Doppler Characteristics for Indoor Mobile-to-Mobile Channels

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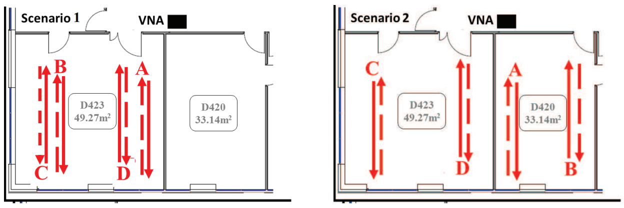
***Abstract*—This paper analyzes Doppler spectra of mobile-to-mobile (M2M) channels, based on a measurement campaign carried out in an indoor environment at 2.48 GHz. The Doppler spectrum is characterized in line-of-sight (LOS) and non-line-of-sight (NLOS) environments for different types of pedestrian movements. Subsequently, an analytical Doppler spectrum model is proposed and successfully compared to the measurement data.**

***Index Terms*— Mobile-to-Mobile channel, indoor, Doppler spectrum, Doppler spread;**



(a) Scenario 1 (b) Scenario 2

Fig. 1. Visual plan of measurement scenarios, including walking patterns

I. Introduction

Doppler spectrum modeling is essential to depict the temporal variations of a wireless channel [1], [2]. In the usual case, when an antenna is moving in a random environment, the channel was described as a fixed-to-mobile (F2M) channel and the Doppler spectrum was modeled by Jakes spectrum considering isotropic fixed scatterers uniformly distributed in azimuth [3]. However, in some cases, both antennas are moving simultaneously giving rise to a mobile-to-mobile (M2M) channel. M2M communication links can take place between two vehicles or two pedestrians carrying wireless nodes. In [4], a Doppler spectrum model for M2M Rayleigh fading channels was presented. The model was extended in [5] to account 3D scattering distribution and in [6] to include the line-of-sight (LOS) in a Rician fading channel. These models were developed for suburban environments. So far, to the best of authors' knowledge, none of them was applied to model the measured Doppler spectra of indoor M2M channels. Indoor M2M links can be employed for cooperative communications in order to increase coverage reliability [7], [8] and for secure short range communications with a low power consumption [9]. Looking at literature, Doppler spectra in indoor premises were studied in [10], [11] for fixed wireless communication. The time-varying channel was resulting from pedestrians walking in the environment.

This paper aims to analyze and model Doppler spectra of indoor M2M channels based on an extensive body-to-body (B2B) measurement campaign carried out in an office environment at 2.48 GHz [12]. The antennas were mounted on helmets placed on the head of moving subjects. This was done to minimize the effects of body shadowing in order to extend our evaluations from B2B specifically towards more general M2M scenarios. Our goals are to present a comparison of Doppler spectra for several pedestrian mobility patterns and to derive an analytical Doppler spectrum model that is able to describe such characteristics. Moreover, a fading channel model implementation preserving the Doppler properties is proposed.

This paper is organized in the following way. A brief description on the measurement campaign is provided in Section II. Section III presents the proposed Doppler spectrum model for M2M channels. Then, it is compared to the measured Doppler spectra of different mobility scenarios given in line-of-sight (LOS) and non-line-of-sight (NLOS) environments. An implementation technique using the proposed Doppler spectrum model in order to generate a stochastic processes which can describe the fading channel characteristics is presented in Section IV. Finally, conclusions are given in Section V.

II. Measurement Campaign

A narrow-band channel measurement campaign was carried out at 2.48 GHz in an office environment. Four monopole antennas were used simultaneously, each one was mounted on a helmet placed on the head of a moving subject. Therefore, four human subjects were involved. They were simultaneously in the same room, a 49 m^2 classical office with desks, storage cabinets and bookshelves. During measurements, furniture was arranged at the sides of the room leaving a large empty part in the center where the subjects were moving. Multiple human mobility scenarios were considered. In this work, we only focus on straight line walking scenarios, including parallel and opposite walks, taking place in line-of-sight (LOS) and non-line-of-sight (NLOS) environments, as described in Fig. 1. A, B, C and D represent the four subjects whereas the arrows and dashed arrows represent the two runs that were performed

TABLE I
TYPES OF WALKING MOVEMENTS

Realizations	Scenario number	Condition	Walking pattern
AB and CD	1	LOS	Parallel walk
AD and BC	1	LOS	Opposite walk
AC and BD	2	NLOS	Parallel walk
AD and BC	2	NLOS	Opposite walk

(cf. Fig. 1). A 4-ports Vector Network Analyzer (VNA) was employed in continuous wave (CW) mode, to recover the time variant channel responses. The duration of each measurement acquisition was 10 s and people were moving at a similar quasi-constant speed. Measurements were recorded each 4 ms, providing 2501 samples for each link.

