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Local Average Signal Strength Estimation for Indoor Multipath Propagation

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ABSTRACT A comprehensive study of approaches for the estimation of the local average of the received signal strength (RSS) for indoor multipath propagation is presented. The effects of the required number of the RSS data samples and the Euclidean distances between the neighboring samples are investigated over 1D, 2D, and 3D configurations. It was found that the effect of fast fading was reduced to an acceptable level using a 2D horizontal arrangement with a relatively large spacing configuration. Furthermore, averaging was enhanced with a larger spacing compared to smaller spacing when considering the same number of samples.

INDEX TERMS Fast fading, indoor propagation, local average RSS, localization, signal strength, WLAN.

I. INTRODUCTION

Wireless communication engineers frequently experience difficulty with the dynamic behavior of wireless radio channels. Wireless channels are more susceptible to noise, interference and other hindrances than wired connections [1]. The challenge, therefore, is to make the channel determinable at any location.

When a signal arrives at a receiver, the signal strength level is influenced by three different scales of variations, the largest scale being path loss, which is range dependent, the signal strength level decaying approximately exponentially. The second scale is due to shadowing, where the signal strength varies around its mean according to a log-normal distribution: such variations take place over ranges of the order of 10λ-30λ. The smallest scale is due to multipath effects, where the signal follows a Rayleigh or Rician distribution and variations are of order 0.5λ [2]. Multipath effects can be observed when the mobile terminal moves distances that are short compared to the correlation shadowing distance, hence this is called small-scale fading. Due to these effects, signal strength (SS) recorded at the receiver becomes very sensitive to any small movement. In fact, even if the receiver is stationary, the recorded SS will still vary noticeably due to other influences on the path; this will make the use of SS in localization impractical and inaccurate.

Researchers have developed techniques to remove the effect of small-scale fading [3] so that the received signal strength (RSS) will be linked to path loss and shadowing only: such integrated representations can be expected to make the RSS-distance relationship more tractable. One of the main problems in localization using RSS is the non-monotonic fading of RSS level with distance and such a problem will lead to ambiguity of location estimation. For example, Fig.1 shows the RSS data along a building hallway that was simulated using *Wireless Insite*® ray tracing software: when the mobile's RSS is −35 dBm, there are five possible locations for the mobile; the range of error is around 18 m which

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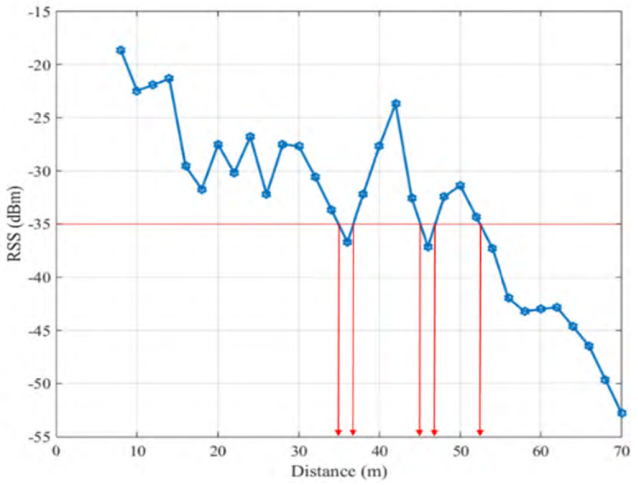

FIGURE 1. RSS-distance ambiguity problem.

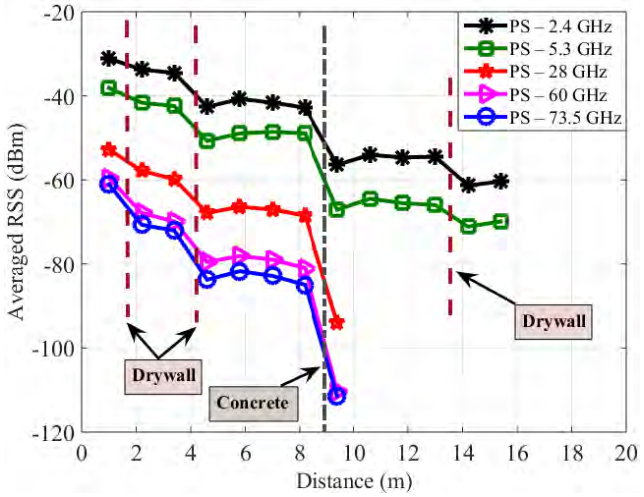

FIGURE 2. PS method performance for a range of frequencies.

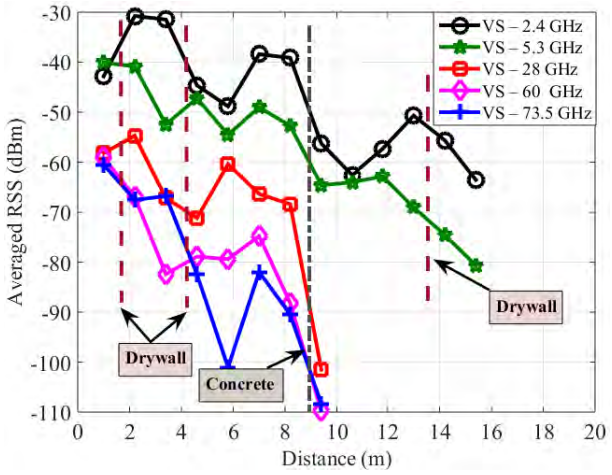

FIGURE 3. VS method performance for a range of frequencies.

is unacceptable for localization purposes in indoor environments. The primary aim is to manipulate this relationship to be unambiguous (i.e. monotonically decreasing). A possible way to achieve this is to average over local means to remove the effects of fast fading [3].

