Modeling of Vehicle-to-Vehicle Channels in the Presence of Moving Scatterers

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***Abstract*—In this paper, we derive a vehicle-to-vehicle (V2V) channel model assuming a typical propagation scenario in which the local scatterers move with random velocities in random directions. The complex channel gain of the proposed V2V channel model is provided. Subsequently, for different scatterer velocity distributions, the corresponding autocorrelation functions (ACFs) are derived, illustrated, and compared with the classical ACF derived under the assumption of fixed scatterers. Furthermore, under specific conditions, highly accurate approximations for the ACFs are provided in closed form. Since the proposed V2V channel model covers several communication scenarios as special cases, including fixed-to-vehicle (F2V) and fixed-to-fixed (F2F) scenarios in the presence of both fixed and moving scatterers, it is obvious that the presented results are important for the designers of cutting-edge vehicular communication systems.**

***Index terms* — Channel modeling, vehicle-to-vehicle channels, fixed-to-vehicle channels, fixed-to-fixed channels, moving scatterers**

I. INTRODUCTION

Vehicular communications has emerged as a promising technology to effectively reduce the number of road accident deaths and injuries. For the development of future V2V communication systems, a deep knowledge of the underlying fading channel characterizations is essential. Different V2V channel models have been proposed in the literature. As an example, the two-ring channel model for V2V communications has been proposed, e.g., in [1] and [2]. In an empirical study, a measured frequency-selective V2V channel has been presented in [3].

The majority of channel models in the literature relies on the assumption of the stationarity of the scatterers. However, moving scatterers are unavoidable. Moving foliage, walking pedestrians, and passing vehicles are only some few examples of scatterers in motion, which can be found in most of the radio propagation areas. In V2V communication systems, the frequency spread of the received signal is a result of the Doppler effect. This effect originates mainly from the moving transmitter and the receiver. However, even if the transmitter and the receiver are fixed (F2F communication), the received signal still experiences Doppler effect [4]. This means moving scatterers can be a significant source of Doppler spread, more especially at millimeter wavelengths [5]. This phenomenon was studied empirically in [6] and [7], as well as analytically in [5] and [4]. In [4], the ACF of an F2F communication link surrounded by moving scatterers was derived. There, it was shown that the velocity of moving scatterers can be modeled appropriately by an exponential distribution function. In [4], Pham *et al.* solely focused on an F2F channel in which the moving scatterers are located on a ring centered on a fixed receiver.

In this paper, we derive a model for a V2V channel without imposing any constraints on the position of the moving scatterers. Starting from the corresponding complex channel gain, we derive the temporal ACF in an integral form, which will then be simplified and examined assuming different scatterer velocity distributions. For the Gaussian, exponential, uniform and the Laplace scatterer velocity distributions, the derived ACF is illustrated and compared with the classical ACF derived under the assumption of fixed scatterers. Under specific conditions, highly accurate closed-form approximations for the derived ACF are provided.

The novelty of this paper arises from the following features. First, owing to the generality of our proposed geometrical model, one is able to derive the ACF of the one-ring, two-ring, and elliptical model from the presented ACF of this paper. Second, the presented V2V channel model includes the F2V and F2F channel models as special cases. Furthermore, the classical channel model, where the local scatterers move with deterministic velocities, can be obtained as a special case of the proposed stochastic model.

The remainder of this paper is organized as follows. Section II presents the propagation scenario by means of a geometrical scattering model. The complex channel gain is presented in Section III. Section IV investigates the ACF of the fading channel, derives its approximation, and illustrates its behavior. Finally, Section V summarizes our main findings and draws the conclusions.

