Doppler Spectrum Analysis in Three-Dimensional 5G Millimeter-Wave Channel Models

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***Abstract*—This article is contextualized in the mobile communications systems where there are multiple factors to consider: mobility, frequency, obstacles, reflectors, etc. In this paper, is presented an evaluation of the Doppler spectrum in a Three-Dimensional (3D) channel model for different frequencies, User Terminal (UT) directions and UT speeds. To commence, it introduces the channel model that is used for the simulations, then the Classical Doppler Spectrum frequently used in Two-Dimensional (2D) channel models is entered. Finally, it tries the Doppler Spectrum for the some typical 5G frequencies, speeds up to 500 km/h and for the motion direction in the 3D space.**

***Index Terms*—5G, three-dimensional, millimeter-wave, channel models, mobile communications system, Doppler spectrum, radio-propagation model, transmitter, receiver, cluster, ray, signal.**

I. INTRODUCTION

The Millimeter-wave (mmWave) constitutes an important portion of the unused spectrum, which is an important resource for the future mobile communication systems, especially nowadays, with the great impact of the new mobile technology, 5G, which aims to support a lot of connected devices. So, the principal interest of this survey is the application in the 5G technology.

Several studies reported research up in frequency to the mmWave band, such as [1] or [2]. This paper focuses in the Doppler spectrum analysis for the channel proposed by [3] that support frequencies up to 100 GHz and mobile speed up to 500 km/h in a three-dimensional radio-propagation model.

In mobile communications it is frequent that the receiver moves relative to their source (or vice versa), it produces the phenomenon known as Doppler Shift (or Doppler Effect) that provokes the shift in the carrier frequency degrading the communication between Transmitter (Tx) and Receiver (Rx). So, due to the multipath, there are different frequency shifts that can be visualized using the Doppler spectrum. Since 5G uses OFDM, the Doppler Effect can result in carrier frequencies orthogonality lost. In addition, it can complicate the recovery of synchronism.

The aims of this article can be summarized as follows:

- Enter the channel model proposed by [3].
- Survey of the Doppler effect in a three-dimensional environment.
- Analyze the impact of frequency and speed on the Doppler spectrum.

The organization of the rest of the paper is as follows. First, the Three-Dimensional (3D) channel model is presented in Section II. Then, a view of the Classical Doppler Spectrum is provided in Section III. In Section IV, it shows, first, how the direction of movement of the User Terminal (UT) affect to the Doppler Spectrum, second, the impact of the speed of movement and, third, the effects of the frequency in the Doppler Effect. Finally, it conclude in Section V.

II. CHANNEL MODEL

According to [1], a narrow band model, where all multipath components arrive to the Rx at same time and all frequency components have the same attenuation level, doesn't represent a real mmWave channel model, so a narrow band model can't be applied to channels with great bandwidth. For this reason, in this report is used the channel model proposed by [3] that is a wide band model which represents the spatial-temporal propagation characteristics of the mmWave channels.

In mobile communications, the channel models used to describe the signal propagation as a ray set or echoes that arrive to the Rx by different paths, is denominated multipath effect. In [3], a Cluster Delay Line model is presented where is possible to build groups of rays that have common spatial-temporal characteristics, these groups are denominated clusters.

In addition, as already advanced in the introduction, [3] describes this channel model as a 3D model, it is an important difference with other previous model as described in [4] and [5]. So, this fact affects the multipath because must take into account horizontal and elevation departure angles in the Tx antennas and horizontal and elevation arrival angles in the Rx antennas. To represent these spatial characteristics, it uses a geometric coordinate system. So, a possible representation of a 3D mmWave propagation can be represented by Figure 1.