The organization of this paper is as follows: section II introduces ray tracing local averaging methods; section III presents the related literature review; in section IV methodology and the simulation setup are explained; the results and discussion are presented in section V and finally conclusions are drawn in section VI.

II. VECTOR SUM vs. POWER SUM PREDICTION METHODS

In ray tracing techniques, there are two methods to perform averaging: the first method takes the power sum of all multipath rays, which is known as "*Power sum prediction (PS)*" [3]

$$\langle P_{PS} \rangle = \sum_{M} P_M \tag{1}$$

where $\langle P_{PS} \rangle$, M and P_M are the averaged power using the PS method, number of multipath rays and power of each individual ray respectively.

The second method takes the average of the squared sum of all electric fields (amplitudes and phases): this is known as "*vector sum prediction (VS)*" [3]:

$$\langle P_{VS} \rangle = \left| \sum_{M} \sqrt{P_M} e^{-j\varphi_M} \right|^2 \tag{2}$$

where $\langle P_{VS} \rangle$ is the averaged power using the VS method and φ_M is the M$^{\text{th}}$ ray phase in radians.

In [4] PS is recommended to be used for frequencies higher than 2 GHz, while VS is recommended for lower frequencies. In [3] the PS method is said to be quicker and better; however, it is hard to implement in practice as it requires the receiver to be capable of distinguishing all incoming rays so that the effect of each ray's phase will be removed; this process requires a very large array antenna to detect arrival angles and it also requires very large bandwidth to detect delays.

The performance of the above methods was investigated over a set of frequencies, including 2.4 GHz, 5.3 GHz, 28 GHz, 60 GHz and 73.5 GHz: simulation results are presented in Fig. 2 and Fig. 3. It can be seen that averaged RSS using the PS method tends to be similar for all frequencies since this method removes the effect of multipath fading so that the only contributors to SS level are the path loss and shadowing. The reason why these averaged RSS curves take the form of similar layers is due to two types of losses: path loss with distance and wall losses, both of which are frequency dependent. On the other hand; The VS method takes into account phase information in estimation of the RSS averaged value. However, due to the presence of many multipath components, where each one has a different phase, the RSS averaged value will have large variations when the position of the receiver is slightly changed, especially at higher frequencies; This will make the SS-distance relationship less likely to be monotonic and therefore will reduce the localization efficacy.

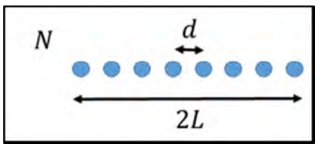

FIGURE 4. Averaging length, spacing and number of samples.

In this paper, the investigated frequency is limited to the 2.4 GHz band only: investigation of further frequencies will be the subject of a forthcoming paper.

III. PREVIOUS RELATED WORK

In averaging estimation process three parameters are considered, as shown in Fig. 4 [5]: the averaging length ($2L$ - also known as window size); the number of samples (N - also known as the number of collection points) and the distance between the samples (d- also known as spacing). Finding two parameters is sufficient to find the third using the relation $2L = Nd$. In a study conducted by [6] over the band 1.8 to 5.2 GHz the window size was found to be equal to 1 m or (5λ-15λ), where the corresponding variance of the estimated local mean signal was around 1 dB [7]. By having a sufficient number of samples the estimated variance will be reduced [8].

A set of measurements was conducted by the authors of [3] at 0.9 and 2.4 GHz and averaging was performed. Two procedures were followed: in the first procedure, many measurements were taken on circular paths around the point of interest, also known as the reference point (RP), then averaging was performed: each circular path had a 0.3 m radius and measurements were taken from 120 points on the circle; the whole process being repeated every 0.6 m.

In the second method, measurements were collected from many points lying on a linear path, where the spacing between the measurement points was λ/4 and averaging was performed over a window size of 10λ. This method was claimed to be appropriate for LOS and measurements in corridors [3]. In [9] the authors performed RSS averaging over regions of dimensions $(2\lambda)^2$. In [10] averaging was performed over regions of dimensions $(3\lambda)^2$, while in [11] and [12] the regions were of size $(3\lambda)^3$. In [13] averaging was conducted over a 10λ interval while the minimum spacing between samples was set to 0.38λ.

Averaging should not distort the effect of large-scale fading; therefore, estimating correlation distance r_c is crucial and this can be determined by estimating 1/e of the normalized shadowing autocorrelation ρ_s. The autocorrelation function is a function of location variability σ_L which is in turn a function of frequency [14]. σ_L tends to increase as frequency increases; therefore, for larger frequencies ρ_s decreases and hence r_c decreases. In [15] the authors considered the shadowing correlation distance to be in the range of 1-2 m, as estimated by [16]: they found that using a 10λ spacing window would be too long while using 4λ would be optimum.

In [17], the authors generalized the Lee model to include different propagation environments, including urban, suburban, rural and indoor environments with the UHF band. They recommended the window size $2L$ to be 5λ-10λ for indoor environments.

In [18] an analysis is reported that aimed to find the best averaging window and spacing; it was found that the best averaging window was within the range 20λ-40λ with a sample spacing of 1.11λ (36 samples) to ensure that samples were uncorrelated. This procedure was also applied for indoor application at 15 GHz [19]. Work done by [18] was generalized for the medium-frequency band [20]: they found that the best window size was 2λ, the optimum distance between samples was 0.17λ and the best number of samples was 8.

