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Attenuation over distance and excess path loss for a large-area indoor commercial topology at 2.4 GHz

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Abstract—**The present work features the evaluation of curve fitting models for the estimation of attenuation over distance and excess path loss, on the basis of extensive measurements performed in a large-area indoor commercial topology at 2.4 GHz. The case study is the departures level of Athens International Airport, including up to three Access Points. The basic propagation mechanisms in this scenario are free space propagation with direct Line-of-Sight, reflection and multipath. Hence, a shadow fading based methodology for the calculation of excess path loss and attenuation over distance is not applicable in this case. For this purpose, an alternate method has been developed, featuring various models which have been employed and fit to the experimental data. Their fitting robustness has been compared in terms of Goodness-of-Fit metrics such as the R-Square and the Adjusted R-Square. Coefficients with 95% confidence bounds have been calculated and put to the test. The excess path loss has been estimated in relation to the distance and the logarithm of the distance. Results vary as to their precision according to the nature of each case study, in terms of propagation mechanisms, and the efficiency of each curve fitting model.**

Keywords- Indoor propagation; Path Loss; Wireless Channel Characterization; Goodness-of-fit; Attenuation over distance

I. INTRODUCTION

The indoor wireless channel presents many challenges for students, academics and industry engineers alike, since it is subject to a large number of propagation mechanisms that influence the signal transmitted from a source to a destination throughout the topology. Free Space propagation is altered by obstructing materials, multipath phenomena and the intrinsic topology characteristics. Many published works and textbooks [1]-[7] have investigated wireless channel characterization for cellular telephony frequencies (900-1800-2100 MHz). There has been, however, a more limited amount of research for path loss modeling in certain higher frequencies, where the nature of propagation mechanisms becomes more dependent on the topology characteristics, leading to a respective classification of indoor topologies by ITU. For the 2.4 GHz in particular, which is of significance due to 802.11g Wi-Fi/WLAN operating networks, while many works have dealt with the issue of small-scale fading [8]-[13], there had been little interest for validation of the most commonly employed path loss models, and extensive radio-frequency (RF) measurements were not that popular.

Recent published works, however, have validated the importance of comparative estimation of the path loss models' reliability in terms of average signal prediction for different indoor propagation environments. In [14], the ITU path loss model was validated for a complex indoor propagation topology, providing numerical adjustments to the original ITU specifications [4] which were proven to be erroneous for the 2.4 GHz. In [15], an empirical method was developed for the calculation of shadow depth based on attenuation losses caused by obstacles, walls, floors and materials of different type and number meddling with the signal path. This method does not require extensive on-site RF measurements, only limited measurements around the obstacles. In [16], the Free Space model, the ITU model and the One-Slope model were validated for a large-area indoor commercial topology, the Athens International Airport. In [17] and [18], more obstacle-dense indoor propagation topologies were examined, and the shadow depth was calculated on the grounds of the empirical formula developed and validated in [15]. In these topologies, empirical models such as the Multi-Wall-Floor [19] and the Motley-Keenan model [20] were also validated in terms of mean error prediction. All measurements in all topologies were performed as late in the evening as possible, in order to avoid interference from people, namely the "body shadowing" [21].

This work focuses on the large-area indoor commercial topology selected for path loss modeling in [16]. In the context of the present work, the attenuation over distance and excess path loss parameters are investigated in terms of curve fitting, since a shadow-based numerical technique cannot be employed, due to the nature of the topology. The paper is structured as follows: Section II introduces the attenuation over distance and excess path loss parameters. The Linear Attenuation Model is presented and a method for the calculation of attenuation over distance and excess path loss is described. Section III presents the large-area indoor commercial propagation topology examined in this work. The fundamental difference of this topology in relation to obstacle-dense environments is addressed, on the basis of which a curve fitting technique will be employed for the estimation of attenuation over distance and excess path loss. Section IV presents the results of the curve fitting for various models compared in terms of Goodness-of-Fit metrics, and the coefficients for 95% confidence bounds. Section V discusses the findings, whereas Section VI sums up the conclusions of this work.

