

## First-Order Statistics of 6.4 GHz Radio Channels Under LOS and QLOS Conditions

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### Abstract

In this paper, we present an investigation of the first-order statistics of radio channels used in IEEE 802.11bn based wireless local area networks (WLANs) operating at the 6.4 GHz. Using surface wave antennas, we compare the channel characteristics for both Line-of-sight (LOS) and quasi-LOS (QLOS) conditions across two environments: an indoor seminar room and an outdoor car parking area, encompassing four mobile client to access point (AP) communication scenarios. This study employed the Rician and Nakagami- $m$  fading models to characterize the small-scale fading. Using the resistor-average distance (RAD), it was established that the Nakagami- $m$  distribution provided a better fit to the small-scale fading across all indoor scenarios, while the Rician distribution is well suited to characterizing outdoor measurement scenarios.

### 1 Introduction

With the increasing demand for wireless connectivity, IEEE 802.11 has emerged as an indispensable technology, enabling seamless wireless connectivity across diverse environments, from residential to industrial spaces. Leveraging the advancements of IEEE 802.11be [1], also known as Wi-Fi 7, IEEE 802.11bn [2, 3] will serve as the foundation for Wi-Fi 8. Wi-Fi 8 offers several key features including ultra-high reliability (UHR), multi-access point (AP) coordination, distributed multi-link operation (MLO), and 16K-QAM modulation schemes [4]. In a recent study, the authors of [5] conducted wireless channel measurements in indoor corridor environments across the 2.4, 5, and 6 GHz bands using a time-domain channel sounder. Their study provided an analysis of channel characteristics such as the average power delay profile (APDP), delay spread, path loss, and Rician  $K$ -factor as well as analyzing their frequency dependence. Although the first-order statistics, such as the probability density function (PDF) and cumulative distribution function (CDF), provide useful insights into the overall distribution of fades in fading channels, they do not capture how these fades change over time. In contrast, second-order statistics, such as the level crossing rate (LCR) and average fade

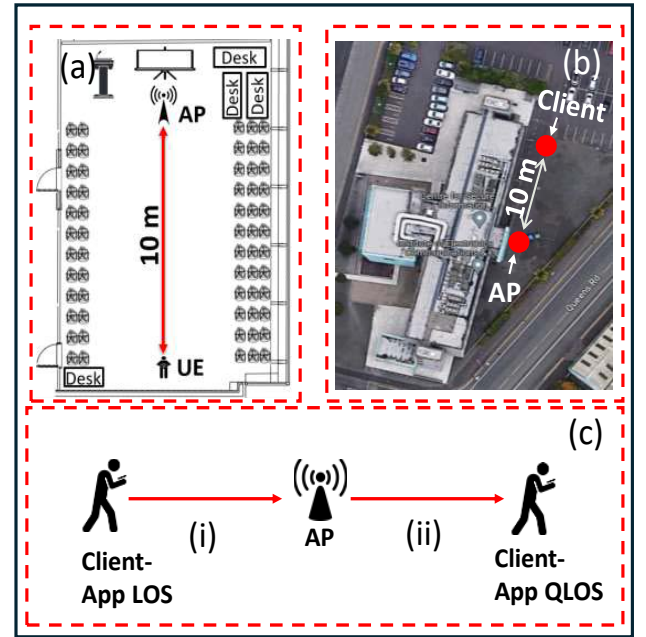


**Figure 1.** Channel measurement environments showing: (a) Floor plan of the indoor seminar room; (b) Satellite view of outdoor car parking area; and (c) An illustration of the channel measurement scenarios considered.

duration (AFD), offer valuable information on the temporal characteristics of the signal fluctuations [6]. In this paper, we present the first-order statistics of a 320 MHz region of electromagnetic (EM) spectrum from 6.425 to 6.745 GHz defined in the IEEE 802.11bn standard. To achieve this, we have conducted a series of frequency domain channel measurements over different indoor and outdoor scenarios, representative of communication between a fixed access point (AP) to a hypothetical mobile client in both line-of-sight (LOS) and quasi-LOS (QLOS) channel conditions. For our study we have used commercial surface wave antennas which achieve close to omnidirectional radiation characteristics and are designed to be resistant to the effects of detuning and shadowing caused by the human body [7].