In [21] averaging over a window size of 40λ was performed at 15 GHz in indoor corridor scenarios in order to obtain small-scale fading characteristics. In [22] a local mean was taken over a rectangular area of $(0.1\text{ m})^2$ at 1.8 GHz, where nine measurements were taken within the grid.

For Nakagami propagation channels it is recommended by [7] to use 40 collection points within a 20λ averaging window for channels with a small number of multiple paths: $2 \leq m < 4$(m is the fading parameter), while for multipath channels in the range $4 \leq m \leq 8$ it was recommended to use 20 collection points within a 10λ averaging window. On the other hand, for channels with a higher number of multiple paths as compared to the Rayleigh case, it was recommended to use 0.5λ spacing between collection points within a 90λ averaging window. In [23] local mean estimation was conducted in a multi-floor building; measurements were collected through routes in the environment: these environments were gridded and then a local mean was estimated. The sizes of these grids were $(k\lambda \times k\lambda)$, where k ranged from 1 to 15; measurements were conducted at 0.9 GHz and 1.9 GHz.

At 0.9 GHz k was in the range of 6.5 to 7.0, while at 1.9 GHz it was in the range from 5.0 to 12.5. The performance was compared to the results in [18], however, neither approach outperformed the other. In [18] the authors assumed a normal distribution for SS while in [24] the SS distribution was found to be left-skewed: skewness is due to the limitation on the maximum achievable RSS at each location.

In [25] the authors conducted simulations of the estimation of the electric field strength at 3 GHz and 5 GHz, using the FDTD method It was found that averaging over a 3D volume, a cube with a side length of 3.3λ, showed agreement between the local mean magnitude of the simulation and the theoretical electric field. Measurements and simulation were conducted at 3 GHz and it was found that as the averaging volume increased the error of estimating the electric field decreased.

Averaging at 900 MHz over 20λ was reported in [26]: the approach was applied in indoor environments in circumstances where either end of the radio link is moving.

IV. METHODOLOGY AND SIMULATION SETUP

In practice, in order to use the PS method, the receiver should possess ultra-wideband bandwidth in order to be able to distinguish the closed multipath; also the receiver should use a large antenna array to detect all angle of arrival signals.

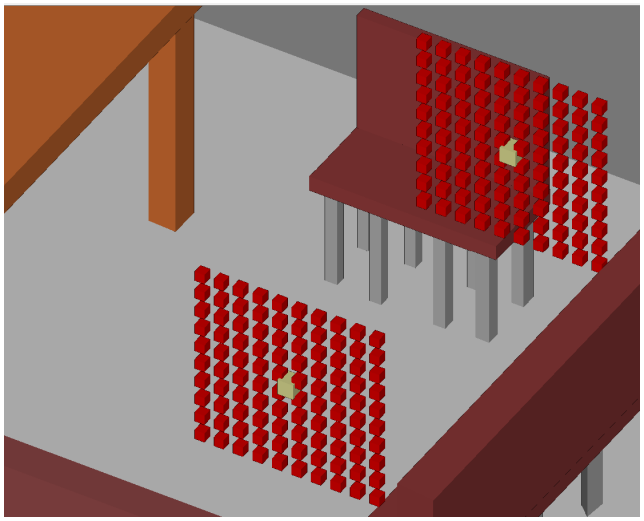

FIGURE 5. Exemplar SS collection points: Red points for averaging, yellow points are the points of interest.

Due to the difficulty of satisfying such requirements in all receivers, ray tracers are used as they provide information about the multipath propagation channel, including its corresponding received signal strength, phases, angles of arrival and departure, and time of arrivals. Therefore, the PS method can be used and the averaged value using the PS method will serve as a reference. Where the performance of different types of configurations that apply the VS method is compared to the reference, the one with the closest performance to the PS method can be deemed to be the best configuration.

Although PS is more accurate than VS, VS is easier to apply, therefore collecting samples (each using VS) and then performing local averaging will enhance the results to be better than those from VS but with less complexity than PS. In the present work, different simulated configurations were used to estimate the averaged RSS using the VS method.

In the simple scenario of the two-ray ground-reflection model, there will be a direct ray and a ground-reflected ray. The two paths have different lengths and hence different phases; thus for a moving terminal, the received power will follow constructive and destructive interference every phase difference of π, representing a path difference of $\lambda/2$. If the signals are coming from opposite directions, then a moving terminal experiences constructive and destructive interference every phase difference of $\pi/2$, representing a path difference of $\lambda/4$. In general, if signals are coming from different directions then a moving terminal experiences constructive and destructive interference within the range of $\lambda/2$ to $\lambda/4$. In real life scenarios, multiple paths tend to be more than two; however, the same concept still applies, therefore, the present work started by averaging over $\lambda/4$, and then the arrangement size was increased by $\lambda/4$ increments each time.

As seen in Fig. 5, the objective is to remove the effect of fast fading from the collected signal strength (SS), therefore a group of collection points (red cubes in the figure) are taken around the point of interest (yellow cubes) and then the corresponding RSS values at the red points are averaged. The averaging process requires conversion of RSS values from the dB scale to linear scale, followed by averaging and then conversion back to dB.

