**Abstract**—A stadium is a multiuser scenario where the wireless system should be able to support real-time service delivery when the stadium is at full capacity during an event. To address radio propagation design for this type of challenging scenario, theoretical and empirical method is needed. Extensive open-space static measurements and research have been conducted at 28 and 60 GHz frequencies in an empty seating area of a stadium with a capacity of 60000 seats. The findings of this work lay a good foundation towards a greater understanding of mmWave channel propagation in a stadium, where a sectorization approach is considered to characterize the path loss behavior in 3D and predict it at unmeasured locations through the Kriging-aided model proposed with only 1 dB RMSE.

**Index Terms**—3D path loss, mmWave, radio propagation design, stadium, Kriging.

## I. INTRODUCTION

ALWAYS motivated by the need of people communication, radio propagation systems have evolved remarkably over the years, providing connectivity and continuous improvements for wireless communication services. While fast-growing, researchers, telecommunication students, and engineers, have to consider innovative approaches to continuously address user demands and provide progressive involvement in technology development, as well as its usefulness and support capabilities for massive consumers. To address the high-density challenge, the exploration of new spectrum bands, as millimeter-wave (mmWave) is becoming increasingly. A stadium is a clear example of multiuser scenario where the wireless system should be able to support real-time service delivery when the stadium is at full capacity during an event. In order to increase network capacity, the sectorization technique is performed in this type of high-density scenario, therefore, it is essential to ensure interference control. To accomplish this aim, the main requirements are issues related to efficient use of network resources as is mentioned in [1], e.g., accurate coverage predictions and clear footprints of each sector.

It is important to emphasize that a stadium is a complex scenario. First, there are the dressing rooms, the commentary box, tunnels, etc., which are similar to any other office building. Additionally, there is the seating area, which is an inclined surface whose modeling is complex. Not forgetting the fact that it is practically an outdoor scenario where it is more difficult to contain the radio signal levels. Therefore, a stadium needs its own radio frequency network, where three-dimensional (3D) modeling is essential since, due to its geometry, users will be at different levels as a result of the inclined surface of the seating area.

Proper path loss characterizing in a stadium accomplishes real knowledge of the network coverage when addressing the challenges that come with i) capacity and spectrum utilization, and ii) high density. Taking into account the first challenge inherent to future wireless communication, in [2], the authors investigated several stationarity properties of a massive multiple input and multiple output (MIMO) channel in a stadium at 1.4 and 4.4 GHz. Also, in [3] the design of two-dimensional (2D) arrays in a stadium was considered for increasing the capacity through large cell sectorization. Regarding the second challenge, measurements and research have been conducted in stadiums in order to analyze the coverage and capacity at 28 and 5 GHz, considering body loss as parameter that can severely affect system performance [4]–[6]. Despite the challenges overcome in [2]–[6], and the research available in [7], where iBwave presented a complete report to design better wireless networks for stadiums describing the best practices and a detailed radio frequency design. These studies do not design a path loss model for radio channel characterizing.

In the performance of wireless communication systems, channel modeling is crucial to understand what happens with the waves over the transmission path. Measurement-based models can predict signal attenuation over a link, considering all propagation factors implicit in field measurements. But, when a large amount of useful data cannot be achieved during sampling in measurement campaigns, Kriging can be included as a powerful and accurate tool to predict unmeasured values [8]. Notwithstanding the relatively realization that mmWave frequencies are viable for mobile communications. Currently, few attempts [9] have been made to understand radio channels in stadiums above 28 GHz where there are much wider unused bandwidth slots available. Therefore, we
considered that 28 and 60 GHz measurements offer some insight to move a step forward for channel modeling at mmWave. To the best of our knowledge, this is the first radio propagation empirical model proposed for stadiums at mmWave frequencies, to achieve accurate predictions for 5G communication systems. Where specially constructed narrowband sounders were employed to recollect careful and extensive measurements, which allow us to report separation distances between the transmitter and receiver much greater than those reported in [9]. The main contributions of this letter are as follows.