## 2 Measurement Setup and Experiments

The channel measurements were conducted in an indoor seminar room (7.92 m x 12.58 m) and outdoor car parking area of the Queen's Titanic Quarter Building at Queen's University Belfast, UK. Figs. 1(a) and (b) show a plan view of the indoor measurement environment and the satellite view of the outdoor car parking area, respectively. In this study, we considered a 320 MHz region of the EM spectrum spanning from 6.425 to 6.745 GHz, which covered 4 resource units (RUs), each containing 996 subcarriers, in compliance with IEEE 802.11bn standard. This section of the spectrum was characterized by dividing it into 4096 equispaced frequency points, each with a subcarrier spacing of 78.125 kHz. In the IEEE 802.11be and IEEE 802.11bn standards, 3984 subcarriers are allocated for use, while 112 unusable subcarriers are reserved for guard bands, direct conversion (DC), and null subcarriers. The measurement setup consisted of a two-port Keysight P5005B Streamline Vector Network Analyzer (VNA) and two 6.5 GHz ultra-wideband (UWB) AntennaWare BodyWave antennas (part number AW-BW-NN65D11).

The transmit and receive antennas were connected to port 1 and port 2 of the VNA using two low-loss, phase-matched, flexible coaxial cables, with the transmit antenna being housed in an acrylonitrile butadiene styrene (ABS) box with dimensions representative of a mobile phone [8], and the RX antenna mounted conformal to the top of a telescopic pole, such that its back plane was parallel with the pole, at heights of 2.7 m and 3.5 m for indoor and outdoor channel settings, respectively, mimicking an AP. As the TX antenna was inside an ABS box held in the user's hand, it will have been susceptible to detuning and shadowing caused by the user's body as well as changing polarization due to movement.

The VNA was programmed to conduct a continuous frequency sweep across 4096 frequency points, coinciding with the center frequency points of the subcarriers used by channel 127 of the IEEE 802.11bn standard. It was configured to record the complex forward path gain,  $S_{21}$ , with an IF bandwidth of 70 kHz. A single frequency sweep took 73 ms to complete. Each indoor trial included a minimum of 600 sweeps, while the outdoor trials covered 400 sweeps. An adult male of height 1.75 m and mass 78 kg, took part in four different different mobile indoor and outdoor client-to-AP use cases (see Fig. 1(c)) where they imitated operating an app on the client i.e., a mobile phone/user equipment (UE), while approaching and receding away from the AP in a straight line, while maintaining an average walking velocity of 0.5 m/s under both LOS and QLOS conditions. It is worth remarking here that some of the scenarios are QLOS as opposed to non-LOS (NLOS) due to the fact that the hypothetical client device is held a small distance in front of the user's body meaning that it may have experienced a mixture of

Table 1.  
SUMMARY STATISTICS OF THE PARAMETER ESTIMATES FOR SMALL-SCALE FADING ACROSS THE 4096 SUBCARRIERS FOR THE MOBILE CHANNEL MEASUREMENT SCENARIOS

| Scenarios |          | Statistics | Rician         |           |           |        | Nakgami- $m$ |                |        |
|-----------|----------|------------|----------------|-----------|-----------|--------|--------------|----------------|--------|
|           |          |            | $\hat{\delta}$ | $\hat{s}$ | $\hat{K}$ | RAD    | $\hat{m}$    | $\hat{\Omega}$ | RAD    |
| Indoor    | App LOS  | Median     | 0.91           | 0.59      | 1.19      | 0.0260 | 1.34         | 1.52           | 0.0147 |
|           |          | IQR        | 0.11           | 0.13      | 0.74      | 0.0146 | 0.22         | 0.12           | 0.0088 |
|           | App QLOS | Median     | 0.62           | 0.81      | 0.29      | 0.0232 | 1.15         | 1.64           | 0.0169 |
|           |          | IQR        | 0.79           | 0.27      | 0.83      | 0.0141 | 0.21         | 0.16           | 0.0084 |
| Outdoor   | App LOS  | Median     | 1.00           | 0.29      | 5.78      | 0.0221 | 3.42         | 1.17           | 0.0221 |
|           |          | IQR        | 0.01           | 0.06      | 2.29      | 0.0225 | 1.08         | 0.06           | 0.0209 |
|           | App QLOS | Median     | 0.78           | 0.72      | 0.58      | 0.0056 | 1.14         | 1.65           | 0.0070 |
|           |          | IQR        | 0.65           | 0.24      | 0.81      | 0.0031 | 0.13         | 0.10           | 0.0030 |