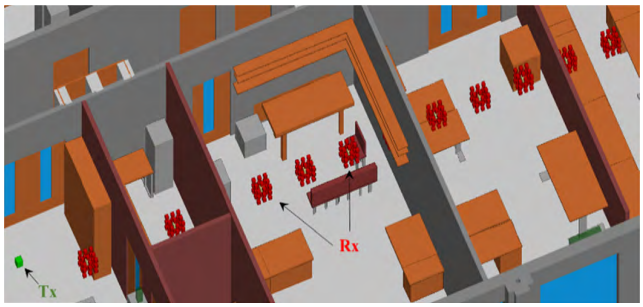

FIGURE 6. Example of a scenario conducted in the Wireless InSite model.

TABLE 1. Wireless insite settings for the investigated scenario.

Property	Setting
Number of reflections	6
Number of transmissions	4
Number of diffractions	1
Number of reflections before the first diffraction	3
Number of reflections after the last diffraction	3
Number of reflections between diffractions	1
Number of transmissions before the first diffraction	2
Number of transmissions after the last diffraction	2
Number of transmissions between diffractions	1
Ray tracing method	SBR
Propagation model	Full 3D

The simulation was conducted using the ray-tracing software *Wireless Insite* ®, which has been extensively validated, especially over the UHF band [27] and over 802.11ac frequencies [28], [29]. The operating frequency used in these simulations was 2.45 GHz and the distance between points of interest (yellow points) was 10λ as this has been reported to give the optimum representative data [18]. Fig. 6 shows an example of a scenario conducted in the Wireless InSite software where different positions in different rooms are evaluated. Wireless Insite settings for these simulations are listed in Table 1, where SBR stands for Shooting-and-Bouncing-Rays.

Simulations were conducted in a simulated environment for the third floor of a typical modern office-type building (the Chesham Building at the University of Bradford, U.K.). As seen in Fig. 7, the model considered different types of materials used in the building: these materials have frequency dependent properties [30] and therefore, their corresponding electrical parameters (relative permittivity ε_r and conductivity σ) will change as frequency changes. Typical values for ε_r and σ are given in Table 2: these were calculated using eqns. (3) and (4), where α, β and γ are given in [30].

$$\sigma = \alpha f_{GHz}^{\beta} S/m \tag{3}$$

$$\epsilon_r = \rho f_{GHz}^{\gamma} \tag{4}$$

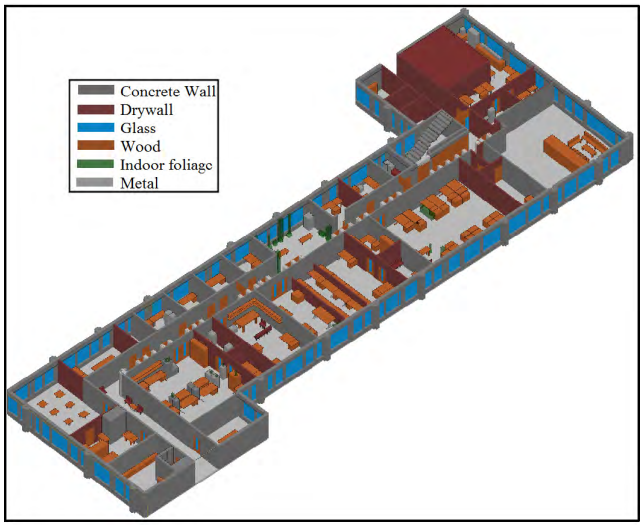

FIGURE 7. Simulated Environment for the 3rd floor of the Chesham Building, University of Bradford.

TABLE 2. Material properties adopted, for frequency 2.45 GHz.

Material	ε_r	σ
Concrete	5.31	0.0663
Glass	6.27	0.0122
Wood	1.99	0.012
Drywall	2.94	0.0216
Wet Ground	30	0.4681

The use of ray tracing software will reduce the effort, time and cost required to perform the experiment; however, without careful consideration of the software settings, the observed results will be pessimistic or underestimated. The simulated results in the indoor environment are also highly dependent on material properties and therefore, precise values for material conductivity and permittivity were chosen from research papers published in respected journals and with a high score of citations.

In this discussion, three parameters are considered: arrangement size, arrangement type and the distance between the collection points (spacing). The total number of scenarios investigated was 406.

A. ARRANGEMENT TYPES

The word *arrangement* refers to the configuration of the overall set of collection points. The shape of the overall set of collection points is termed the *arrangement type*, while the dimensions of this configuration are termed the *arrangement size*. In this analysis, different types of arrangement have been studied to validate the best one for averaging. Seven arrangement types have been studied, a three-dimensional arrangement (3D), a two-dimensional arrangement where the collection points lie on a plane horizontal to the floor (2D-H), a two dimensional arrangement where the collection points lie on a plane perpendicular to the floor (2D-V), a one-dimensional arrangement perpendicular to the floor (1D-V), a one-dimensional arrangement perpendicular to the line joining the points of interest and horizontal to the floor (1D-P), a one-dimensional arrangement parallel (horizontal) to both the line joining the points of interest and the floor (1D-H) and a combination of all one-dimensional averaging loci, termed as hybrid (HYB). In all tested scenarios the collection points were equally spaced: see Fig. 8