More details about the measurement campaign, post-processing and preliminary results on the channel characteristics can be found in [12]–[14].

III. DOPPLER SPECTRUM ANALYSIS AND MODELING

In this section, an analytical Doppler spectrum model for indoor M2M channels is proposed and compared to the measurement data. The Doppler spectra are characterized in terms of mobility patterns and propagation conditions. In other words, for a given walking pattern and scenario condition, the Doppler spectrum was calculated by averaging the measured power spectral densities (PSDs). The power spectral density (PSD) of a realization was calculated as the Fourier transform of its time correlation function such as:

$$PSD(\nu) = \int_{-\infty}^{+\infty} R\left(\Delta t\right) e^{-i2\pi\nu\Delta t} d\Delta t \tag{1}$$

where $R\left(\Delta t\right)$ is the time correlation function of channel transfer function normalized with respect to its path loss. The time correlation functions of the measured channels and its properties were studied in [14]. Table I presents the realizations considered in this paper to estimate the Doppler spectra.

A. Doppler Spectrum Model

An analytical Doppler spectrum model was derived in [4] for M2M channels considering a uniform pattern of fixed isotropic scatterers, as:

$$S(\nu) = \frac{\sigma^2}{\pi^2 \nu_d \sqrt{\alpha}} K \left[\frac{(1+\alpha)}{2\sqrt{\alpha}} \sqrt{1 - \left(\frac{\nu}{(1+\alpha)\nu_d} \right)^2} \right] \tag{2}$$

for $\nu \leq (1+\alpha)\nu_d$, and 0 otherwise; where $K[.]$ is an elliptic integral of the first kind, σ^2 is the average received power and $\nu_d = max(\nu_{m_1}, \nu_{m_2})$ where ν_{m_1} and ν_{m_2} are the maximum Doppler frequencies due to the mobility of transmitter and receiver, respectively. The parameter α represents the degree of mobility which is computed as: $\alpha = max(\nu_{m_1}, \nu_{m_2})/min(\nu_{m_1}, \nu_{m_2})$.

Considering equal speed at terminals, this analytical formula (2) reduces to:

$$S(\nu) = \frac{\sigma^2}{\pi^2 \nu_d} K \left[\sqrt{1 - \left(\frac{\nu}{2\nu_d} \right)^2} \right] \tag{3}$$

This model (3) was also used to characterize Doppler spectra for indoor fixed wireless communication surrounded by scatterers moving at the same speed [4], [5]. At this point, it's worth to note that the M2M channels with fixed scatterers can be seen as a dual of fixed-to-fixed (F2F) channels in the presence of moving scatterers. If we consider a non-uniform scattering pattern, the Doppler spectrum of F2F channels in the presence of moving scatterers can be represented as a summation of Legendre functions with non-integer orders [11]. However, due to its computational complexity, a simple analytical model was proposed in [11]:

$$S(\nu) = \frac{1}{b\nu^2 + 1} \tag{4}$$

where b is a parameter to be estimated from the measurement data.

As will be shown later, none of these models can well depict the Doppler spectra of indoor M2M channels. Therefore, the following analytical model is proposed:

$$S(\nu) = \begin{cases} \frac{1-\beta_1-\beta_2}{\pi\nu_d^{TR}\sqrt{1-\left(\frac{\nu}{\nu_d^{TR}}\right)^2}} + \frac{\beta_2}{\beta_3\nu^2+1} + \beta_1 e^{-\left(\frac{\nu}{\bar{\nu}_d^{TS}}\right)^2} & ; |\nu| \leq \nu_d^{TR} \\ \beta_1 e^{-\left(\frac{\nu}{\bar{\nu}_d^{TS}}\right)^2} + \frac{\beta_2}{\beta_3\nu^2+1}; & \text{Otherwise} \end{cases} \tag{5}$$

where β_i, where $i = 1, 2, 3$ are parameters to be estimated from measurement data, $\bar{\nu}_d^{TS}$ is the average of maximum Doppler frequencies due to the mobility of scatterers seen by the transmitter and ν_d^{TR} is the maximum Doppler frequency resulting from the relative mobility between terminals.