Table 2.  
STATISTICS OF THE PARAMETER ESTIMATES FOR SMALL-SCALE FADING ACROSS THE FIRST, MIDDLE, AND LAST SUBCARRIERS FOR THE MOBILE CHANNEL MEASUREMENT SCENARIOS

| Scenarios |          | Subcarrier | Rician         |           |           |        | Nakagami- $m$ |                |        |
|-----------|----------|------------|----------------|-----------|-----------|--------|---------------|----------------|--------|
|           |          |            | $\hat{\delta}$ | $\hat{s}$ | $\hat{K}$ | RAD    | $\hat{m}$     | $\hat{\Omega}$ | RAD    |
| Indoor    | App LOS  | 1          | 0.72           | 0.74      | 0.47      | 0.0256 | 1.16          | 1.63           | 0.0198 |
|           |          | 2049       | 0.97           | 0.45      | 2.26      | 0.0697 | 1.87          | 1.35           | 0.0261 |
|           |          | 4096       | 0.85           | 0.64      | 0.87      | 0.0321 | 1.29          | 1.55           | 0.0194 |
|           | App QLOS | 1          | 0.81           | 0.70      | 0.66      | 0.0197 | 1.14          | 1.64           | 0.0146 |
|           |          | 2049       | 0.90           | 0.60      | 1.11      | 0.0293 | 1.32          | 1.53           | 0.0152 |
|           |          | 4096       | 0.91           | 0.58      | 1.25      | 0.0384 | 1.40          | 1.50           | 0.0189 |
| Outdoor   | App LOS  | 1          | 1.00           | 0.30      | 5.68      | 0.0503 | 3.35          | 1.17           | 0.0164 |
|           |          | 2049       | 0.99           | 0.32      | 4.71      | 0.0675 | 2.95          | 1.20           | 0.0298 |
|           |          | 4096       | 1.00           | 0.28      | 6.16      | 0.0327 | 3.62          | 1.15           | 0.0105 |
|           | App QLOS | 1          | 0.89           | 0.64      | 0.96      | 0.0129 | 1.19          | 1.61           | 0.0082 |
|           |          | 2049       | 0.77           | 0.73      | 0.56      | 0.0151 | 1.13          | 1.66           | 0.0107 |
|           |          | 4096       | 0.93           | 0.58      | 1.26      | 0.0164 | 1.31          | 1.54           | 0.0097 |

LOS and NLOS conditions.

## 3 First-Order Statistics

Previous studies on channel modeling have shown that small-scale fading can be modeled using the Rician [9], and Nakagami- $m$  distributions [10]. The Rician distribution is particularly suited for modeling fading signals where a dominant path, such as LOS or a specular reflection, exists alongside scattered multipath between the transmitter and receiver. The PDF and CDF of the received envelope,  $R$ , in the Rician fading channel can be expressed as follows [11]:

$$f_R(r) = \frac{2(K+1)rI_0\left(2\sqrt{\frac{K(K+1)r^2}{\Omega}}\right)}{\Omega \exp\left(K + \frac{(K+1)r^2}{\Omega}\right)}, \quad (1)$$

$$F_R(r) = 1 - Q\left(\sqrt{2K}, \sqrt{\frac{2(K+1)r^2}{\Omega}}\right), \quad (2)$$

where  $I_0(\cdot)$  is the modified Bessel function of the first kind with order zero, and  $Q(\cdot)$  represents the Marcum Q-function. The Rician  $K$ -factor is defined as the ratio of the power of the dominant component,  $\delta^2$ , to the power of the scattered multipath component,  $2s^2$ , such that  $K = \frac{\delta^2}{2s^2}$ ,

while  $\Omega = E[r^2] = \delta^2 + 2s^2$  represents the mean signal power, with  $E[\cdot]$  denoting the expectation operator. For a Nakagami- $m$  fading channel, the PDF and CDF of the signal envelope,  $R$ , are given by [12]:

$$f_R(r) = \frac{2m^m r^{2m-1}}{\Gamma(m)\Omega^m} \exp\left(-\frac{mr^2}{\Omega}\right), \quad (3)$$

$$F_R(r) = \frac{\gamma(m, mr^2/\Omega)}{\Gamma(m)}, \quad (4)$$

where  $\Gamma(\cdot)$  and  $\gamma(\cdot, \cdot)$  denote the gamma and lower incomplete gamma functions, respectively. The parameter  $m$  characterizes the severity of fading.