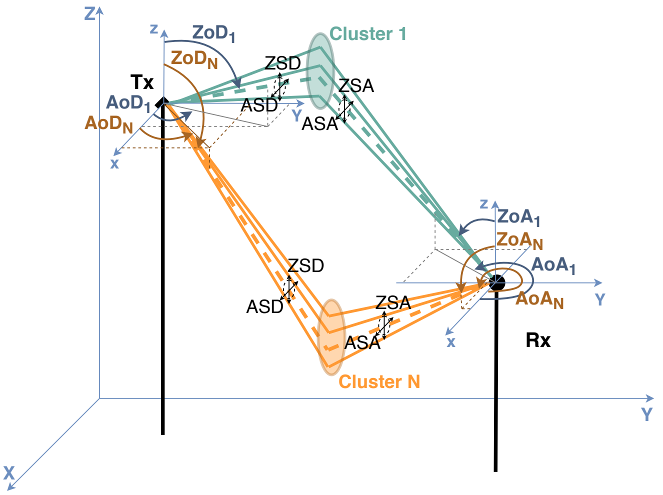

Fig. 1. Spacial geometry of the clusters and rays (acronyms description in Table I).

Finally, it is important to contextualize the propagation environment where the communication of the information occurs. The channel model of [3] disposes of three outdoor scenarios: Rural Macro (RMa) for rural environments, Urban Macro (UMa) and Urban Micro (UMi) for urban environments and, two indoor scenarios: Indoor Hotspot - Open Office (InH-OO) for spaces without many obstacles and Indoor Hotspot - Mixed Office (InH-MO) for spaces with obstacles like walls or columns.

TABLE I
ACRONYMS OF THE FIGURE 1

AoA_N	Azimuth angle of Arrival of the cluster N
AoD_N	Azimuth angle of Departure of the cluster N
ASA	Azimuth Spread of Arrival angle
ASD	Azimuth Spread of Departure angle
ZoA_N	Zenith angle of Arrival of the cluster N
ZoD_N	Zenith angle of Departure of the cluster N
ZSA	Zenith Spread of Arrival angle
ZSD	Zenith Spread of Departure angle

III. CLASSICAL DOPPLER SPECTRUM

In channels below of mmWave frequency, it is frequent to use uniform scattering environment models typical in Rayleigh channels where infinite replicas of the signal reach the Rx at same time from all directions on an azimuthal plane following a uniform distribution, according to [6]. So, a continuous spectrum is generated which is frequently called Classical Doppler Spectrum (Figure 2) that can be modeled following the Jakes's model, [7].

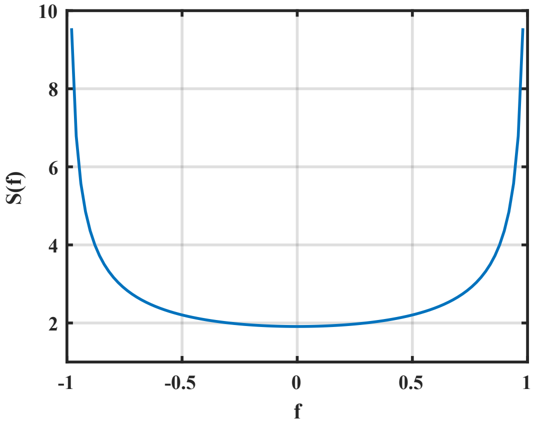

Fig. 2. Classical Doppler Spectrum (Spectral Power Density $S(f)$, frequency f).

IV. DOPPLER SPECTRUM SURVEY IN THE MMWAVE CHANNEL

As already advanced in the introduction, the user motion provokes the Doppler Effect shifting the carrier frequency of the transmission. In Two-Dimensional (2D), it is well known that the frequency perceived by the Rx is determined by the Equation 1, which is related with the Figure 3, where is defined the angle ρ how the angle formed by the straight line that connects the Tx with the Rx and the velocity vector (directly measured on the plane).

$$f_{Rx} = f_{Tx} - \frac{|\vec{v}|}{\lambda} \cdot \cos\rho \tag{1}$$

where f_{Rx} is the received frequency, f_{Tx} is the transmitted frequency, $\vec{v}$ is the velocity vector, λ is the wavelength and ρ is the angle formed by the straight line that connects the Tx with the Rx and the velocity vector.

Fig. 3. Angle definition of the Doppler Effect in 2D.