- A suitable sectorization approach is studied to understand and characterize radio wave propagation in a stadium at mmWave frequencies in terms of the traditional single slope (SS) model. Considering possible 3D effects, as the transmitter and receiver are at different heights on the inclined surface.
- The inclusion of Kriging is an effective tool to improve modeling accuracy for mmWave propagation as it considers all the singularities in the seating area and stadium-associated features that are implicit in measured samples.
- Better understanding and modeling of path loss at a stadium considering the effect of different transmitter heights (i.e., 3D) validating the benefits of using Kriging to ensure accurate path loss predictions with the best and least amount of training samples.

II. DATA COLLECTION PROCEDURE

An extensive amount of carefully calibrated signal strength radio measurements at mmWave frequencies was performed in the 8089 m$^2$ of the seating area of the Sausalito Stadium in Vina del Mar, Chile. Universidad Técnica Federico Santa María (USM) in collaboration with Pontificia Universidad Católica de Valparaíso (PUCV) and Nokia Bell Laboratories constructed the two narrowband sounders used during measurement campaign at 28 GHz [10] and 60 GHz. Measurements were carried out with the seating area empty to assure a static scenario. The radio systems at both frequencies transmit a continuous wave (CW) tone into a vertically polarized horn antenna with 55° half-power beamwidths and a gain of 10 dBi.

At 28 GHz the transmitted power is 22 dBm and at 60 GHz is 20.5 dBm. The narrowband sounder platform at 28 and 60 GHz are visualized in Fig. 1a and Fig. 2a. Both receive the signal with an omnidirectional (omni) antenna and amplify it with several adjustable gain low-noise amplifiers, mixed with a local oscillator, resulting in an intermediate frequency (IF) signal centered at 100 MHz. The IF signal power (filtered by a 200 kHz-wide bandpass filter) is measured and converted to digital values through a logarithmic-gain power meter that generates 740 samples/second. Finally, these samples are transmitted to a laptop computer. Measurable path loss extends to 171 dB at 28 GHz and to 167 dB at 60 GHz with directional antenna gains.

For 28 GHz the omni antenna has a gain of 1.4 dBi and at 60 GHz 2 dBi with a vertical half-power beamwidth of 30°. As pictured in Fig. 1a and Fig. 2a the receiver (Rx) is placed on a rotating 360° platform with the omni antenna describing a circle of 20 cm radius, thus, the received power is calculated based on the spatially averaged received when the transmitter (Tx) system (Fig. 1b and Fig. 2b) is moved at each desired location. The Rx and Tx were always placed at 1.66 m height and the horn antenna of the Tx was manually aimed to get maximum average received power at each measurement location. In order to properly characterize and represent the complete seating area of a typical stadium, 100 locations were carefully selected, as is illustrated in Fig. 3. Besides, according to the radio system size, the transmitting system was selected to be strategically moved through the seating area locations, emulating a mobile user equipment, as is visualized in Fig. 1 and Fig. 2. While the receiving antenna was fixed to the first or the second location under the roof in the seating area, emulating a base station.
During the measurement campaign, some places were unreachable due to the seating area was separated by barriers, as illustrated in Fig. 3 with the blocked access legend. As a result of considered two different receiving locations at two frequencies, four scenarios were assessed for the measurement campaign. Where 100-samples were recollected at each scenario, yielding a total of 400 received power samples.

### III. PATH LOSS ANALYSIS FOR RADIO WAVE PROPAGATION

From the received power measurements $P_{RX}$ and the features of the radio system, i.e., the transmitted power $P_{TX}$ and the antenna gains ($G_{TX}$, $G_{RX}$), the path loss is extracted from the link budget at each location with $L = P_{TX} + G_{TX} + G_{RX} - P_{RX}$. In order to illustrate the behavior of radio propagation in a stadium, Fig. 4 shows the path loss measured when the receiver is located at the second point. As is mentioned in [11], theoretically, the path loss in free space decreases quadratically as frequency increases, so long as the effective aperture of the antenna is kept constant over frequency at both link ends.

Towards path loss modeling, it will be possible to contemplate a stadium venue as a free space scenario, however, despite the fact that the physical size of both antennas is kept constant and the venue suggests a pure line-of-sight (LOS) link between the transmitter and receiver antenna, the behavior of the path loss needs to be investigated due to it is not accurately characterized as free space (FSPL), and, as is shown in Fig. 5, is clear that the radiofrequency propagation environment differs vastly within the stadium, from LOS without reflections to LOS with a lot of reflections in the seating area. In order to provide an average tendency of measured path loss a fitting green curve is illustrated in Fig. 5 for both frequencies used during the measurement campaign. This green curve is computed through the traditional SS model [12, Ch. 9]

$$L = L_0 + 10n \log(d) + L_s,$$

with $L_0$ as the free space path loss at a 1 m distance, $n$ as the path loss exponent (PLE), $d$ as the Euclidean distance of the link, and $L_s$ as the shadowing component, i.e., a zero-mean Gaussian random variable with a standard deviation $\sigma$.