## 4 Results and Discussion

Over 2000 samples of the complex forward path gain, S21, were considered for four different measurement scenarios. Estimates of the path loss were obtained by initially transforming the magnitude of the S21 into the received signal power in dBm. In our analysis, the large-scale fading was extracted by calculating the local mean over a distance of ten wavelengths. To obtain the small-scale fading, both the path loss and large-scale fading were removed from the received signal power before transforming it into its linear amplitude. The Rician and Nakagami- $m$  distributions were used to model the small-scale fading and the parameter estimates were also obtained using maximum-likelihood estimation (MLE) performed in MATLAB. Table 1 provides a summary of the parameter estimates across all subcarriers. This can be seen from the estimated  $\hat{\delta}$  parameter, where the IQR for the estimates of  $\delta$ , which represents the amplitude of the dominant component, is much greater for the QLOS scenarios compared to the LOS ones, indicating increased variability of the dominant path. As expected, the LOS scenarios experienced the highest estimated  $\hat{K}$  factors, although for the indoor LOS path despite having a median  $\hat{\delta}$  comparable to the outdoor case, had a significantly lower  $\hat{K}$  estimate due to the increase in the scattered multipath  $\hat{s}$ . As shown in Table 1, the  $\hat{m}$  parameter of the Nakagami- $m$  fading model was found to be greater than unity across all indoor and outdoor app LOS and QLOS scenarios, which suggests clustering in the channel. The resistor-average distance (RAD) [13], which is a symmetric version of Kullback-Leibler divergence (KLD) [14], was used to assess the information loss associated with the use of the aforementioned distributions to model the empirical distributions. The Nakagami- $m$  distribution proved to be a more suitable fit to model the small-scale fading in both indoor LOS and QLOS scenarios, as indicated by the median RAD values given in Table 1. The Nakagami- $m$  and Rician distributions provided a comparable fit to the small-scale fading for the outdoor LOS app scenario, while the Rician distribution was favored for the outdoor QLOS app scenario. Table 2 provides examples of the parameter estimates for the small-scale fading for the first, middle, and last subcarriers (1, 2049, and 4096) across the

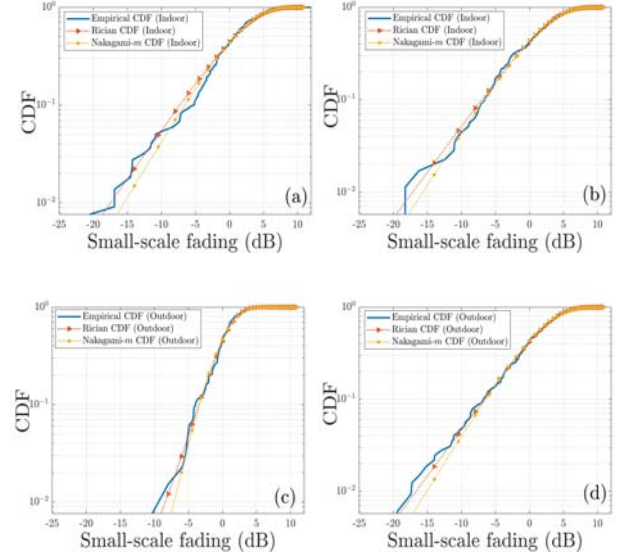


**Figure 2.** CDFs of the Rician and Nakagami- $m$  distributions fitted to empirical data (subcarrier 1) for: (a) Indoor app LOS; (b) Indoor app QLOS; (c) Outdoor app LOS; (d) Outdoor app QLOS measurement scenarios.

different scenarios. As we can see with the exception of the outdoor LOS app scenario, the parameter estimates vary across the subcarriers, showing the frequency selectivity of the channels. As examples of the small-scale fading, Figs. 2(a)-(d) show the CDF of the Rician and Nakagami- $m$  distributions fitted to the empirical data (subcarrier 1) for the indoor and outdoor app usage scenarios under LOS and QLOS channel conditions.