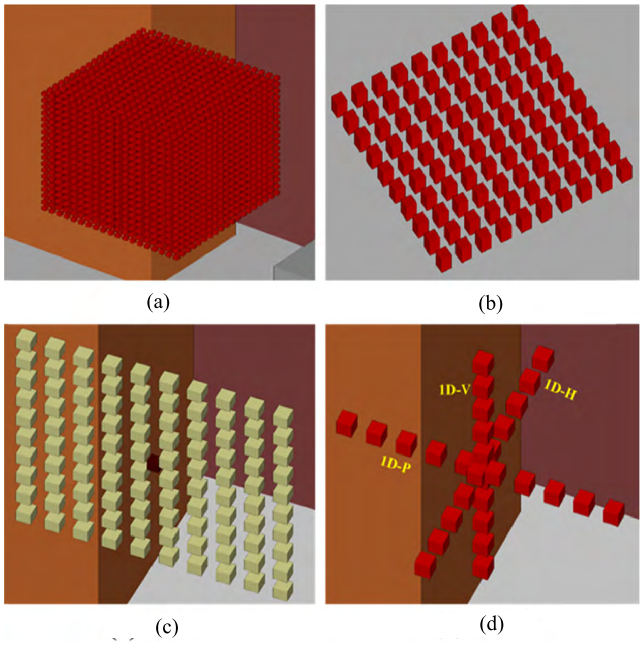

FIGURE 8. Arrangement types used in the simulation. (a) 3D. (b) 2D-H. (c) 2D-V. (d) HYB.

In the 3D arrangement, a set of measurements was taken with equal spacing, forming a cube as seen in Fig. 8a, where the point of interest is at the center of this cube. For example, a $(4.5\lambda)^3$ arrangement is a cube with edge length 4.5λ. For both 2D-H and 2D-V, the collection points form a square which is concentric with the point of interest, as seen in Fig. 8b and 8c. The 1D-H, 1D-P, 1D-V and HYB are symmetrical about the point of interest, as seen in Fig. 8-d.

B. ARRANGEMENT SIZE

Different arrangement sizes have been investigated, from 0.25λ up to 4.5λ with 0.25λ incremental steps.

C. SPACING BETWEEN POINTS

Initially, for each arrangement size, the spacing between the adjacent points was set to be 0.25λ; then, in order to investigate the effect of spacing between points, the spacing was increased by an increment of 0.25λ each time (i.e. Spacings: 0.25λ, 0.5λ, 0.75λ ... up to maximum arrangement size). However, not all arrangement sizes can maintain the same size when the spacing is increased (for example, if the spacing for the 4.25λ size were incremented by 0.5λ then the resultant arrangement would be either 4.5λ or 4λ; therefore, spacing by this increment cannot be used). Table 3 lists the arrangement sizes used in the simulations along with arrangement types and their possible spacings; the table also shows the number

TABLE 3. Arrangement sizes and their possible spacings, with the required number of points for averaging.

	Size.	*Spacing*	3D	2D-H	2D-V	1D-H	1D-V	1D-P	HYB
1	4.5λ	0.25λ	6859	361	361	19	19	19	57
2		0.5λ	1000	100	100	10	10	10	30
3		0.75λ	343	49	49	7	7	7	21
4		1.5λ	64	16	16	4	4	4	12
5		2.25λ	27	9	9	3	3	3	9
6		4.5λ	8	4	4	2	2	2	6
7	4.25λ	0.25λ	5832	324	324	18	18	18	54
8		4.25λ	8	4	4	2	2	2	6
9	4λ	0.25λ	4913	289	289	17	17	17	51
10		0.5λ	729	81	81	9	9	9	27
11		λ	125	25	25	5	5	5	15
12		2λ	27	9	9	3	3	3	9
13		4λ	8	4	4	2	2	2	6
14	3.75λ	0.25λ	4096	256	256	16	16	16	48
15		0.75λ	216	36	36	6	6	6	18
16		1.25λ	64	16	16	4	4	4	12
17		3.75λ	8	4	4	2	2	2	6
18	3.5λ	0.25λ	3375	225	225	15	15	15	45
19		0.5λ	512	64	64	8	8	8	24
20		1.75λ	27	9	9	3	3	3	9
21		3.5λ	8	4	4	2	2	2	6
22	3.25λ	0.25λ	2744	196	196	14	14	14	42
23		3.25λ	8	4	4	2	2	2	6
24	3λ	0.25λ	2197	169	169	13	13	13	39
25		0.5λ	343	49	49	7	7	7	21
26		0.75λ	125	25	25	5	5	5	15
27		λ	64	16	16	4	4	4	12
28		1.5λ	27	9	9	3	3	3	9
29		3λ	8	4	4	2	2	2	6
30	2.75λ	0.25λ	1728	144	144	12	12	12	36
31		2.25λ	8	4	4	2	2	2	6
32	2.5λ	0.25λ	1331	121	121	11	11	11	33
33		0.5λ	216	36	36	6	6	6	18
34		1.25λ	27	9	9	3	3	3	9
35		2.5λ	8	4	4	2	2	2	6
36	2.25λ	0.25λ	1000	100	100	10	10	10	30
37		0.75λ	64	16	16	4	4	4	12
38		2.25λ	8	4	4	2	2	2	6
39	2λ	0.25λ	729	81	81	9	9	9	27
40		0.5λ	125	25	25	5	5	5	15
41		λ	27	9	9	3	3	3	9
42		2λ	8	4	4	2	2	2	6
43	1.75λ	0.25λ	512	64	64	8	8	8	24
44		1.75λ	8	4	4	2	2	2	6
45	1.5λ	0.25λ	343	49	49	7	7	7	21
46		0.5λ	64	16	16	4	4	4	12
47		0.75λ	27	9	9	3	3	3	9
48		1.5λ	8	4	4	2	2	2	6
49	1.25λ	0.25λ	216	36	36	6	6	6	18
50		1.25λ	8	4	4	2	2	2	6
51	λ	0.25λ	125	25	25	5	5	5	15
52		0.5λ	27	9	9	3	3	3	9
53		λ	8	4	4	2	2	2	6
54	0.75λ	0.25λ	64	16	16	4	4	4	12
55		0.75λ	8	4	4	2	2	2	6
56	0.5λ	0.25λ	27	9	9	3	3	3	9
57		0.5λ	8	4	4	2	2	2	6
58	0.25λ	0.25λ	8	4	4	2	2	2	6

of points required for averaging for all 406 scenarios. Omni-directional antennas were implemented for both transmitters and receivers.