This model includes the effects of moving scatterers and receiver with respect to transmitter. In fact, taking the transmitter as the observational frame reference, M2M channels can be seen as F2M channels with moving scatterers. Therefore, the first term in the proposed model (5) is Jakes spectrum and it is employed to depict the Doppler effects due to the mobility of receiver with respect to transmitter. At this point, it's worth to note that the Jakes spectrum was usually used to model the F2M channels with fixed scatterers. To model the impact of non-uniform moving scatterers, equation (4) is used and presented by the second term in equation (5). Moreover, it was found that a Gauss model, the third term, is needed to improve the model interpretation. Classically, the Gauss spectrum was used to model the Doppler properties of diffuse scatterer channels [15], and it is here employed to represent the cap given by the measurement data.

B. LOS Scenarios

Doppler spectra of parallel and opposite walking movements in LOS scenarios are presented in Fig. 2. The Doppler frequency axis is normalized with respect to the maximum Doppler frequency due to the mobility of terminals ν_D (cf. Table II). As seen, the Doppler spectrum properties depend on the type of pedestrian movements; and for that reason, it was characterized not only based on the propagation environment but also on the mobility pattern. The difference of Doppler spectrum between both patterns can be simply linked to a difference of relative speed between terminals. In fact, the relative speed in the parallel walking case is zero and it is indicated by the presence of peak around 0 whereas for opposite direction, it is equal twice the speed of terminal and this explain the presence of peaks around 2 (cf. Figure 2).

Considering the parallel walking movements, namely AB and CD realizations in scenario 1 (cf. Fig. 1a), the terminals were moving simultaneously with the same velocity vector, i.e. in the same direction and at the same speed. This type of link can be described as a fixed-to-fixed (F2F) link in the presence of moving scatterers, taking the terminals' point of view. This explains why the Doppler spectrum is centered around 0 Hz, as found for indoor fixed wireless communications surrounded by moving scatterers [16]–[18]. Therefore, from the transmitter's point of view, the receiver is static, i.e. ν_d^{TR} is equal to 0 Hz, whereas the environment and the two other persons move at speed v and $2v$ respectively, where v is the node speed and it was approximately equal to 0.5 m/s in LOS scenarios. Thus, the average of maximum Doppler frequencies due to the moving scatterers with respect to transmitter $\bar{\nu}_d^{TS}$ is equal to $3v/(2\lambda)$, i.e. 6.2 Hz, in our experiments (cf. Table II).

Fig. 3 compares the Doppler spectrum of parallel walking movement given in LOS condition to the analytical models (3), (4) and (5). The maximum Doppler frequency ν_d in equation (3) was calculated from the node speed 0.5 m/s, i.e. $\nu_d = 4.113$ Hz, while b in the equation (4) was taking equal to 0.5 in order to attain a suitable fitting for the main part of the measured power. The Doppler parameters in equation (5), β_i, were estimated using a nonlinear least square method [19], [20] (cf. Table III). It could be noticed that the proposed model fits better the measurement data compared to those proposed in literature.

Now, observing the Doppler spectrum of opposite walking movements, one can readily detect the presence of Jakes spectrum (cf. Fig. 2). In fact, from the transmitter's point of view, the link can be described as a fixed-to-mobile channel in the presence of local moving scatterers where the mobile terminal is moving with a velocity equal twice the human subject speed. This explains the presence of peaks in the Doppler spectrum around 2 ($2\nu_d = \nu_d^{TR} = 8.2667$ Hz) (cf. Fig. 2). The Doppler frequency shifts ν_d^{TR} and $\bar{\nu}_d^{TS}$ are equal to 8.2667 Hz and 6.2 Hz, respectively (cf. Table II). Fig. 4 shows a good agreement between the measured Doppler spectrum and the proposed model.

Finally, Table IV presents the Doppler spreads of the measurement data and proposed model. Doppler spread is calculated as the root mean square (RMS) of second central moment of the Doppler spectrum. As noticed, the Doppler spreads of the proposed model are in line with the measured ones. Moreover, looking at the literature, the Doppler spread of parallel movement is similar to those obtained in indoor fixed wireless communication with moving scatterers [21].