II. THE GEOMETRICAL SCATTERING MODEL

The geometrical scattering model presented in Fig. 1 is an appropriate model to describe typical propagation scenarios in urban areas, where both the transmitter and the receiver vehicles are surrounded by N local scatterers denoted by S_n $(n = 1, 2, ..., N)$. It is assumed that the transmitter and the receiver move with constant velocities v_T and v_R in the directions determined by the fixed angles α_v^T and α_v^R, respectively. Each of the local scatterers S_n $(n = 1, 2, ..., N)$ is in motion with a random velocity v_{S_n} in a random direction determined by $\alpha_v^{S_n}$. Owing to high path loss, we neglect the contributions from remote scatterers and assume that a

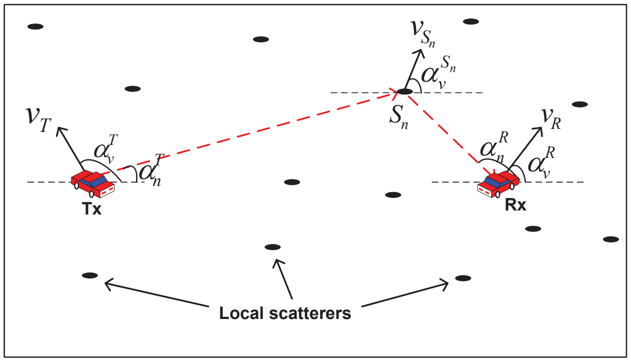

Fig. 1. Typical propagation scenario with moving transmitter (Tx) and moving receiver (Rx) illustrating the effect of single-bounce scattering in the presence of moving scatterers.

wave emitted from the transmitter vehicle at an angle-of-departure (AoD) α_n^T reaches the receiver vehicle at an angle-of-arrival (AoA) α_n^R after a single bounce by the nth moving scatterer S_n inside the propagation area.

III. Channel Characterization

The described propagation scenario is an extended version of the typical fixed-to-mobile scenario with fixed scatterers studied in [8, pp. 56–60]. It was shown there that the complex channel gain of frequency-nonselective F2V channels can be modeled by

$$\mu(t) = \sum_{n=1}^{N} c_n e^{j(2\pi f_n t + \theta_n)}. \tag{1}$$

This gain is a complex stochastic process representing the sum of all scattered components, in which c_n designates the attenuation factor caused by the interaction of the emitted wave with the nth scatterer S_n, and and f_n represents the Doppler frequency[1] caused by the movement of the receiver. Moreover, the random variable θ_n denotes the phase shift of the nth path, which is usually assumed to be uniformly distributed between 0 and 2π [8]. The channel impulse response described above cannot directly be used to model the propagation scenario in Section II. To make it compatible, the effects of both the moving transmitter and the moving scatterers have to be considered. Indeed, the main differences between the proposed V2V channel in the presence of moving scatterers and the model presented in [8], are the additional Doppler shifts caused by the mobile transmitter and the moving scatterers. To capture the overall Doppler effect caused by the moving vehicles and the moving scatterers, we have to replace f_n in (1) by

$$f_n = f_n^T + f_n^{TS} + f_n^{SR} + f_n^R. \tag{2}$$

In the equation above, the first frequency shift f_n^T is caused by the movement of the transmitter. The second shift f_n^{TS} is due to the fact that the transmitted signal impinges on the nth moving scatterer. The third frequency shift f_n^{SR} is the contribution which arises when the moving scatterer redirects the signal to the receiver. Finally, the last Doppler shift f_n^R is due to the movement of the receiver. The four Doppler components in (2) can be written explicitly as

$$
\begin{aligned}
f_n^T &= f_0 \frac{v_T}{c_0} \cos\left(\alpha_v^T - \alpha_n^T\right) && (3)\\
f_n^{TS} &= (f_0 + f_n^T) \frac{v_{S_n}}{c_0} \cos\left(\pi + \alpha_n^T - \alpha_v^{S_n}\right) \\
&\approx -f_0 \frac{v_{S_n}}{c_0} \cos\left(\alpha_n^T - \alpha_v^{S_n}\right) && (4)\\
f_n^{SR} &= (f_0 + f_n^{TS}) \frac{v_{S_n}}{c_0} \cos\left(\pi + \alpha_v^{S_n} - \alpha_n^R\right) \\
&\approx -f_0 \frac{v_{S_n}}{c_0} \cos\left(\alpha_v^{S_n} - \alpha_n^R\right) && (5)\\
f_n^R &= (f_0 + f_n^{SR}) \frac{v_R}{c_0} \cos\left(\alpha_v^R - \alpha_n^R\right) \\
&\approx f_0 \frac{v_R}{c_0} \cos\left(\alpha_v^R - \alpha_n^R\right), && (6)
\end{aligned}
$$