As seen in the table, using a 3D arrangement with a size of 4.5λ and spacing of 0.25λ will be computationally expensive as it requires 6859 collection points for averaging. This is the most extreme case, but in this analysis, the aim is to find the best arrangement type, size and spacing for estimating the local mean of RSS.

V. RESULTS AND DISCUSSIONS

The root mean square error (RMSE) is used as a performance metric. It is taken between each scenario (vector sum) and the reference case (power sum); therefore, there are 406 RMSE results. It is worth mentioning that the smaller the RMSE between the averaged result and the power sum result, the better is the averaging performance. In other words, the aim is to have an averaged value as close as possible to the power sum method result.

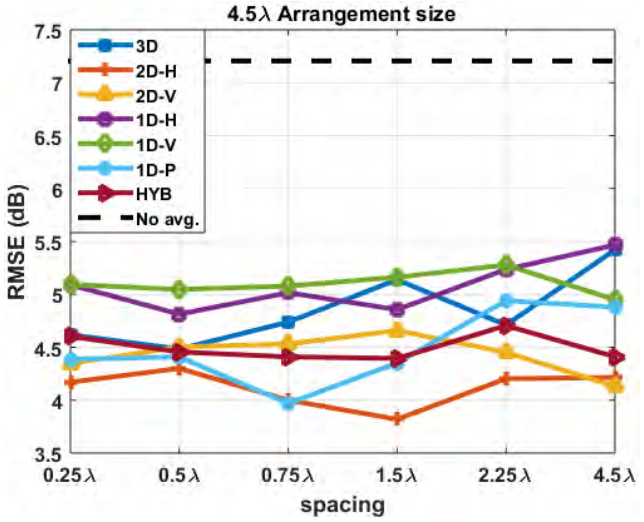

FIGURE 9. 4.5λ arrangement averaging (RMSE = r.m.s. error).

A. ARRANGEMENT SIZE

Averaging over each arrangement size and type, and its behavior with different spacings between collection points was examined: examples of the results are presented and general observations on the analyses for all arrangements are presented after these examples.

Fig. 9 presents averaging over a 4.5λ arrangement size for all types and all possible spacings (0.25λ, 0.5λ, 0.75λ, 1.5λ, 2.25λ and 4.5λ). As seen in Table 3, the number of points used ranged from 6859 in the 3D/0.25λ (arrangement type/spacing) case to 2 points in the 1D/4.5λ cases. In the figure, it can be seen that using simpler arrangement types gives better results compared to the computationally demanding 3D cases. Averaging over a huge number of points as in the 3D/0.25λ case does not provide significant reduction of fast fading; increasing the number of points does not necessarily improve the result. Generally, the results obtained from the 3D arrangement are not satisfactory, because 3D arrangements use many points with different heights, thus many of them will examine different multipath rays, and hence the averaged value will be different from the power sum result.

As seen in the figure, all averaging results show enhancement compared to the no-averaging case (single measurement per location). For this arrangement size, the best arrangement type performance is 2D-H/1.5λ as it has the lowest RMSE; further, it requires only 16 collection points for averaging. The descending order of RMSE performance for all arrangement types is 2D-H, 2D-V, 1D-P, HYB, 3D, 1D-H and 1D-V.

Averaging over 0.25λ arrangement size is presented in Fig. 10: the number of SS collection points ranged from

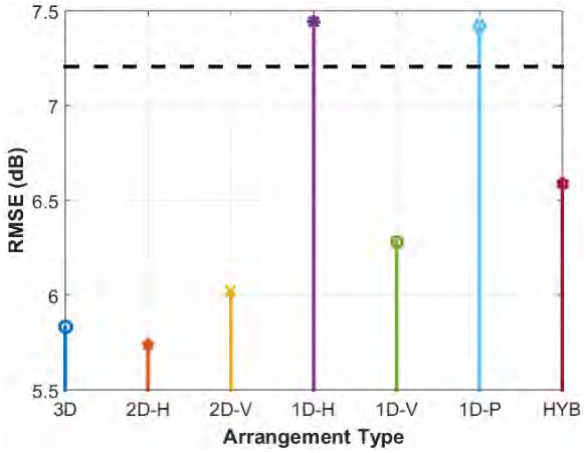

FIGURE 10. 0.25λ arrangement averaging.

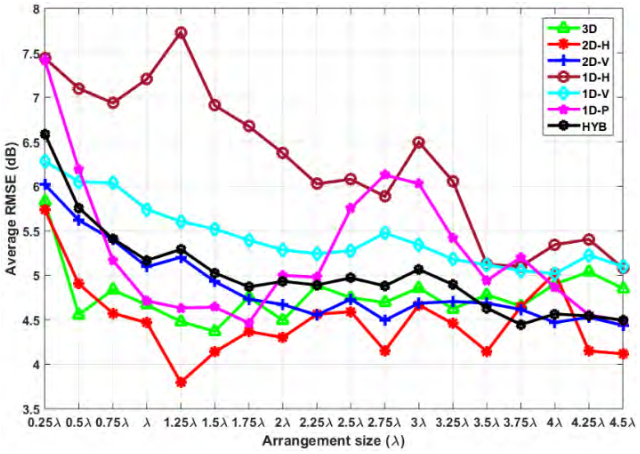

FIGURE 11. Averaged RMSE for the investigated arrangement types at all spacings for each arrangement size.