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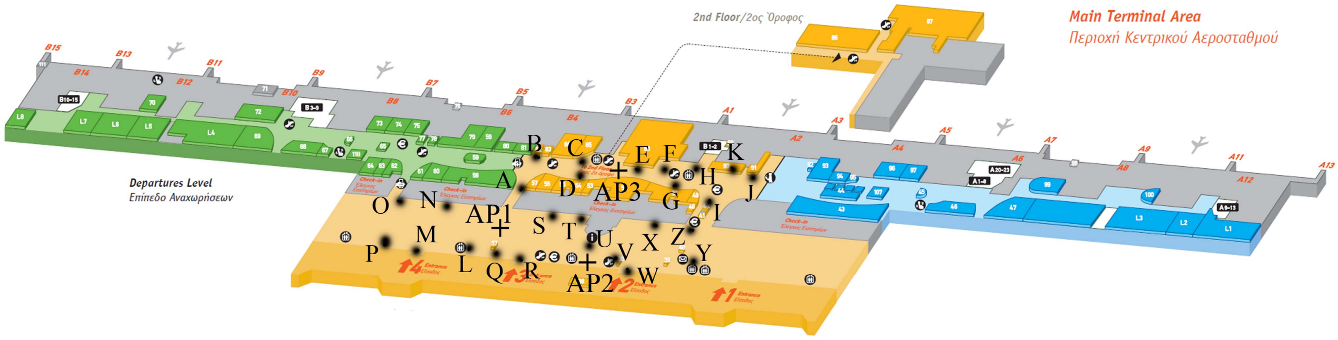

Figure 1. Departures Level of Athens International Airport

II. ATTENUATION OVER DISTANCE

Attenuation over distance (dB/m) is an important parameter in wireless communications. In the context of wireless channel characterization, attenuation over distance expresses the impact of topology characteristics on the propagated signal and is a key metric of the attenuation losses when signal propagation occurs throughout a given topology. These attenuation losses are frequency-dependent and distance-dependent. A mathematical formula that links the attenuation over distance to the average path loss is the Linear Attenuation Model, also known as Devasirvatham model [5]:

$$P_L(dB) = P_{L0}(dB) + 10n\log_{10}(d) + ad \qquad (1)$$

Where $P_L(dB)$ stands for the average path loss (dB), $P_{L0}(dB)$ stands for the frequency-dependent reference path loss (path loss at 1m distance from the transmitter), n is the path loss exponent that expresses the rate of attenuation losses, a the attenuation over distance (dB/m), and d the transmitter-receiver distance (T-R separation), in meters. The product of $a(dB/m)*d(m)$ can also be used to express the excess path loss, defined by Jakes as “the difference (in decibels) between the computed value of the received signal strength in free space and the actual measured value of the local mean received signal” [22]. By employing the Devasirvatham model, the excess path loss is directly linked to the attenuation over distance.

If a pool of experimentally measured local-mean received power values is available for a given topology, and the total Effective Isotropically Radiated Power (EIRP) is known, then the attenuation over distance can be calculated from the measured values of the local mean signal. Past works have focused on such calculations for the cellular telephony frequency bands [23]. For the 2.4 GHz frequency, the attenuation over distance has been calculated from an extensive experimental set of data in [24], on the grounds of Eq.2 (40 dB stands for reference path loss at 2.4 GHz):

$$a = \frac{EIRP(dBm) - P_r(dBm) - 10n\log_{10} d - 40dB}{d} \qquad (2)$$

For the calculations in [24], three different methods have been proposed regarding the value of the path loss exponent. In this work, a fixed path loss exponent of n=1.8 is considered. This value has been suggested in a number of published works [5], as the path loss exponent that corresponds to free space propagation. This way, attenuation over distance is considered to be the excess path loss according to Jakes’ definition. This method has also been endorsed in [15], where the shadow depth has been calculated as the excess path loss (independent of free space propagation) on the basis of attenuation introduced by obstacles, walls and floors meddling with the signal path. The link of shadowing to excess path loss as a process independent of free space propagation has also been investigated in outdoor propagation scenarios [25]. This method does not require an extensive set of measurements throughout the topology, as in Eq.2, only limited measurements around the obstacles meddling with the signal path. However, such a method is suitable for obstacle-dense topologies. The case study examined in this work is a different type of indoor topology and requires a radically different approach.