where the approximations come from the fact that the Doppler shifts $f_n^{(\cdot)}$ are negligible compared to the carrier frequency f_0. Obviously, no modifications on the path gains c_n and the phase shifts θ_n need to be done. Accordingly, in the presence of moving scatterers, the complex channel gain of the considered V2V channel can be modeled by (1), in which we replace f_n by

$$
\begin{aligned}
f_n = \frac{k_0}{2\pi} \Big[& v_T \cos\left(\alpha_v^T - \alpha_n^T\right) - v_{S_n} \Big(\cos\left(\alpha_n^T - \alpha_v^{S_n}\right) \\
& + \cos\left(\alpha_v^{S_n} - \alpha_n^R\right) \Big) + v_R \cos\left(\alpha_v^R - \alpha_n^R\right) \Big], \qquad (7)
\end{aligned}
$$

where $k_0 = 2\pi f_0 / c_0$ denotes the free-space wave number.

Note that if the number of paths N tends to infinity, then one may invoke the central limit theorem, which states that the complex channel gain $\mu(t)$ in (1) equals a complex-valued Gaussian process with zero mean and variance $2\sigma_0^2 = \lim_{N\to\infty} \sum_{n=1}^{N} E\{c_n^2\}$ [8].

IV. The ACF of the V2V Channel Model

In this section, we first derive an exact expression of the ACF of the proposed V2V channel model in an integral form. Then, a closed-form approximation for the obtained ACF will be presented and its accuracy will be discussed.

A. Exact Solution of the ACF

The ACF of the channel can be determined by using the definition

$$r_{\mu\mu}(\tau) := E\left\{\mu^*(t)\mu(t+\tau)\right\}, \tag{8}$$

in which $E\{\cdot\}$ denotes the expectation operator. Substituting (1) in (8) gives us

$$
\begin{aligned}
r_{\mu\mu}(\tau) &= \lim_{N\to\infty} \lim_{M\to\infty} \sum_{n=1}^{N} \sum_{m=1}^{M} c_n c_m \\
&\times E\left\{ e^{j(2\pi(f_m - f_n)t + (\theta_m - \theta_n) + 2\pi f_m \tau)} \right\}. \qquad (9)
\end{aligned}
$$

[1] The frequency shift caused by the Doppler effect is given by $f = f_{\max}\cos(\alpha)$, where $f_{\max} = f_0 v / c_0$ denotes the maximum Doppler frequency, f_0 is the carrier frequency, c_0 denotes the speed of light, and α is the angle between the AoA and the angle of movement [9].

The expectation has to be performed regarding the uniformly distributed random phases as well as the Doppler frequencies in (2). Computing first the expected value with respect to θ_m and θ_n and noticing that $E\{e^{j(\theta_m-\theta_n)}\}$ equals 1 for $m = n$ and 0 for $m \neq n$ result in

$$r_{\mu\mu}(\tau) = \lim_{N\to\infty} \sum_{n=1}^{N} c_n^2 E\{e^{j2\pi f_n \tau}\}. \tag{10}$$

