Characterization of Second-Order Fading Statistics of 28GHz Indoor Radio Propagation Channels

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Abstract

Extension of usable frequency spectrum from microwave to millimeter-wave (mmWave) range is one of the key research directions in addressing the capacity demands of 5th generation (5G) land mobile radio communication networks. This paper presents a thorough analysis on the second-order fading statistics of indoor mmWave range radio propagation channels. The well-established analytical relationship of plain angular statistics of a radio propagation channel with the channel’s fading statistics is utilized to study the fading characteristics of indoor mmWave radio propagation channels. The plain angle-of-arrival (AoA) measurement results published in the open literature for three different indoor radio propagation scenarios at 28GHz band are extracted by using different graphical interpretation techniques. The extracted plain AoA statistics are extended to study the dispersion of energy in angular domain and second-order fading statistics of the channel. The considered quantifiers for energy dispersion in angular domain and second-order fading statistics are true standard-deviation, angular spread, angular constriction, and direction of maximum fading; and spatial coherence distance, spatial auto-covariance, average fade duration (AFD), and level-crossing-rate (LCR), respectively. The conducted analysis on angular spread and second-order fading statistics is of high significance in designing antenna-beams, error-correction techniques, channel estimation and equalization schemes, modulation schemes, and interleaving algorithms; for 28GHz indoor radio propagation environments.

Keywords: Angular spread, coherence distance, average fade duration, level-crossing-rate, mmWave range.

I. INTRODUCTION

In the recent years, an explosive growth in mobile communication networks is observed, which has lead to a boom of new applications and data services. This growth has emerged as a global challenge for the service providers and researchers to meet the capacity demands of emerging 5th generation (5G) of wireless communication networks. In this context, the extension and efficient-utilization of usable frequency spectrum is believed to be of vital importance. Expansion of usable frequency spectrum to higher bands of frequencies, i.e., millimeter-wave (mmWave) range, is through to be a potential research direction to address the capacity demands. Accurate understanding of radio propagation channel’s characteristics helps in devising efficient signal processing algorithms and designs for receiver to meet the capacity demands of emerging wireless communication networks. Several studies [1–3] have been presented in literature to study the channel characteristics for mmWave band, mainly at 28GHz. In [1], measurements are presented which were conducted for outdoor cellular propagation environments at 28GHz in New York City; where Path-loss, angular statistics, and delay statistics are studied. A study presented in [4], provides an analytical relationship for second-order fading statistics of mmWave communication channels. In [2], spatial and temporal characteristics of indoor radio channels for 28GHz mmWave band are studied; particularly for an indoor office environment. Various dynamic challenges in addressing the demands of emerging 5G communication networks, demand conduction of an
intensive research to study the both the large- and small-scale fading statistics of both indoor and outdoor mmWave radio propagation channels.

Mobility of mobile user terminals and the spread of energy in angular domain determines Doppler spread, which further has a direct relationship with the rate of fluctuations in the received signals envelopes. These fluctuations at small and large scale in the received signal’s envelope affect the performance of error-correction algorithms, modulation schemes, equalization, diversity, and channel coding techniques. Therefore, it is imperative to have a comprehensive understanding of the dispersion of energy in angular domain, which further helps in characterization of second-order statistics of the channels. A theory of multipath shape factors (SFs) is proposed by Durgin et al. in [5, 6], which provides a direct analytical method for quantification of the dispersion of energy along azimuth angle-of-arrival (AoA). The proposed SFs are named as, angular spread, angular constriction, and direction-of-maximum-fading. Moreover, novel analytical relationships of these SFs with second-order fading statistics of the radio propagation channels are also proposed. These second-order fading statistics quantifiers are spatial auto-covariance, coherence distance, average-fade-duration (AFD), and level-crossing-rate (LCR). In [7, 8], a new angular spread quantifier, named true standard deviation, is proposed on the basis of trigonometric moments; moreover, a new definition of SFs is also provided. These SFs are used to study the Nakagami-m and Nakagami-hoyt fading channels in [9] and [10], respectively. A detailed analysis on characterization of angular spread and second-order fading statistics of air-to-ground and different outdoor landmobile radio communication channels for both empirical and geometric channel models is conducted in [11–13]. A study conducted [14], presents an analysis on second-order fading statistics of mmWave communication channel in outdoor radio propagation environment. No such study, for angular-spread and second-order fading statistics quantification of indoor mmWave (28GHz) radio propagation channels is available in the literature, to the best of authors’ knowledge. Therefore, there is a significant scope to conduct a through study for quantification of angular spread and characterization of fading statistics of indoor mmWave radio propagation channels.