III. CASE STUDY: ATHENS INTERNATIONAL AIRPORT

Athens International Airport was selected as a de facto large-area indoor commercial topology, according to ITU specifications. Measurements were performed throughout the departures level public hall, depicted in Fig.1 [16]. A total of 26 measurement locations were selected, monitoring and recording the signal originating from three Access Points (APs) in each location within range. Each AP corresponds to a different Line-of-Sight (LOS) and Obstructed-Line-of-Sight (OLOS) balance scheme. AP1 provided both OLOS and LOS cases, with a relatively dominant OLOS scheme (OLOS/LOS). AP2 featured a dominant LOS scheme and AP3 both LOS and OLOS cases, with a relatively dominant LOS scheme (LOS/OLOS).

In this topology, the excess path loss and the attenuation over distance cannot be calculated on the basis of shadow fading. The basic propagation mechanisms are free space-LOS, reflection and multipath. Therefore, curve fitting models will be applied and evaluated in relation to the measured data. The purpose of the model fitting is to develop, via Goodness-of-Fit analysis and evaluation of confidence bounds, estimation tools for these parameters.

IV. RESULTS

A. Attenuation over distance

As shown in [24], the attenuation over distance for the large-area Athens International Airport topology provided radically smaller values than any other indoor topology examined. The Power model, depicted in Eq.3, and the 4-th degree Polynomial, depicted in Eq.4, have been employed to fit the measurement-based values of attenuation over distance.

In Tables I-III, the Goodness-of-Fit of these two models is compared in terms of R-Square and adjusted R-Square for all three APs. Based on these findings, the Power model is deemed more appropriate as an estimate tool, and the 95% confidence bounds of the fit to the attenuation over distance data set are depicted numerically and graphically in Table IV and Fig.2-4 respectively.

$$f(x) = ax^b + c \tag{3}$$

$$f(x) = p_1x^4 + p_2x^3 + p_3x^2 + p_4x + p_5 \tag{4}$$

TABLE I. AP1

Goodness-of-Fit	**Power Model**	**4-th degree Polynomial**
R-Square	0.890	0.869
Adjusted R-Square	0.873	0.822

TABLE II. AP2

Goodness-of-Fit	**Power Model**	**4-th degree Polynomial**
R-Square	0.647	0.443
Adjusted R-Square	0.569	0.125

TABLE III. AP3

Goodness-of-Fit	**Power Model**	**4-th degree Polynomial**
R-Square	0.771	0.905
Adjusted R-Square	0.713	0.842

TABLE IV. POWER MODEL COEFFICIENTS

AP1	**AP2**	**AP3**
Coefficients (with 95% confidence bounds): a = 1.39e+012 (-1.703e+017, 1.703e+017) b = -13.43 (-5.967e+004, 5.965e+004) c = 0.07056 (-0.01079, 0.1519)	Coefficients (with 95% confidence bounds): a = -1.63e+010 (-7.738e+011, 7.412e+011) b = -9.351 (-27.57, 8.87) c = 0.09237 (-0.03268, 0.2174)	Coefficients (with 95% confidence bounds): a = 1.385e+010 (-1.328e+017, 1.328e+017) b = -13.46 (-5.455e+006, 5.455e+006) c = -0.005011 (-0.1096, 0.09958)