As in this model the user is able to move in the three spatial dimensions, the problem is bigger than in the 2D models. To the best of authors' knowledge, there are few surveys treating the Doppler Effect in 3D radio-propagation mobile channel models, such as [8]. A possible representation of the movement in three dimensions is shown in Figure 4 along with a definition of the angles in the spherical coordinate system. For this reason, in this paper the Doppler Effect is analyzed to know if it is agree with the classical theory of Doppler Effect previously mentioned.

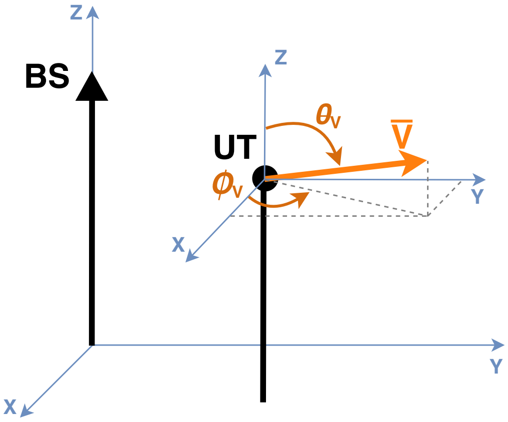

Fig. 4. Velocity vector in 3D (azimuth angle of velocity ϕ_v and zenith angle of velocity θ_v).

As already advanced previously, the Doppler Effect is a frequency shift and, this fact attached to multipath effect, provokes the broadening of the Doppler Spectrum of the channel. It can be represented by the Doppler Delay Spread Function of the channel. So, two different situations are going to be used: On the one hand, the maximum frequency shift is shown using links with Line of Sight (LOS) and, on the other hand, the broadening of the Doppler Spectrum is going to be represented using links with Non-Line of Sight (NLOS).

A. Impact of the UT movement direction

First, to reduce the complexity, the problem is going to be separated in two planes, horizontal (XY plane) and vertical (ZX plane), to be able to study more easily these situations.

So, if source and receiver have the same height, using the Equation 1, is easy to see that the minimum and maximum shift in frequency occurs when $\rho = 0^o$ or $\rho = 180^o$, respectively and, when $\rho = 90^o$ or $\rho = 270^o$ the perceived frequency in reception must be the same as the transmitted frequency.

This situation can be carried out by placing a Tx and a Rx with the same height (10 m) and 10 m apart on the Y axis in a scenario type UMi. How is shown in Figure 5, six different cases with six different movement directions of the Rx are going to be analyzed. In these cases, the Rx speed is $v = 50km/h$ (this can represent the movement of a car in a city) and the carrier frequency chosen for the link is $f_c = 28GHz$ because is a 5G frequency very close to mmWave band (it is within the n257 operating band of FR2 bands, part 2 of [9]). Finally, to appreciate the maximum frequency shift, is important to fix the state of vision of the link to LOS.

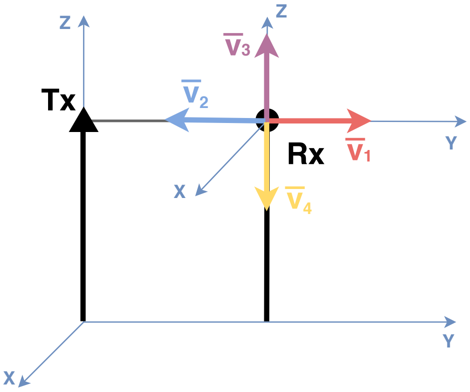

Fig. 5. Simple directions of movement of a receiver.

1) In XY plane: The cases 1 ($\rho = 0^o$) and 2 ($\rho = 180^o$) of the Figure 5 can be analyzed. In Figure 6, the frequency shifts are shown where is possible to appreciate that these frequency increments correspond with theory shift of the Equation 1.

2) In ZX plane: The cases 3 ($\rho = 90^o$) and 4 ($\rho = 270^o$) of the Figure 5 can be represented. The Figure 6 shows what is expected to happen.