Under the assumption of isotropic scattering, meaning the AoA α^R is uniformly distributed between 0 and 2π, it can be concluded that all path gains c_n have the same size, namely $c_n = \sigma_0\sqrt{2/N}$ [8]. In this case, we find the ACF of the underlying V2V channel model as presented in (11) [see the top of the next page], in which $p_{\alpha_v^S}(\alpha_v^S)$ and $p_{v_S}(v_S)$ denote the distribution of the direction and the distribution of the velocity of the moving scatterers, respectively. Furthermore, $p_{\alpha^T\alpha^R}(\alpha^T,\alpha^R)$ describes the joint distribution of the AoD α^T and the AoA α^R. From the general expression of the ACF in (11), different special cases can be derived. As an example, an F2V scenario with fixed scatterers is obtained by setting both v_T and v_S to zero. In this case, the ACF results in $r_{\mu\mu}(\tau) = 2\sigma_0^2 J_0(k_0 v_R \tau)$, where $J_0(\cdot)$ denotes the zeroth-order Bessel function of the first kind. This model is known in the literature as the Jakes model [9]. Furthermore, an F2F scenario with moving scatterers can be obtained by setting $v_T = v_R = 0$. Assuming a uniform distribution between 0 and 2π for $\alpha_v^{S_n}$, and arranging the local scatterers on a ring around the receiver, the asymptotic result reported in [4, Eq. (17)] can be derived from (11) as another special case.

Let us return to the V2V communication scenario and assume that the AoD α^T is uniformly distributed between 0 and 2π. The same assumption holds for $\alpha_v^{S_n}$. It is also assumed that α^T is independent of AoA α^R. Now, if $v_S = 0$, the ACF in (11) results in $r_{\mu\mu}(\tau) = 2\sigma_0^2 J_0(k_0 v_T \tau) J_0(k_0 v_R \tau)$, which equals the ACF of the classical V2V channel model in the presence of fixed scatterers reported in [1, Eq. (46)] and [2, Eq. (19)]. If $v_S \neq 0$, one can integrate over the uniformly distributed variable $\alpha_v^{S_n}$ in (11), which simplifies the ACF $r_{\mu\mu}(\tau)$ to (12) [see the top of the next page]. The latter presentation of the ACF has an appropriate form to be examined with different scatterer velocity distributions.

We have used the Gaussian, Laplace, and the uniform distributions to describe the velocity of fast moving scatterers. While, the exponential and the uniform distributions have been chosen to model the velocity of slow moving scatterers. In fact, since the scatterer velocity v_S is always positive or equal to zero, the negative tail of the Gaussian or the Laplace distribution avoids us to describe the velocity of slow moving scatterers by these distributions. However, this negative tail can be neglected if the average velocity is chosen sufficiently large. In this regard, the average scatterer velocity under the assumption of both the Laplace and the Gaussian distributions has been set to $m_{v_S} = 10$ m/s. While their variance equals $\sigma_{v_S}^2 = 1$.

Figures 2 and 3 demonstrate the ACF of the V2V link in the presence of moving scatterers for different scatterer

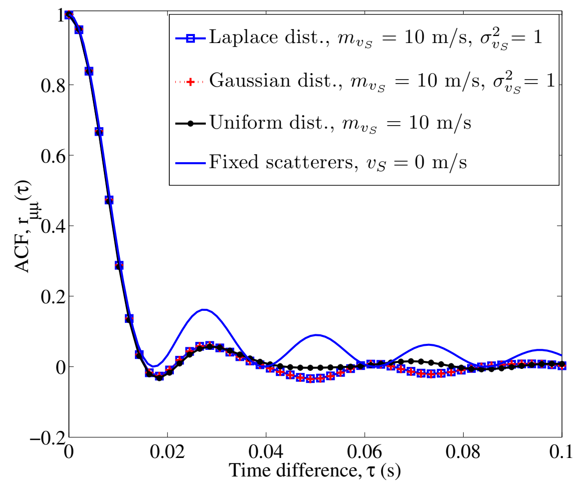

Fig. 2. The behavior of the ACF in (12) for a V2V scenario with fast moving scatterers and $v_T = v_R = 22.22$ m/s. The signal power $2\sigma_0^2$ has been set to 1.

velocity distributions. For comparison reasons, these figures also show the results for the case of fixed scatterers. As can be seen in Fig. 2, there exists a considerable difference between the ACF of the V2V link in the presence of fast moving scatterers with an average speed of $m_{v_S} = 10$ m/s and the ACF corresponding to fixed scatterers, $v_S = 0$. However, referring to Fig. 3, the ACF of the V2V link in the presence of slow moving scatterers with an average speed of $m_{v_S} = 1$ m/s closely follows the ACF corresponding to fixed scatterers. This comparison allows us to conclude that foliage movements, which can be considered as slow moving scatterers, are not a significant source of the Doppler shifts. However, passing vehicles, which can be regarded as fast moving scatterers, contribute considerably to the Doppler effect. Furthermore, as can be observed in Fig. 2, different scatterer velocity distributions result in separate curves for the ACF. To find the best statistical description for the velocity of the scatterers, comparisons between the illustrated ACFs and measurement data need to be done.