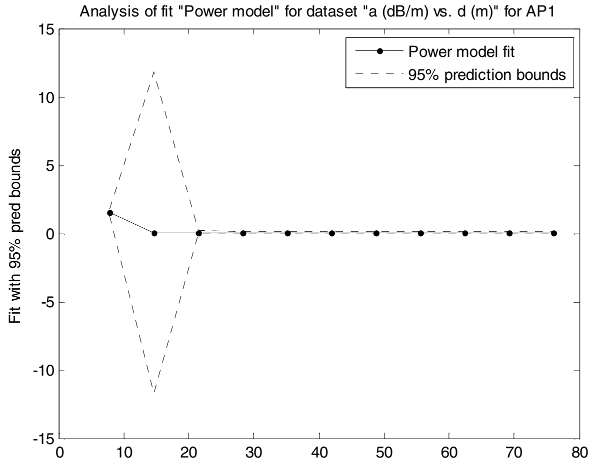

Figure 2. Fit with 95% prediction bounds for AP1

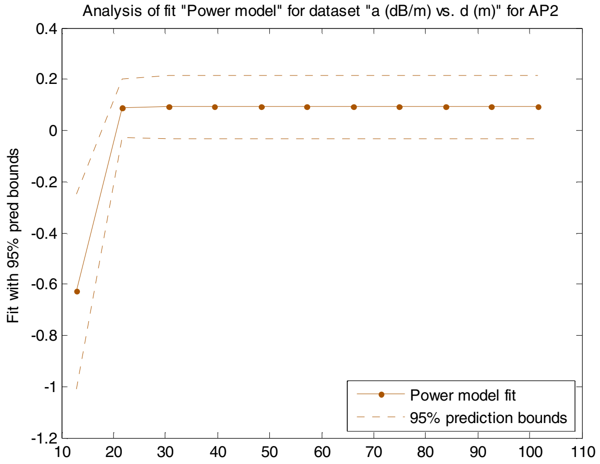

Figure 3. Fit with 95% prediction bounds for AP2

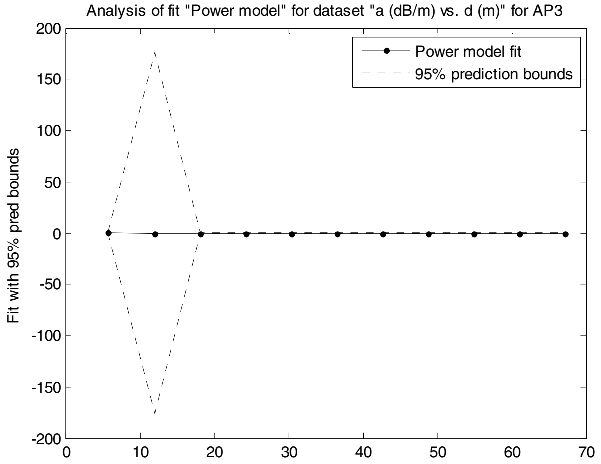

Figure 4. Fit with 95% prediction bounds for AP3

B. *Excess path loss*

In this work, the product of a (dB/m) and distance (m) will be considered as the metric of excess path loss. This is in compliance with Jakes' definition of excess path loss [22]. Since Athens International Airport has been chosen and investigated as a case study of large-area, LOS-dominant indoor commercial topology with heavy reflection phenomena, the empirical method based on shadow depth calculation due to obstacles, materials and walls – as it has been developed in [15], [25] - will not be employed for estimating excess path loss. Therefore, other models will be applied to fit the experimental data of excess path loss, including the Gaussian model, shown in Eq.5, the General Sinusoid model shown in Eq.6, and the Cubic, Quadratic and Linear Polynomial, which can be derived out of Eq.4.

The Goodness-of-Fit for the data set of 'excess path loss' versus distance (m) for each AP is performed in terms in R-Square and Adjusted R-Square. The curve fitting is shown in Fig.5-7. The Goodness-of-Fit results are depicted in Tables V, VI, and VII respectively.