TABLE 4. Ten best arrangement results.

Arrang. type	Arrang. size/Spacing	No. of points	RMSE			
	No averaging		7.205	5.46	7.239	2.854
2D-H	1.25λ/1.25λ	4	3.525	4.308	3.230	3.769
2D-H	1.5λ/1.5λ	4	3.699	3.479	2.764	2.833
2D-H	4.5λ/1.5λ	16	3.82	2.54	3.697	3.330
2D-H	3.5λ/1.75λ	9	3.831	2.619	2.429	3.042
2D-H	3.75λ/0.25λ	256	3.835	2.436	2.787	2.660
2D-H	1.5λ/0.75λ	9	3.946	2.496	2.103	3.873
1D-P	4.5λ/0.75λ	7	3.970	2.439	2.940	3.178
2D-H	4.5λ/0.75λ	49	3.999	2.148	3.176	2.952
HYB	3.75λ/3.75λ	6	4.009	2.293	3.665	2.714
2D-H	1.75λ/0.25λ	64	4.069	2.799	2.331	2.598

eight to two, as seen in Table 3. All arrangements have poor performance as their RMSE values are more than 5.5 dB; however, 1D-H and 1D-P have results that are worse than the no-averaging case. It can be concluded that averaging with this arrangement size is not recommended.

Table 4 shows the ten best averaging results found in the whole experiment; the first RMSE column represents the ten best averaging arrangements, eight of them are of the 2D-H type. Among the top 20 arrangements, 13 are 2D-H and among the best 50 arrangements, 26 are 2D-H. On the other hand, the 2D-H arrangement type had only 4 poor results amongst the worst 100 results. Therefore, it is very plausible to recommend that this arrangement type is used for averaging. As seen in the table the best two arrangements have only four points each: although this appears promising, making a general conclusion from these results would be premature and thus a need for more trials was indicated. Therefore, the best 10 arrangements were examined in more environments in order to study more generalized results. The scenarios included LOS (propagation along a corridor) and NLOS (propagation through rooms with different antenna heights).

It was observed that the best overall performance was 2D-H 3.75λ/0.25λ, this observation is rational as many points were used for averaging; however, using 256 points is very demanding in time and effort. The second-best performance was 2D-H 1.75λ/0.25λ where 64 points are used, while the third-best performance was 2D-H 3.5λ/1.75λ which needs only 9 points: this arrangement has acceptable performance and requires much less computation, thus it is recommended to be used.

An interesting observation was noted, in that the worst performances were for 2D-H 1.25λ/1.25λ and 2D-H 1. 5λ/1. 5λ, this indicates that using only four points for averaging is not recommended.

Another interesting observation is the case of the LOS scenario: as shown in the table, RMSE for no averaging (2.854 dB) tends to be very similar to the averaging results. This is presumed to be a consequence of the fact that the resultant RSS with no averaging depends on the LOS component, as the latter is the dominant path, whereas the multipath components will not affect the main path reading. Therefore, averaging in LOS scenarios will not enhance RSS readings, provided that the transmitter and receiver antennas are omnidirectional.

A comparison between arrangement type performances for all spacings with each arrangement size is presented in Fig.11. 2D-H has the best overall performance for almost all of the arrangement sizes and this result can be explained as the width of the floor is likely to be larger than its height, therefore, most of the reflections (which contribute toward the fading effects) are thus occurring on the horizontal plane. It can be seen also that both 2D-H and 3D performances were not enhanced significantly after a certain size; hence it may be better to use arrangements with a smaller size as they need fewer points. The descending order of performance for all arrangement types and for all arrangement sizes is seen to be 2D-H, 3D, 2D-V, HYB, 1D-P, 1D-V then 1D-H.

In Fig. 11, the overall performance for 1D and HYB arrangement types for all spacings and all arrangement sizes is presented. 1D-H has the worst performance for the majority of the examined sizes, while the HYB tends to have the best performance for the majority of the arrangement sizes. Although HYB shows better performance in general, averaging with the 1D-P arrangement tends to have the lowest

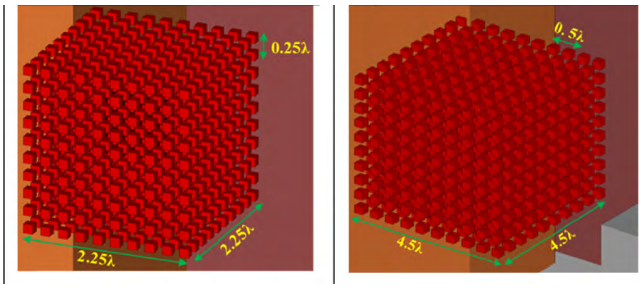

FIGURE 12. Example of arrangements (2.25λ/0.25λ) and (4.5λ/0.5λ) which have the same number of points but different spacing.