To illustrate the effect of moving scatterers on the ACF of an F2F communication link, let us consider non-moving transmitter and the receiver vehicles, i.e., $v_T = v_R = 0$. Then, the ACF in (12) reduces to the expression

$$r_{\mu\mu}(\tau) = \frac{2\sigma_0^2}{(2\pi)^2} \int_{v_S} \int_0^{2\pi} \int_0^{2\pi} J_0\left(2k_0 v_S \cos\left(\frac{\alpha^T - \alpha^R}{2}\right)\tau\right) \times p_{v_S}(v_S)\, d\alpha^T d\alpha^R dv_S \tag{13}$$

which can be evaluated for different scatterer velocity distributions $p_{v_S}(v_S)$. Figures 4 and 5 illustrate the ACF of the underlying F2F link in (13) for various scatterer velocity distributions. In this regard, Fig. 4 shows the effect of fast moving scatterers on the ACF of the channel, where the scatterer velocity distributions are modeled by the Laplace,

$$r_{\mu\mu}(\tau) = 2\sigma_0^2 \int\limits_{v_S}\int\limits_{\alpha^T}\int\limits_0^{2\pi}\int\limits_0^{2\pi} e^{j\left[k_0 v_T \cos\left(\alpha_v^T-\alpha^T\right)-2k_0 v_S \cos\left(\frac{\alpha^T-\alpha^R}{2}\right)\cos\left(\frac{\alpha^T+\alpha^R}{2}-\alpha_v^S\right)+k_0 v_R \cos\left(\alpha_v^R-\alpha^R\right)\right]\tau} \times p_{\alpha_v^S}\left(\alpha_v^S\right) p_{\alpha^T\alpha^R}\left(\alpha^T,\alpha^R\right) p_{v_S}(v_S) d\alpha_v^S d\alpha^R d\alpha^T dv_S \quad (11)$$

$$r_{\mu\mu}(\tau) = \frac{2\sigma_0^2}{(2\pi)^2}\int\limits_{v_S}\int\limits_0^{2\pi}\int\limits_0^{2\pi} e^{jk_0 v_T \cos\left(\alpha_v^T-\alpha^T\right)\tau} J_0\left(2k_0 v_S \cos\left(\frac{\alpha^T-\alpha^R}{2}\right)\tau\right) e^{jk_0 v_R \cos\left(\alpha_v^R-\alpha^R\right)\tau} \times p_{v_S}(v_S) d\alpha^T d\alpha^R dv_S \quad (12)$$

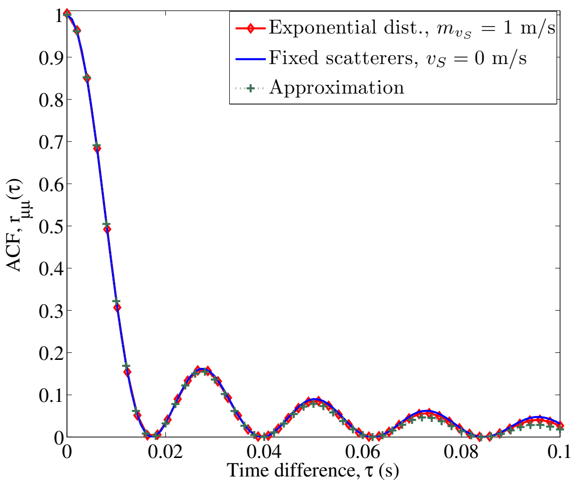

Fig. 3. The behavior of the ACF in (12) for a V2V scenario with slow moving scatterers and $v_T = v_R = 22.22$ m/s. The signal power $2\sigma_0^2$ has been set to 1.