On average, the measured path loss difference at each location between 60 and 28 GHz was 7.8 dB. Which initially shows a similarity with the theoretical value calculated by the FSPL equation ($20 \times \log_{10}(60/28) = 6.6$ dB). Besides, as seen in Fig. 5, the measured path loss difference between the fitting green curves and FSPL is only 1 dB at 60 GHz and 2.3 dB at 28 GHz. However, both green curves have an $n$ less than 2, suggesting a better scenario than free space, with $n = 1.95$ at 60 GHz and $n = 1.89$ at 28 GHz.

In the design of a radio network, the main purpose of sectorization is to consider specific areas to cover, reducing the interference as well as improving capacity. Thus, and in seeking of a further analysis in the radio propagation in stadiums, three different cases are analyzed for signal propagation description: the first, sectorized the stadium in 4 zones according to the coordinates in the seating area of the stadium, case illustrated on the left side of Fig. 6; the second, sectorized the measurements according to the altitude reported for the transmitted antenna location, yielding 5 zones visualized in the right side of Fig. 6; and the third, consider all the measurements without constraint the selection of the samples. The first and second cases were motivated by the sectorization schemes released in [7].
IV. PATH LOSS PREDICTIONS

Based on the geostatistical fact that there is an implied connection between the observed values (measured path loss) and its location in the space (3D coordinates), two main procedures are considered to predict the path loss: variography, for modeling the variogram and Kriging, for interpolation [13]. The aim of the variogram model is to describe the spatial dependency of the path loss measured between the blue locations illustrated in Fig. 3. This variogram is used to predict the unknown path loss $\hat{L}$ at an unobserved location $c_0$ according to a weight $\lambda_i$ estimated from known path loss measurements $L_{ci}$ through ordinary Kriging:

$$\hat{L}_{c_0} = \sum_{i=1}^{N(h)} \lambda_i \cdot L_{ci}, \quad (2)$$

where $N(h)$ is the number of pairs of measured locations within the lag interval $h$ selected to estimate the path loss at an unmeasured point with $c(0)$ 3D coordinates, in other words, $h$ is the size of a distance class into which pairs of locations $N(h)$ are grouped. An extensive mathematical description of the variography and ordinary Kriging process is described in [14].

To overview our findings, Table I is presented to show $n$ as well as $\sigma$ for signal propagation description when a SS model is considered for the 3-cases previously described. To compute (1), the measurements gathered at both receiver locations are joined according to the frequency and employed to tune the model.

The main conclusions of the summary provided in Table I are: i) The least path loss variations occur in zone 2 when sectorization is achieved according to case 1, due to the position of the receiver antenna. Which, for this zone, is located exactly in front of the transmitter positions; ii) The highest standard deviation in the measured path loss is found in zone 1 for case 2, this is largely related to the sectorization approach since in this case, zone 1 is located around the entire soccer field and measurements are probably affected by the reflections that occurred due to the proximity to the fence net and field; and iii) At both frequencies when all samples are taking into account (case 3) the PLE is less than free space, i.e., 2, which becomes our goal to further investigate propagation in a stadium by predicting path loss with an accurate model.

To train and validate the accuracy of the Kriging-aided model, two datasets are extracted from the measurements: the first dataset, named as samples in Table II, is used to calculate $\lambda_i$ and $L_{ci}$ in (2); and the remaining dataset is designated to validate the path loss predicted at those locations. In addition, and towards decrease the quantity of required samples to train Kriging, the $20 – 120$ samples were extracted with a percentage varying from $10 – 60$ percent. The boundary of 60 percent was selected according to the findings reported in [14]. The datasets are selected according to the three cases described in Section III, e.g., for case 1 in Table II, if 60 percent is selected to extract samples, it is ensured that this percentage is randomly-extracted from each zone of the first case (illustrated in Fig. 6), resulting in 120-random samples available to train Kriging; the remaining 80-random samples (40 percent) are intended for testing and validating the model in terms of the root-mean-square error (RMSE).