## 5 Conclusion

In this paper, we have performed a first-order statistical characterization of a 320 MHz region of spectrum defined in the IEEE 802.11bn standard. Parameter estimates for the small-scale fading under four separate indoor and outdoor LOS and QLOS scenarios have been obtained. Using the RAD, it was shown that the Nakagami- $m$  distribution provided a better fit to the small-scale fading across all indoor LOS and QLOS scenarios. In contrast, the Rician distribution was favored for the small-scale fading across the majority of subcarriers for outdoor LOS and QLOS measurement scenarios. The next stage of this work will study the second order statistics of these channels including the level crossing rate (LCR) and average fade duration (AFD) which are fundamental metrics for understanding the time-varying nature of the fading channels in mobile radio communications.

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## References

- [1] C. Chen *et al.*, “Overview and performance evaluation of Wi-Fi 7,” *IEEE Commun. Standards Mag.*, vol. 6, pp. 12–18, Jun. 2022.
- [2] L. Galati-Giordano, G. Geraci, M. Carrascosa, and B. Bellalta, “What will Wi-Fi 8 be? a primer on IEEE 802.11bn ultra high reliability,” *IEEE Commun. Mag.*, vol. 62, no. 8, pp. 126–132, 2024.
- [3] M. Doone *et al.*, “Signal propagation characteristics at 6 GHz and 60 GHz for Wi-Fi 8 UHR in future factories,” in *IEEE Int. Symp. Antennas Propag./USNC-URSI Radio Sci. Meeting (AP-S/INC-USNC-URSI)*, Firenze, Italy, pp. 2189–2190, Jul. 2024.
- [4] R. P. F. Hoefel, “LLR metrics for 16K-QAM soft-decision: implementation in IEEE 802.11 bn (Wi-Fi 8),” in *IEEE Latin-American Conf. Commun. (LATINCOM)*, Dominican Republic, pp. 1–6, 2023.
- [5] Z. Zhou *et al.*, “Multi-frequency wireless channel measurements and characteristics analysis in indoor corridor scenarios,” in *Proc. IEEE 94th Veh. Technol. Conf. (VTC-Fall)*, pp. 1–5, Sep. 2021.
- [6] J. M. Morris and J. L. Chang, “Burst error statistics of simulated Viterbi decoded BFSK and high-rate punctured codes on fading and scintillating channels,” *IEEE Trans. Commun.*, vol. 43, pp. 695–700, 1995.
- [7] “BodyWave Antenna.” <https://antennaware.co.uk/product/bodywave/uwb-antenna>. (Accessed: Mar. 06, 2025).
- [8] S. L. Cotton, “Human body shadowing in cellular device-to-device communications: Channel modeling using the shadowed  $\kappa - \mu$  fading model,” *IEEE J. Sel. Areas Commun.*, vol. 33, no. 1, pp. 111–119, 2015.
- [9] S. K. Yoo *et al.*, “Channel characteristics of dynamic off-body communications at 60 GHz under line-of-sight (LOS) and non-LOS conditions,” *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 1553–1556, 2017.
- [10] M. Nakagami, “The  $m$ -distribution—A general formula of intensity distribution of rapid fading,” in *Statistical Methods in Radio Wave Propagation*, pp. 3–36, Elsevier, 1960.
- [11] A. Abdi, K. Wills, H. A. Barger, M.-S. Alouini, and M. Kaveh, “Comparison of the level crossing rate and average fade duration of Rayleigh, Rice and Nakagami fading models with mobile channel data,” in *IEEE VTC*, vol. 4, pp. 1850–1857, 2000.
- [12] S. L. Cotton and W. G. Scanlon, “A statistical analysis of indoor multipath fading for a narrowband wireless body area network,” in *Proc. 17th IEEE Int. Symp. Personal Indoor Mobile Radio Commun. (PIMRC)*, pp. 1–5, Sep. 2006.
- [13] D. H. Johnson and S. Sinanovic, *Symmetrizing the Kullback–Leibler Distance*. Houston, TX, USA: Rice Univ. Working Paper, 2001.
- [14] S. Kullback, *Information theory and statistics*. New York, NY, USA: Wiley, 1959.