Gaussian, and the uniform distribution and the average velocity m_{v_S} of the moving scatterers has been set in all cases to 10 m/s. Figure 5 demonstrates the effect of slow moving scatterers on the ACF of the F2F link, in which the velocity v_S of the moving scatterers follows in one case the exponential and in the other the uniform distribution. The average velocity m_{v_S} in both cases has been set to 1 m/s.

Now, let us compare the effect of slow moving scatterers on the ACF of the V2V and the F2F scenarios illustrated in Figs. 3 and 5, respectively. As mentioned before and referring to Fig. 3, the ACF of the V2V link in the presence of slow moving scatterers closely follows the ACF corresponding to the scenario with fixed scatterers. However, the ACF of the channel gain of the F2F link in the presence of slow moving scatterers is completely different from that of fixed scatterers. Owing to the triviality of the F2F channel model with fixed scatterers, we avoid to merge its ACF into Fig. 5. Indeed, by fixing the local scatterers, i.e., $v_S = 0$, the ACF in (13) results in a constant value, which is different from the graphs plotted in Fig. 5. It can be concluded that the Doppler shifts due to slow moving objects, like foliage or walking pedestrians, are much more important to be taken into consideration in the performance analysis of an F2F link as compared to a V2V link. The importance of moving scatterers in F2F channels was extensively studied in [4], [5], [6], and [7]. It should be mentioned as well that fast moving scatterers are important to be taken into account in both F2F and V2V communication scenarios as they are significant sources of the Doppler effect.

B. Approximate Solution of the ACF

An approximate ACF can be derived from the exact solution presented in Section IV-A. Recall that the AoD α^T and the AoA α^R are uniformly and independently distributed between 0 and 2π. It might be concluded that the difference $\alpha^T - \alpha^R$ is zero in average. As a consequence, the term $\cos\left((\alpha^T-\alpha^R)/2\right)$ in (12) might be approximated by one. It follows that the zeroth-order Bessel function in (12) is no longer a function of α^T and α^R. This helps us to analytically integrate over both α^T and α^R in (12), which was not possible before. By applying the aforementioned procedure, the ACF in (12) simplifies to

$$r_{\mu\mu}(\tau) \approx 2\sigma_0^2 J_0(k_0 v_T\tau)J_0(k_0 v_R\tau) \times \int\limits_{v_S} J_0(2k_0 v_S\tau) p_{v_S}(v_S) dv_S. \quad (14)$$

The accuracy of the approximation depends on the velocities of the local scatterers, the transmitter, and the receiver vehicles. Obviously, the approximation in (14) meets the exact result for the ACF $r_{\mu\mu}(\tau) = 2\sigma_0^2 J_0(k_0 v_T\tau)J_0(k_0 v_R\tau)$ of the V2V scenario in the presence of fixed scatterers ($v_S = 0$), which was studied in [1] and [2]. The accuracy of the approximation decreases by increasing the scatterer velocity and with decreasing the transmitter and the receiver velocities. This is due to the fact that in these cases, the argument of the Bessel function in (12) becomes important and needs to be taken into account precisely. In what follows, we derive closed-form approximations for the ACF of the proposed V2V channel model under the assumption of different scatterer velocity distributions.

Let us assume that v_S is a deterministic value. Hence, $p_{v_S}(x) = \delta(x - v_S)$ describes its probability density function.