In this paper, the measurement results presented in [2], are extended from plain spatial characteristics of 28GHz indoor radio propagation channels to the quantification of energy in angular domain and characterization of second-order fading statistics of the radio channel. Analysis on the basis of SFs is presented. Furthermore, a detailed analysis on the impact of various physical and statistical parameters on the second-order fading statistics (like AFD, LCR, coherence distance, and spatial auto-covariance) of indoor mmWave radio channels is conducted. The remaining of the paper is organized as follows: Measurement setup is given in Section II. The proposed methodology is presented in Section III. Discussion on obtained results is given in Section IV. Finally, the conclusions are given in Section V.
II. OVERVIEW OF MEASUREMENT SETUP AND USED DATA-EXTRACTION METHOD

In [2], for studying spatial characteristics of 28GHz mmWave, a channel measurement campaign is conducted by utilizing direction scan-sounding in an indoor office environment. Office environment consists of aligned cubicles offices separated by cardboards and a wide entrance hall and corridors. The transmitter was positioned inside the entrance hall and measurements were taken by fixing a transmit horn antenna pointing in the corridor. Three scenarios, a line-of-sight (LoS) and two non-LoS (NLoS), were considered by changing the location of receiver. The detailed map and measurement setup details are provided in [2]. The measured data is provided as contour-maps for joint azimuth AoA and time-of-arrival (ToA). For extension of analysis, in this study we have extracted data samples by using image processing tools through color decoding from the published contour-maps. Then marginal probability distribution function (PDF) of azimuth AoA is obtained by numerically integrating the extracted joint data samples for AoA and ToA. After performing some normalization and scaling (to set peak at value 1), the marginal PDF of azimuth AoA for the selected three scenarios is plotted in Fig 1.

III. CHANNEL STATISTICS

The extracted measurement data for the PDF of azimuth AoA for mentioned indoor office environments is represented by \( p(\theta) \), where \( \theta \) represents the azimuth direction of signal’s arrival. The quantification of angular spread is conducted by adopting the theory of multipath shape factors and definition of true standard deviation proposed in [6] and [7, 8], respectively.
TABLE I. QUANTIFICATION OF ANGULAR SPREAD FOR 28GHz INDOOR RADIO PROPAGATION CHANNELS

| Spread Quantifiers | Mathematical Expression | Range | Description | Scenario 1 | Scenario 2 | Scenario 3 |
|--------------------|-------------------------|-------|-------------|------------|------------|------------|
| Name of Quantifier | | | | LoS Scenario (Fig. 8(b) of [2]) | NLoS Scenario 1 (Fig. 8(e) of [2]) | NLoS Scenario 2 (Fig. 8(b) of [2]) |
| Angular Spread [6] | Λθ = √1 - |R1|^2 | 0 ∼ 1 | Denotes concentration of multipaths around a single direction. 0 indicates the concentration of energy around exactly one path, while 1 indicates no bias. | 0.9049 | 0.7906 | 0.4125 |
| True Standard Deviation [7, 8] | σθ = -2 ln(|R1|) | 0 ∼ 2π (0° ∼ 360°) | Denotes measure of energy dispersion in angular domain. Measures the spread in true scientific notation, i.e., radians or degrees. | 74.8965° | 56.7513° | 24.7478° |
| Angular Constriction [6] | γθ = |R2 - R1|^2 / |R1|^2 | 0 ∼ 1 | Denotes concentration of multipaths about two directions. 1 indicates the concentration of energy about exactly two paths, while 0 indicates no bias. | 0.6834 | 0.3881 | 0.9212 |
| Direction of Maximum Fading [6] | θMF = \frac{1}{2} \text{phase}\{R2 - R1\} | -π ∼ π (−180° ∼ +180°) | Denotes the physical direction of maximum fading in radians. | −3.27° | 77° | −72° |