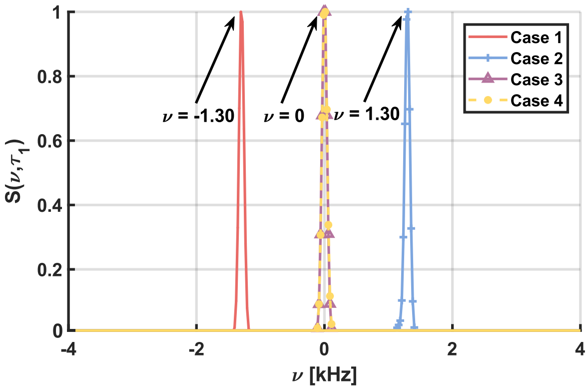

Fig. 6. Maximum frequency shifts of the first cluster in LOS state ($f_c = 28GHz, v = 50km/h$). (Doppler Delay Spread Function $S(\nu,\tau)$, frequency ν, time of the first cluster τ_1).

Now, it is going to analyze the broadening of the Doppler Spectrum fixing the vision state of the link to NLOS and using the same previous scenario where, Tx and Rx have the same height (10 m) and a separation of 10 m. To increment the effect, the velocity of Rx is fixed to the maximum of the model (500 km/h) because it is the worst case and it can be representative of a high-speed train. It moves away from the Tx in a straight line, also, the carrier frequency of 28 GHz is used. Here, only the rays of the first cluster are going to be represented to be able to show an image without many rays and, to be able to distinguish the different paths followed by the signal. After the simulation, the reflectors represented in Figure 7 are obtained and, the Doppler Spectrum simulated is showed in Figure 8, whose main shifts are according with the Equation 1. So, it is possible to conclude that this channel model doesn't agree with the Classical Doppler Spectrum because of there aren't infinite echoes arriving to the Rx with equal probability at same time, also, this spectrum isn't continuous for the same reason.

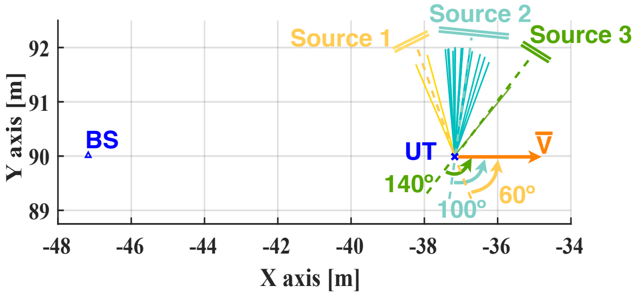

Fig. 7. Sources for the simulation in NLOS state.

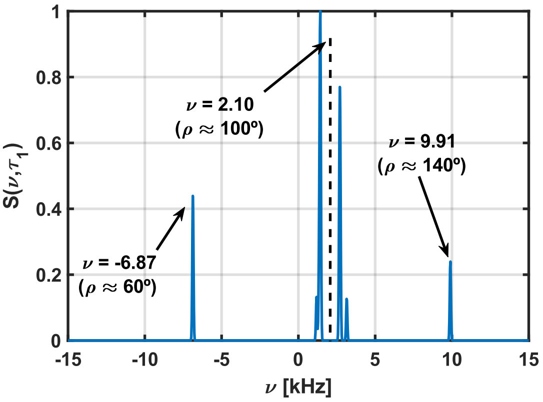

Fig. 8. Broadening of the Doppler Spectrum of the first cluster in NLOS state ($f_c = 28GHz, v = 500km/h$).

To end this section, if the problem isn't separated in the two planes, it is necessary to obtain a new expression to calculate the frequency shift when the movement produces in any direction in the 3D space. So, the same expression that in Equation 1 can be used but the angle ρ in this situation is calculated according to the Equation 2.

$$\cos\rho = \frac{\vec{u}\cdot\vec{v}}{|\vec{u}|\cdot|\vec{v}|} \qquad (2)$$

where $\vec{u}$ is the vector of the line that connect Tx and Rx, $\vec{v}$ is the velocity vector and ρ is the angle formed by the straight line that connects the Tx with the Rx and the velocity vector in 3D.