In this case, the ACF in (14) can be presented in closed form as follows

$$r_{\mu\mu}(\tau) \approx 2\sigma_0^2 J_0(k_0 v_T \tau) J_0(k_0 v_R \tau) J_0(2k_0 v_S \tau). \qquad (15)$$

If v_S follows the exponential distribution with mean m_{v_S}, the ACF can be approximated by

$$r_{\mu\mu}(\tau) \approx \frac{2\sigma_0^2 J_0(k_0 v_T \tau) J_0(k_0 v_R \tau)}{\sqrt{1 + (2k_0 m_{v_S} \tau)^2}}. \qquad (16)$$

If v_S follows the one-sided Gaussian distribution with variance $\sigma_{v_S}^2$, the approximate ACF can be presented as

$$r_{\mu\mu}(\tau) \approx 2\sigma_0^2 J_0(k_0 v_T \tau) J_0(k_0 v_R \tau) I_0(k_0 \sigma^2 \tau^2) e^{-k_0^2 \sigma_{v_S}^2 \tau^2} \qquad (17)$$

where $I_0(\cdot)$ denotes that modified Bessel function of the first kind. Owing to space restrictions, we avoid to provide closed-form approximations for the ACF of the underlying V2V channel for other scatterer velocity distributions, like the uniform and the Laplace distributions here.

As an example, a plot of the approximate ACF in (16) is presented in Fig. 3. As can be seen, the approximation is highly accurate for the V2V scenario in the presence of slow moving scatterers.

V. Conclusion

Starting from a very general geometrical model, the complex channel gain of a V2V communication channel in the presence of moving scatterers has been presented. Accordingly, the ACF of the V2V link has been determined. By fixing either the transmitter or the receiver vehicles or both, we have simplified the analytical ACF of the V2V link to the F2V and the F2F links. Furthermore, the effect of fixing local scatterers in all above-mentioned scenarios has been studied. It has been shown that fast moving scatterers have a major impact on both V2V and F2F communication links as they are significant sources of the Doppler spread. However, slow moving scatterers are mainly important in F2F scenarios. Highly accurate closed-form approximations for different scatterer velocity distributions have been provided as well. Validating the analytical results with the corresponding measurement data and deriving further statistical characterizations are topics of future work.

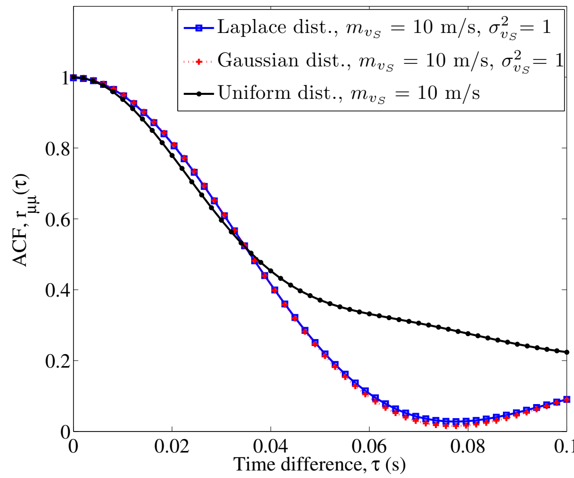

Fig. 4. The behavior of the ACF in (13) for an F2F scenario with fast moving scatterers. The signal power $2\sigma_0^2$ has been set to 1.

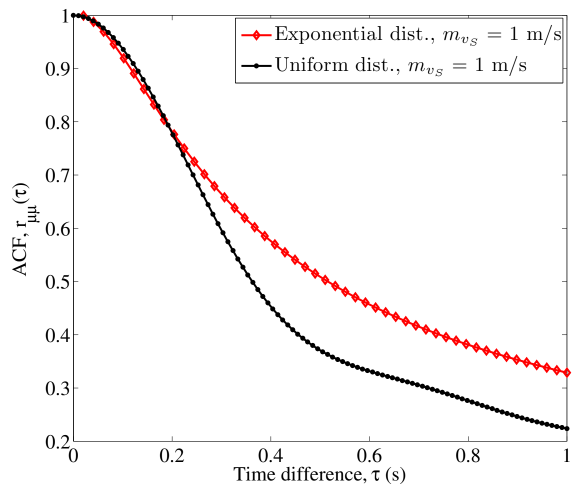

Fig. 5. The behavior of the ACF in (13) for an F2F scenario with slow moving scatterers. The signal power $2\sigma_0^2$ has been set to 1.

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