A. Definition of Angular Spread Quantifiers
The Definition of quantifiers used to gauge the spread in dispersion of energy in angular domain is presented in Table I. The \( n \)th complex trigonometric moments of angular energy’s distribution function is \( \tilde{R}_n = \tilde{C}_n + j\tilde{S}_n \); where \( \tilde{C}_n = \frac{1}{2\pi} \int_0^{2\pi} p(\theta) \cos(n\theta) d\theta \) and \( \tilde{S}_n = \frac{1}{2\pi} \int_0^{2\pi} p(\theta) \sin(n\theta) d\theta \); while the 0th coefficient represents total power. The trigonometric moments can be modified for discrete data case. In characterization of the SFs, only first and second moments are used; while \(|.|\) and \text{phase}\{\}\} represents the magnitude and phase of a complex number.

B. Characterization of Angular Spread for 28GHz Indoor Radio Propagation Channels
The computed numerical results for angular spread, angular constriction, direction-of-maximum fading, and true standard deviation for all the three measurement scenarios of AoA are presented in Table I. For the LoS case, the angular spread is observed as 0.9049, i.e., close to the highest value of 1. This is because, there also exists another dominant path other than the LoS path, which is from the direction exactly opposite from the LoS direction. This leads to the understanding that the receiver is receiving the signals from multiple directions with no clear bias to a single particular direction. For the same case, the angular constriction is observed to have a strong bias in two physical paths, with a dominant value of 0.6834, see Table I. The true standard deviation follows the similar trend as of angular spread, but it provides a true physical meanings to the quantified spread by measuring it in a true scientific unit, i.e., radians/degrees. In an indoor environment, the high density of scattering objects in the close vicinity of both the communicating nodes results in a wider angular span. A shift in angular spread and true standard deviation is clearly evident in the results, with a shift from LoS to NLoS channel conditions.
The second-order fading statistics as provided in [6] can be computed in terms of SFs. The LCR, $N_R$, measures the count of signal’s envelope’s crossings for a given signal envelope level $R$ which can be expressed as,

$$N_R = \int_0^\infty \hat{r} f_R(R, \hat{r}) d\hat{r}$$  \hspace{1cm} (1)

AFD ($\bar{\tau}$) is the time that the signal spends below the threshold level $R$ and can be defined as below,

$$\bar{\tau} = \frac{1}{N_R} \int_0^R f_R(r) dr$$  \hspace{1cm} (2)

For LOS scenario, the envelope follows a Rician fading, whose PDF is given as,

$$f_R(r) = \frac{2(K + 1)r}{P_o} \exp\left(-K - \frac{(K + 1)r^2}{P_o}\right) I_0\left(2\sqrt{\frac{K(K + 1)r}{P_o}}\right),$$  \hspace{1cm} (3)

where $K$ and $I_0(.)$ represent the Rician factor and 0th-order modified bessel function, respectively. For NLOS scenario, the envelope follows Rayleigh fading, whose PDF is given below,

$$f_R(r) = r \sqrt{\frac{2}{P_o}} \exp\left(\frac{r^2}{P_o}\right).$$  \hspace{1cm} (4)

By substituting (4) in (1) and (2), the closed-form expressions for LCR and AFD in Rayleigh fading channels are given below in terms of SFs.

$$N_R = \sqrt{2} \pi \Lambda_\theta f_m \rho \sqrt{1 + \gamma_\theta} \cos(2(\theta_v - \theta_{MF})) \exp(-\rho^2),$$  \hspace{1cm} (5)

where, $\rho$ is normalised threshold level which is equal to $R^2/P_o$, $\theta_v$ is the direction of receiver’s motion and $f_m$ is the maximum Doppler frequency.