To continue, an example of this situation is simulated using an environment type RMa where the Tx has 25m of height and the Rx has 1.5 m. The direction of the velocity vector is $(\phi_v, \theta_v) = (0^o, 30^o)$ and its module is 13.89 (speed in m/s). The direction of the vector of the line between Tx and Rx is $(\phi_u, \theta_u) = (45^o, 156.95^o)$. Also, these are placed to 10 m of distance with LOS state. So, according to the Equation 1 and Equation 2, the maximum frequency shift must be $\nu = 0.85KHz$ when the carrier frequency is 28 GHz. So, after performing the simulation, the Figure 9 is obtained where we can see that the simulated value match it.

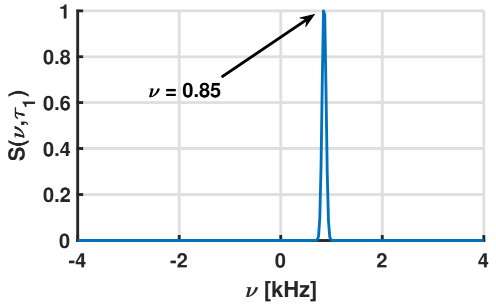

Fig. 9. Maximum frequency shift in 3D of the first cluster in LOS state $(f_c = 28GHz, v = 50km/h)$.

B. Impact of UT speed

From Equation 1 is also extracted that increasing the speed provokes an increment of the maximum frequency shift. To prove this, it uses three users whose links have LOS state and everyone moves towards the Base Station (BS) formed an angle $\rho = 180^o$ in the XY plane and with velocities: 0 km/h, 100 km/h and 500 km/h, respectively. To represent this situation, once again, Tx and Rx have the same height (10 m) and use 28 GHz for the carrier frequency. It is possible to check that the theoretical shifts coincide with the Figure 10 that is obtained after performing the simulation.

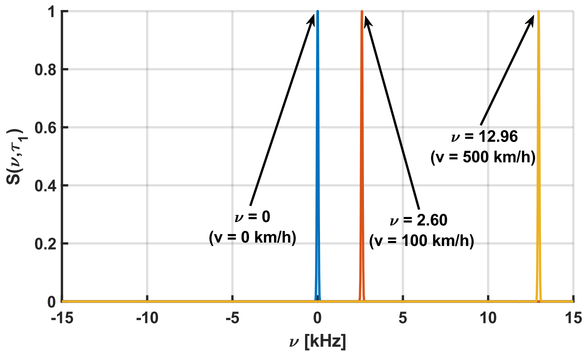

Fig. 10. Influence of the speed in the frequency shift $(f_c = 28GHz)$.

C. Impact of frequency

In this section, the same scenario that in Section IV-B is used but, now, the velocity is fixed to 50 km/h and the frequency is changed using 3.5 GHz (it isn't a mmWave frequency but is within the n78 band of FR1 bands of [9] Part 1), 28 GHz and 73 GHz (possibly useful for indoors environments in 5G, [1]). Observing the Figure 11, it obtains similar conclusions as with the speed.

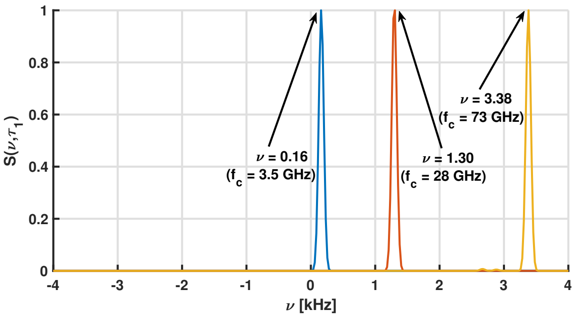

Fig. 11. Influence of the carrier frequency in the frequency shift $(v = 50km/h)$.

V. CONCLUSIONS

In this paper, the salient Doppler characteristics have been reviewed. For this reason, it uses a mmWave channel model that support the three spatial dimensions and mobility of users in different directions. So, this report has discussed the impact on the Doppler Spectrum of the carrier frequency in the mmWave band, of the speed of movement and of the movement direction comparing it with the Doppler Effect theory in 2D and then, extending to 3D. Also, it has shown an example of the Doppler Spectrum generated when the transmitted signal propagates in a real scenario model with reflectors that provoke replicas of the signal that arrive to the receiver with different angles and paths.

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