AP1 features a scenario of OLOS and LOS cases, with a relatively dominant OLOS scheme. The Power model and the Cubic Polynomial are employed.

$$f(x) = a_1 e^{-\left(\frac{x-b_1}{c_1}\right)^2} \tag{5}$$

$$f(x) = a_1 \sin(b_1 x + c_1) \tag{6}$$

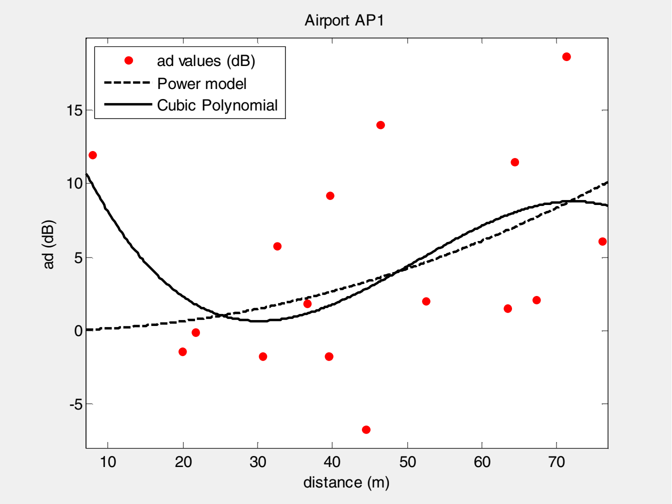

Figure 5. Goodness-of-fit for excess path loss vs. d (AP1)

TABLE V. GOODNESS-OF-FIT FOR AP1

Goodness-of-Fit	**Power Model**	**Cubic Polynomial**
R-Square	0.091	0.250
Adjusted R-Square	0.026	0.063

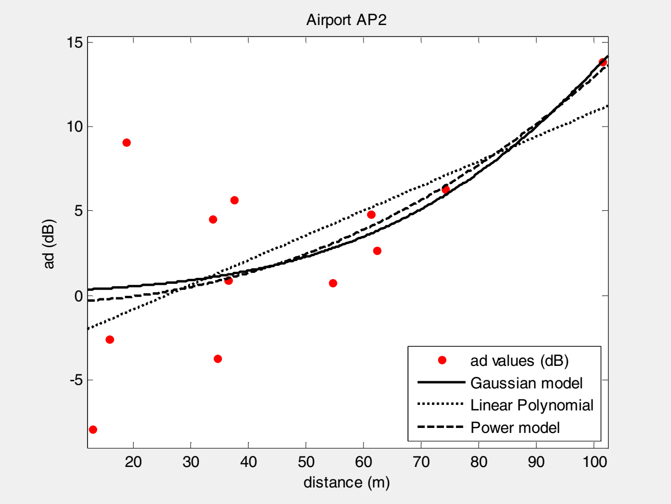

Figure 6. Goodness-of-fit for excess path loss vs. d (AP2)

TABLE VI. GOODNESS-OF-FIT FOR AP2

Goodness-of-Fit	**Power Model**	**Linear Polyn.**	**Gaussian**
R-Square	0.446	0.427	0.446
Adjusted R-Square	0.323	0.369	0.323

AP2 features a dominant LOS scheme. The Gaussian model, the Linear Polynomial, and the Power model are employed. For AP3, which includes both LOS and OLOS cases with a relatively dominant LOS scenario, the Gaussian model, the Cubic Polynomial and the Sinusoid model are employed.

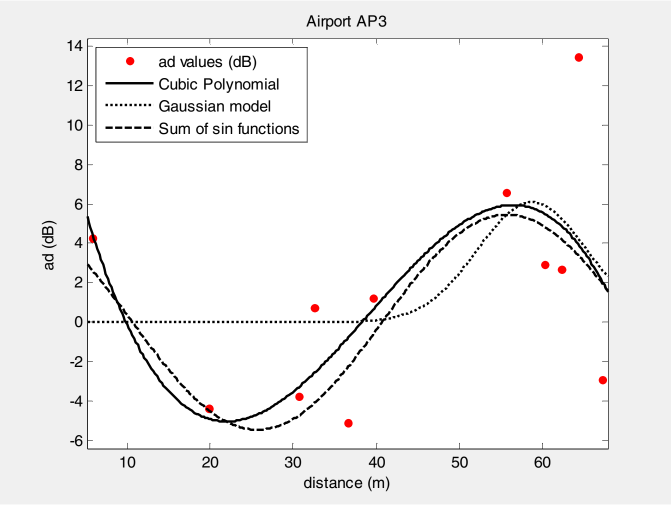

Figure 7. Goodness-of-fit for excess path loss vs. d (AP3)