$$\bar{\tau} = \frac{\exp(-\rho^2) - 1}{\sqrt{2} \pi \Lambda_\theta f_m \rho \sqrt{1 + \gamma_\theta} \cos(2(\theta_v - \theta_{MF}))}. \hspace{1cm} (6)$$

Another useful measure of second-order fading statistics is spatial auto-covariance, which determines the correlation of received signal at two spatial positions. The relationship of spatial auto-covariance with multipath SFs, given in [6], is shown as follows,

$$p(r, \theta_v) \approx \exp\left[-23 \Lambda_\theta^2 (1 + \gamma_\theta \cos(2(\theta_v - \theta_{MF}))) \left(\frac{K}{\Lambda}\right)^2\right].$$  \hspace{1cm} (7)

It gives correlation of envelope between the received signal at two different spatial positions separated by a distance
Fig. 2. LCR plotted against different values of threshold level and maximum Doppler shift in (a) and (b), respectively.

Fig. 3. Normalized AFD plotted against different threshold levels and maximum Doppler in (a) and (b), respectively.

Fig. 4. Spatial auto-covariance and coherence distance in (a) and (b), respectively.

The separation in space for which the response of channel remains unchanged (more than 50% correlated) is termed as coherence distance, denoted by \( D_c \). Studying coherence distance is of high significance in terms of spatial diversity and receivers design. The expression for coherence distance is shown below,

\[
D_c \approx \frac{\lambda \sqrt{\ln(2)}}{\Lambda \theta \sqrt{23 \left( 1 + \gamma \cos(2 (\theta_v - \theta_{MF})) \right)}}.
\] (8)

These analytical relationships can be used to extend the analysis conducted on SFs in Table I to study second-order
fading statistics of indoor mmWave band radio propagation environments.

D. Characterization of Second-Order Fading statistics for 28GHz Indoor Radio Propagation Channels

The impact of change in the maximum Doppler-shift and received signal’s envelope’s threshold level on the LCR, AFD, spatial auto-covariance, and coherence distance are studied in this section. In this context, the normalized LCR against different values of received signal’s envelope’s threshold level and maximum Doppler frequency is plotted in Fig. 2 (a) and (b), respectively. An increase at a slow rate in the LCR can be observed with an increase in the threshold level up to a certain threshold level, and a converse behaviour of LCR can be observed for higher values of the threshold level. However, LCR has a smaller value for NLoS scenarios as compared to the LoS scenario, for all the threshold levels and maximum Doppler shift value. The normalized AFD against different values of received signal’s envelope’s threshold level and maximum Doppler shift is plotted in Fig. 3 (a) and (b), respectively. The AFD is observed to increase and decrease with an increase in threshold level and increase in maximum Doppler shift, respectively. Moreover, a lower value of AFD is observed for the LoS scenario as compared to the NLoS scenarios. Spatial auto-covariance is plotted in Fig. 4(a) for the considered three scenarios against the distance in spatial points of observations normalized with the wavelength ($r/\lambda$). The rate of drop in spatial auto-covariance for the LoS scenarios compared to the NLoS scenarios is observed to be higher along an increase in the distance between the spatial positions of observation. Coherence distance for different scenarios of indoor mmWave channels is plotted in Fig. 4(b). The coherence indicates the separation distance between two observation points such that the spatial auto-variance remains at least 50%. Coherence distance is observed to have higher value for the LoS scenario as compared to the NLoS scenarios.

IV. Conclusions

A through analysis on dispersion of energy in angular domain and characterization of second-order fading statistics of 28GHz indoor radio propagation channels has been conducted. Plain AoA measurements conducted for 28GHz frequency band for indoor radio propagation scenarios has been first extracted from the open literature, and then extended to derive angular spread and second-order fading statistics of the radio channel. A detailed analysis on the impact of received signal’s threshold-level, maximum Doppler frequency, and/or wave-length on fading statistics of the radio channel has been conducted. The conducted analysis provide various useful insights into the behaviour of mmWave indoor radio propagation mechanism. The conducted analysis is of high significance in designing effective antenna-beams, interleaving schemes, channel estimation and equalization schemes, and error-correction codes.

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