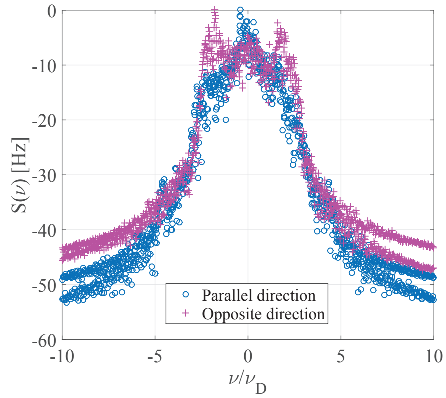


Fig. 2. Doppler spectra in LOS scenarios: parallel movement (blue circles) and opposite movement (pink plus signs)

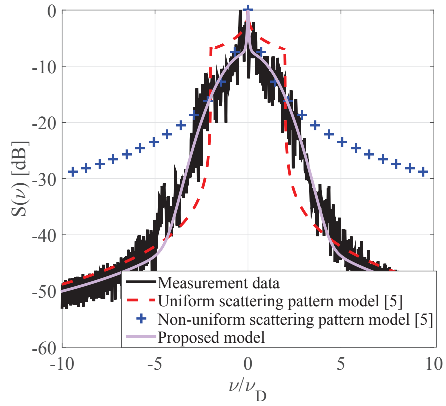


Fig. 3. Measured Doppler spectrum and proposed models for parallel walking in LOS condition

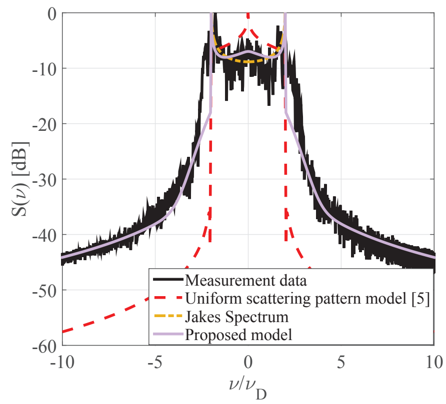


Fig. 4. Doppler spectrum and proposed model for opposite walking in LOS condition

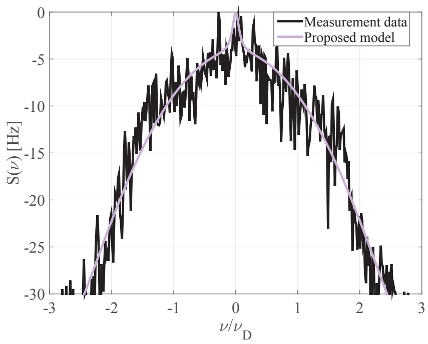


Fig. 5. Doppler spectrum and proposed models for parallel walking in NLOS condition

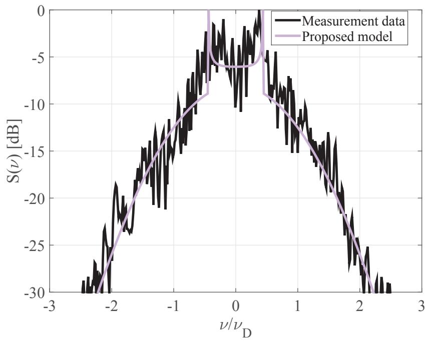


Fig. 6. Measured Doppler spectrum and proposed model for opposite walking in NLOS condition

TABLE II
MAXIMUM DOPPLER FREQUENCY

Scenario	Walking pattern	ν_D (Hz)	$\bar{\nu}_d^{TS}$ (Hz)	ν_d^{TR} (Hz)
LOS	Parallel walk	4.133	6.2	0
LOS	Opposite walk	4.133	6.2	8.266
NLOS	Parallel walk	4.96	4.85	0
NLOS	Opposite walk	4.96	4.85	2.18

C. NLOS Scenarios

Similarly to the previous section, the parallel and opposite walking movements in NLOS scenarios can be seen as F2F and F2M links surrounded by moving scatterers, respectively, considering the transmitter's point of view (cf. Fig. 1b). Table II presents the Doppler frequency shifts and Table III exhibits the Doppler parameters of equation (5), β_i, estimated using a nonlinear least square method. Subsequently, Fig. 5 and 6 show the good agreement of the proposed model with the measurement data. This is also verified for the Doppler spread in Table IV.

IV. Channel Model Implementation Including Doppler Filter

In this section, a fading channel implementation based on the proposed Doppler model is presented. The method can be described as an extension to Young and Baulieu model [22].