TABLE VII. GOODNESS-OF-FIT FOR AP3

Goodness-of-Fit	**Sin. Model**	**Cubic Polyn.**	**Gaussian**
R-Square	0.442	0.487	0.308
Adjusted R-Square	0.303	0.268	0.134

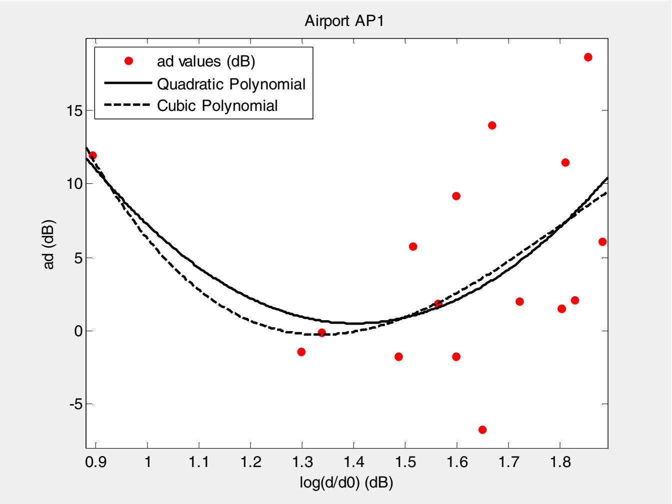

Figure 8. Goodness-of-fit for excess path loss vs. logd (AP1)

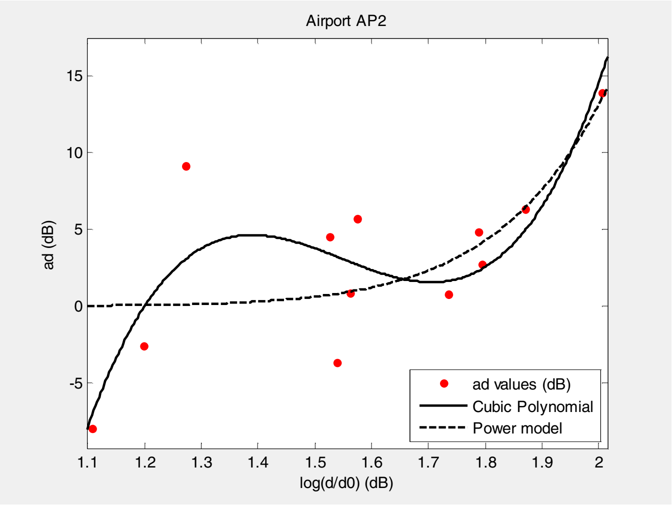

Figure 9. Goodness-of-fit for excess path loss vs. logd (AP2)

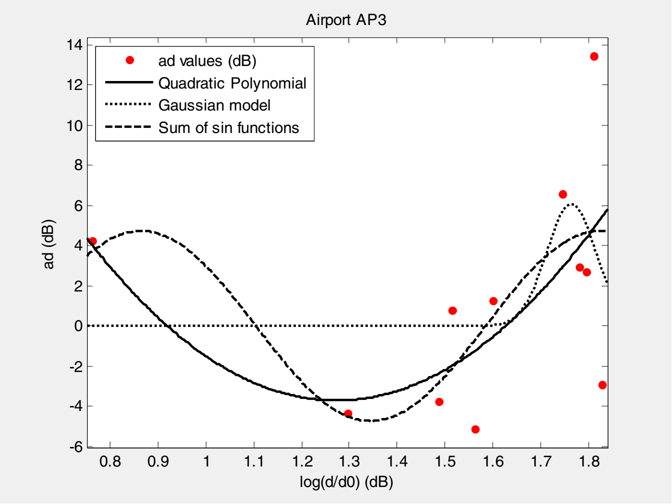

Figure 10. Goodness-of-fit for excess path loss vs. logd (AP3)

TABLE VIII. GOODNESS-OF-FIT FOR AP1

Goodness-of-Fit	**Quadr. Polyn**	**Cubic Polynomial**
R-Square	0.283	0.290
Adjusted R-Square	0.173	0.112