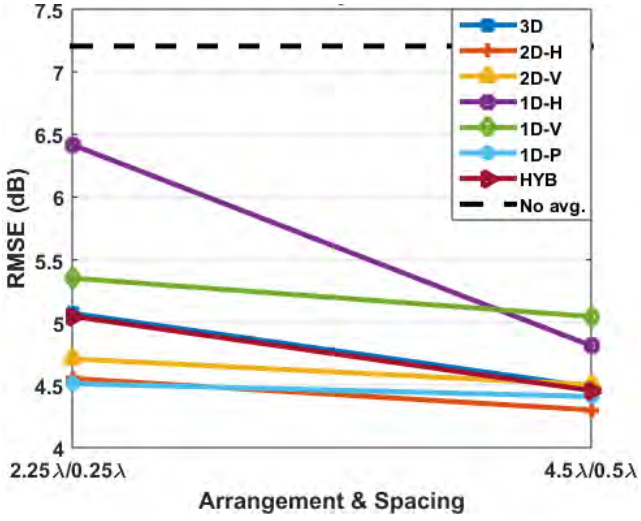

FIGURE 13. Performance comparison for arrangements with 10 layers of data collection points.

average RMSE for arrangement sizes from 0.75λ to 2λ; therefore, it may be better to use this arrangement type as it needs a lower number of collection points. It should be noted that these values are averaged over all spacings, therefore when choosing any arrangement type for averaging it is recommended to check the individual averaging result for each spacing with each arrangement size.

B. NUMBER OF POINTS

Several arrangement configurations have the same number of collection points, for example, arrangement types employing 4.5λ/0.5λ and 2.25λ/0.25λ have the same number of points (see Table 3 and Fig. 12). The aim of this part of the study was to find the optimum spacing for the same number of points.

Data in Table 3 rows 2 and 36 are presented in Fig. 13, these data have the same number of points but, by increasing the spacing between the points, the RMSE tends to decrease as the RMSE was reduced by 0.6 dB

Fixing the number of points and changing the spacing does not improve the 3D and 2D-H results significantly but it gives improvement for 2D-V, 1D-V, 1D-H and HYB, and in some cases 1D-P also shows a better performance.

C. ARRANGEMENT TYPE

Since 2D-H gives the best results it is worthwhile to investigate this arrangement's relationship with spacing and size and its effect on RMSE. Fig. 14 presents the RMSE relationship with spacing for the 2D-H arrangement type for all arrangement sizes. It was found that for small arrangement sizes ($\leq$ 1.5λ) RMSE decreases as spacing increases. For large ($\geq$ 3.25λ) and medium arrangement sizes no significant spacing relationship between spacing and RMSE was found, therefore it can be recommended to use the 2D-H arrangement with smaller size and larger spacing.

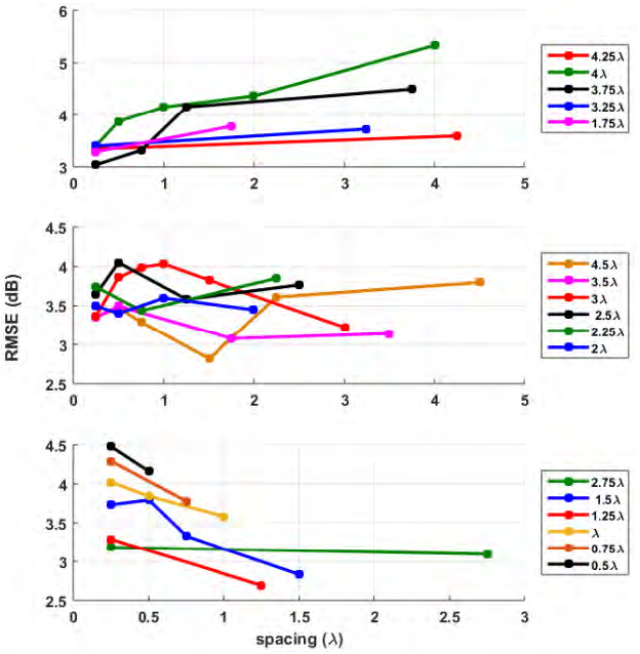

FIGURE 14. RMSE relationship with spacing for the 2D-H arrangement type.

Generally, for the 3D, 2D-H, 1D-V and 1D-P arrangements, smaller arrangement sizes give better results as spacing increases. The 2D-V and 1D-H type have better results for large arrangement sizes as spacing increases. The 1D-V type has better results for most medium arrangement sizes as spacing increases. The HYB type tends to have good results as spacing increases for most of the arrangement sizes.

VI. CONCLUSIONS

In this paper a set of comprehensive studies on estimation of local average signal strength for indoor multipath propagation was conducted, covering 406 tested scenarios in a typical modern office-type building. The work investigated the importance of averaging and its effect on localization. The set of results indicated the best-performing arrangement types, the effect of changing sample spacing for the same number of samples, and the relationship between arrangement type and spacing for all arrangement sizes. It was found that using a horizontal two-dimensional configuration of samples reduces the effect of fast fading significantly; also, using the same number of samples with larger spacing enhanced averaging compared to small spacings. The use of larger configurations improves averaging for some arrangement types while it does not improve it for others. Smaller arrangement sizes

demonstrated better results as spacing was increased for the cases of the 3D, 2D-H, 1D-V and 1D-P arrangement types, while the HYB type gave good results as spacing increased for most of the arrangements.

The results suggest the use of a grid size larger than 0.75λ as the RMSE tends to be less than for the smaller arrangement sizes. Arrangements with at least 9 points may be an optimum choice as they provide good results and require manageable numbers of collection points.

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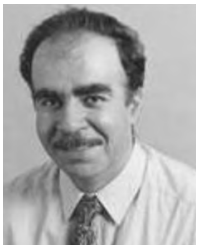

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