \( t = 1.5s \) were captured.

Figure 5 illustrates the special case having constant AOAs, which has been discussed in parameter calculation methods. Here, we adopt the extended method of exact Doppler spread [20] to calculate the original AOAs and we have \( \phi_{n}^{(n)} = \frac{2\pi}{N} \left( \frac{m - 1}{4} \right) \).

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VI. CONCLUSION

This paper was devoted to derive a non-stationary MIMO channel model for vehicular communications. We modeled the scatterers around the MS by a ring pattern. Different with traditional one-ring scattering environments, we considered that both the base and mobile stations are in motion. We removed the assumption made in the traditional one-ring channel model that ring’s radius is much smaller than the distance between the two stations. All the considerations brought a totally new form for the mathematical channel model. We presented the methodology of including the time-variant influence when characterizing non-stationary channels by the geometrical channel modeling approach. We also studied the local ACF and 3D space CCF of the model. It can be seen from theory and numerical results that the statistical properties of non-stationary channel models change against time. We demonstrated that our non-stationary channel model includes the existing wide-sense stationary one-ring channel model as its special case.

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Fig. 7. CF \( \rho_{bb} (\delta \lambda, t) = \rho_{bb} (\delta \lambda, t) \) of the developed channel model with the constant AOAs \( \phi_b \).

Fig. 8. Time-dependent CF \( \rho_{bb} (\delta \lambda, t) \) of the developed channel model with the time-variant AOAs \( \phi_b(t) \).


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