TABLE IX. GOODNESS-OF-FIT FOR AP2

Goodness-of-Fit	**Power Model**	**Cubic Polynomial**
R-Square	0.441	0.697
Adjusted R-Square	0.385	0.583

TABLE X. GOODNESS-OF-FIT FOR AP3

Goodness-of-Fit	**Sin. Model**	**Quadr. Polyn.**	**Gaussian**
R-Square	0.421	0.379	0.304
Adjusted R-Square	0.276	0.224	0.130

Another approach to the estimation of excess path loss and fit to the experimental data can be accomplished by plotting the excess path loss ad not versus distance (m), but versus $\log_{10}(d)$. Based on Eq.1, a simpler $y = f(x)$ function is attempted to be modeled. In that case, the Cubic and Quadratic Polynomial, the Gaussian model, the Power model and the Sinusoid model are applied.

The curve fitting graphs are shown in Fig.8-10. The R-Square and Adjusted R-Square values for each model and each case study (AP) are depicted in Tables VIII, IX and X respectively. The overall results are discussed in the following section.

V. DISCUSSION

Curve fitting and Goodness-of-Fit in terms of R-Square and Adjusted R-Square demonstrated that the Power model fits the experimentally measured data of attenuation over distance better than the 4-th degree Polynomial. The Power model is marginally better than the 4-th degree Polynomial for AP1 (OLOS/LOS scheme), whereas the 4-th degree Polynomial works better for the AP3 case study (LOS/OLOS scheme). However, concerning AP2 (where a dominant LOS scheme is featured), the Power model, though with less accuracy than the other two scenarios, fits the data much better than the 4-th degree Polynomial. Hence, it is selected for further analysis of its coefficients and data fit performance for 95% confidence bounds. The subsequent plots and numerical results confirm that the model is more inconsistent for AP2 (dominant LOS scheme), as seen from Fig. 3. In addition, for specific locations in AP1 and AP3, the model seems largely unstable. These cases correspond to locations with small distances from the transmitter but really close to edge of corridors and walls, where the behavior of the propagated RF signal is different than expected (reflection, multipath). This bears an impact on the calculated values of attenuation over distance for these locations, and subsequently on the curve fitting process.

The excess path loss is considered, for the purpose of this work, to be equal to the $a(dB/m)*d(m)$ product. Approximating ad versus distance (m) dataset for AP1, with an OLOS/LOS scheme, proves to be erroneous for both the Power model and the Cubic Polynomial, which the latter fitting the data relatively better. For AP2 (featuring a dominant LOS scheme), the Power model, the Linear Polynomial and the Gaussian model are applied with nearly identical, moderate results in terms of Goodness-of-Fit. For AP3 (LOS/OLOS scheme), the Sinusoid model and the Cubic Polynomial fit the experimental data moderately, whereas the Gaussian model performs less adequately.

Studying the curve fitting for ad versus $\log_{10}(d)$, for AP1, the Cubic Polynomial provides a relatively better fit than the ad versus distance (m) dataset, whereas the Quadratic Polynomial provides similar fitting results. Concerning AP2, the Cubic Polynomial fits the data substantially better than the Power model, that provides a similarly average fit as in the ad versus distance (m) dataset. For AP3, the Sinusoid model fits the data marginally less precisely than in the ad vs. distance dataset, the Gaussian model provides an unsatisfactory fit, whereas the Quadratic Polynomial fits the data moderately.

VI. CONCLUSIONS

In this work, curve fitting with 95% confidence bounds for the model coefficients was performed for the attenuation over distance values derived out of extensive measurements at a large-area indoor commercial topology: Athens International Airport. The power model provided the best fit, though performing moderately for the LOS-dominant scenario and in certain topologies with multipath phenomena (corridors, walls). The excess path loss, considered to be equal to the $a(dB/m)*d(m)$ product, was estimated versus distance for all schemes, and the curve fitting for the dataset of ad versus $\log_{10}(d)$ was also provided, with varied fitting statistical results for all considered models.

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