In order to include the largest number of possible randomly drawn samples, 1000-tests were assessed to calculate the RMSE of predictions. After 1000-RMSE were assessed for each case, results were averaged and reported in Table II, aiming to quantify and validate the accuracy of the Kriging-aided model (K) proposed.

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It is evident that when the sample size—with which Kriging is trained—increases, the confidence in the estimates also increases, as well as the accuracy, decreasing the RMSE. For the 3 cases, at both frequencies, from 20% to 60% of the sample size selected (40 - 120 samples), there is not an evident RMSE difference between the cases analyzed for the sectorization approach. This allows us to conclude that for this type of scenario there is not necessary to zone the sampled field to extract the training dataset, as in the last case, which provides an excellent trade-off between the number of samples employed and the error in the prediction. On average, for the third case, tuning the model with 80 to 120 samples the RMSE is only $1.7$ dB for 28 GHz and $1$ dB for 60 GHz.

By comparing case 3 against cases 1 and 2, we can understand the potential of the methodology followed by Kriging, which first, analyzes the spatial variability of the samples, and later, in accordance with the previous analysis, interpolates the best set of samples to achieve suitable predictions at unmeasured locations. Furthermore, Table II suggests that from 80 samples the RMSE converges to the lowest reported error, i.e., only 40% of randomly-separated samples represent enough quantity to sample a stadium with a seating area of
TABLE III
RMSEs for Path Loss Predictions Employing SS and K Models

| Frequency [GHz] | RMSE value | RMSE<sub>SS</sub> [dB] | RMSE<sub>K</sub> [dB] |
|----------------|------------|------------------------|------------------------|
| 28             | Min        | 1.4                    | 1.3                     |
|                | 1000-averaged | 1.8                    | 1.7                     |
|                | Max        | 2.2                    | 2.0                     |
| 60             | Min        | 1.2                    | 0.6                     |
|                | 1000-averaged | 1.7                    | 0.9                     |
|                | Max        | 2.2                    | 1.6                     |

an 8089 m<sup>2</sup> for suitably Kriging-training and accurate radio propagation predictions.

To compare the performance of the model here proposed, Table III provides a summary of the 1000-RMSEs achieved when a 60/40 percentage rate is extracted from all stadium measurements to tune/test both the well-known SS model employed for LOS links, described in (1), and the K model, described in (2). In Table III, RMSE<sub>SS</sub> refers to the RMSE calculated when (1) is employed, and RMSE<sub>K</sub> when (2) is used to predict the path loss at testing locations.

Through the RMSE values listed in Table III, we conclude that the K model is very robust: Firstly, despite the complex scenario considered to provide predictions in an inclined surface, minor RMSE values are presented when the K model is employed; Secondly, averaging 1000-iterations achieved, the RMSE reported is just 1.7 and 0.9 dB for 28 and 60 GHz scenarios, respectively, which justifies including Kriging as part of the post-processing to predict unmeasured data reducing the RMSE by 0.2 dB for 28 GHz and 0.8 dB for 60 GHz when it is compared to SS model RMSEs; Thirdly, the K model performs just as well when tested against stadium as indoor [8], [14] and outdoor-to-indoor [15] measurements at mmWave frequencies. After tests were achieved by analyzing maximum, average, and minimum RMSEs listed in Table III, it was possible to validate the consistency and the adaptability of the K model for this complex scenario ensuring its usefulness for path loss predictions.

V. CONCLUSION

This letter studied the propagation environment of a not well investigated venue as is a stadium, provided a path loss analysis when sectorizing measurements according to its locations, and validated the potential of employing Kriging for path loss prediction when few samples are considered, allowing RMSE as small as 1 dB. Besides, it was corroborated that the usefulness of the model proposed can be extended not only for indoor scenarios, as reported in [8], [14], but also for a complex venue as is a stadium. The processed data and the findings according to the Kriging-aided approach will help with mmWave wireless network design for this specific scenario. Additionally, and on behalf to outperform the Kriging-aided path loss model, a characterization of small-scale fading in stadiums could be interesting future work, considering the possibility of increasing statistical precision when designing a wireless communication system.

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