TABLE III
VALUES OF β_i PARAMETERS

Scenario	walking pattern	β_1	β_2	β_3
LOS	Parallel walk	0.1667	0.8333	49.2138
LOS	Opposite walk	0.03	0.01	0.5
NLOS	Parallel walk	0.3668	0.6332	15.5163
NLOS	Opposite walk	0.2066	0.00023	0.00932

TABLE IV
DOPPLER SPREAD

Scenario	Walking pattern	Measurement data	Proposed model
LOS	Parallel walk	4.3 Hz	4.49 Hz
LOS	Opposite walk	6.66 Hz	5.65 Hz
NLOS	Parallel walk	4.1 Hz	3.6 Hz
NLOS	Opposite walk	3.18 Hz	3.25 Hz

TABLE V
MEASUREMENT DATA VS. SIMULATION DATA FOR OPPOSITE WALKING SCENARIO IN LOS CONDITION

	σ	s	Doppler spread (Hz)
Measurement data	0.37	0.85	6.66
Simulation data	0.37	0.85	5.78

Referring to the results in [14], similarities in terms of coherence time and shape of the time correlation function, between the channel transfer function and the short-term fading were presented. Thus, the Doppler spectrum of the channel mainly depends on the one of short-term fading. This is intuitively evident since the short-term fading is due to the rapid fluctuation of the received signal caused by the mobility of terminals and scatterers in the environment. Therefore, in this section, a channel implementation technique based on the proposed Doppler model that can generate a correlated short-term fading is exhibited.

Fig. 7 presents the block diagrams of the simulation method. Two identical independent Gaussian random variables are used in order to generate the in- phase and quadrature components of the short-term fading channel, each passing through the same filter, which has a transfer function equal to $\sqrt{|S(\nu)|}$. Then, the correlated data are transformed to the time domain using the inverse discrete Fourier transform (IDFT). After that, the short-term fading results from summing the correlated data, scaled by the measured standard deviation σ and shifted using the desired non-centrality parameter s.

Taking the square root of the proposed Doppler spectrum model as the transfer function of the filter, one can generate a short-term fading that has the same Doppler spectrum of the channel. Fig. 8 and Table V show an excellent agreement of Rician distribution and Doppler spectrum for short-term fading obtained in opposite walking scenario under the LOS condition between the measurement data and the data generated with the proposed method.

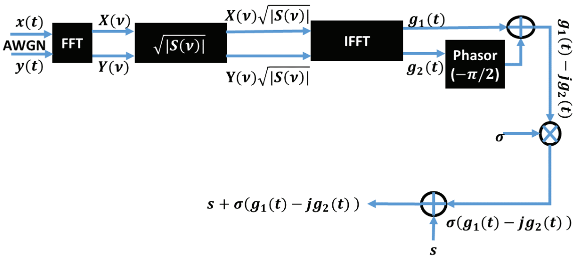


Fig. 7. Block diagram to generate correlated short-term fading

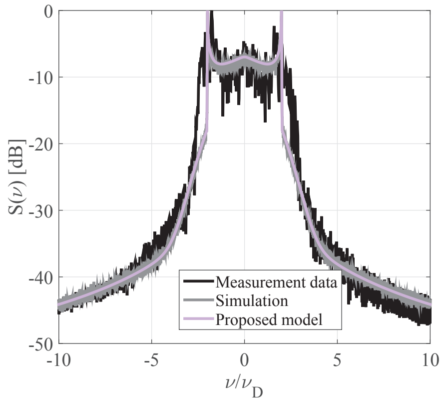


Fig. 8. Analytical and measured Doppler spectra versus simulated Doppler spectrum for opposite walking in LOS condition

V. Conclusion

The Doppler spectra of M2M channels were analyzed for different pedestrian mobility patterns based on a measurement campaign carried out in LOS and NLOS indoor environments. It was shown that the characteristics of Doppler spectrum depend on the propagation condition as well as the mobility pattern. An analytical model was developed in order to retrieve such characteristics. The proposed model is simple, only two parameters need to be estimated from the measurement data. Also, it allows to reproduce with good accuracy the Doppler properties of different indoor M2M scenarios including LOS and NLOS conditions, by means of a closed analytical formula. Due to the physical interpretation behind it, it can account other different indoor M2M scenarios, e.g. the cross walking scenarios. Moreover, an extension version that can account more complex scenarios, e.g. the statistical distribution of multiple moving persons presence in the room, will be the subject of further investigation. Similarities in terms of coherence time and auto-correlation function, between the channel transfer function and short-term fading, were presented in [14], therefore, the proposed model is exploited to implement a short-term fading channel model that preserve the Doppler properties.

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