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Towards reconfigurable and cognitive communications/Vers des communications reconfigurables et cognitives

Influence of the level of description of the indoor environment on the characteristic parameters of a MIMO channel

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Abstract

Modelling of the environment is an important factor in electromagnetic wave propagation simulation, performed by a 3D ray-tracing method. The aim of this work is to study the effect of indoor environment modelling accuracy on MIMO (Multiple Input Multiple Output) channel characterisation. The first of the two environments investigated is the hall of our building, while the second one is a more confined environment and represents the floor of our laboratory. For these two indoor environments, three description levels are proposed in order to establish geometrical and electrical modelling impact on MIMO channel characterisation. Results are obtained by analysing the capacity and variation in correlation in relation to the polarisation, the presence of LOS (Line of sight) or NLOS configurations, the spacing between antennae and the number of transmitter and receiver antennae. ***To cite this article: C. Pereira et al., C. R. Physique 7 (2006).***

Résumé

Influence de la modélisation des environnements indoor sur les paramètres caractéristiques du canal MIMO. La modélisation des environnements est un facteur déterminant pour la prédiction de la propagation des ondes radio réalisée par une méthode à tracé de rayons 3D. Ainsi, ce travail traite de l'influence de la finesse de description d'environnements indoor sur la caractérisation de canaux MIMO (Multiple Input Multiple Output) simulés. Deux scènes sont considérées : la première est un milieu de type hall ; la seconde est un espace plus confiné représentant un étage. Pour ces deux environnements, trois niveaux de description tant géométrique qu'électrique sont proposés. Les résultats produits sont obtenus par analyse de l'évolution de la capacité du canal et de la corrélation entre les différentes liaisons radio en fonction de la polarisation, du caractère LOS ou NLOS des liaisons, de l'espacement entre antennes et du nombre d'antennes à l'émission et à la réception. ***Pour citer cet article : C. Pereira et al., C. R. Physique 7 (2006).***

Keywords: Environment modelling; 3D ray-tracing; Polarisation; MIMO channel characterisation

Mots-clés : Modélisation d'environnement ; Tracé de rayon 3D ; Polarisation ; Caractérisation du canal MIMO

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doi:10.1016/j.crhy.2006.07.013

1. Introduction

It has become necessary for mobile communication systems to handle multimedia services in the form of wide-band systems, mobile radio channels being considered as wide-band channels. Moreover, these transmission media achieve their information propagation through a multi-path mechanism. Received signals arrive from various directions, these variations being closely related to transmission quality. To overcome this drawback, traditional mobile communication systems exploit time or frequency diversity. However, to retain high spectral efficiency, a new solution consists in capitalising on spatial diversity by introducing antenna arrays at the base and/or mobile stations of cellular networks. In order to optimise the design of array-processing algorithms, these transmissions, named Multiple Input Multiple Output (MIMO) systems, call for a thorough knowledge of the radio propagation channel.

In most cases, MIMO channel characteristic parameters are evaluated by a set of measurements in studied environments, or by simulating propagation models [1,2]. The former approach requires MIMO experimental measurement platforms, which give access to pertinent information about the radio channel for both indoor and outdoor wireless communication scenarios. However, this approach presents difficulties, for example in relation to the calibration step and high cost.

Consequently, an approach based on simulations is sought. There are two families of models: the statistical type and the deterministic type. The first sort is connected with experimental investigations carried out in both indoor and outdoor environments. They have the advantage of being rapid in terms of computation time. The disadvantage is that they cannot be applied to all environment configurations. The deterministic approach is more complex, but also more accurate for MIMO characterisation applications, whatever the configuration. Unfortunately, the complexity entails that this is time-consuming in terms of computation.

Considering previous research involving deterministic simulation, several studies investigated MIMO channel characterisation in pico-realistic environments [3]. Variations in the spatial correlation and the capacity of the channel, based on a channel transfer matrix, were considered in relation to, on the one hand, the spacing between antennae, and on the other hand, the number of antennae. These studies also allowed the polarisation diversity effect on MIMO channel performance to be described [4,5]. It should be noted that the impact of complex wall structures on the capacity of MIMO wireless communication systems has been investigated [6], it being found that complex walls cannot be appropriately characterised by simple concrete slab walls.

To the authors' knowledge, however, in relation to larger-scale description of LOS and NLOS configurations, no investigation has been carried out concerning the influence of the geometric description level and the electrical properties of the environmental materials on MIMO channel characterisation. Thus, this investigation sets out to answer the question: Is it necessary or not, for MIMO characterisation, to describe the studied area in detail? More precisely, we want to know if an accurate MIMO channel characterisation simulation is sensitive to approximations in the description of the environment, as is the case for SISO (Single Input Single Output) characterisation [7].

It is to be underlined that environment modelling complexity entails inordinately large computation time. Thus, the aim of this study is also to find the simplest environment modelling that can ensure a satisfactory level of accuracy while not involving excessive computation time. In this article, we consider a deterministic model based on an optimised 3D deterministic ray-tracing method [8,9] associated with characterisation software [10]. In order to provide statistically robust results, a large number of simulations are undertaken, the approach being considered as a semi-deterministic MIMO characterisation. Two indoor environments are studied, the first being the large-sized hall of our building and the second being the first floor of our laboratory. These environments are modelled according to three levels of description, varying from simple parallelepipeds where all materials are assumed to be concrete to more complex rooms taking into account the actual electrical properties of realistic materials. Geometrical and electrical effects are analysed by comparing channel characteristic parameters generated at each level of description.

This article is organized as follows. Section 2 presents the tools and characteristic parameters of the MIMO channel (spatial correlation and capacity). Section 3 is dedicated to indoor environment modelling. It details the characteristics of modelling levels, including geometrical and electrical descriptions. Section 4 defines simulation conditions: polarisation, LOS and NLOS, the spacing between antennae and the number of antennae. Finally, Section 5 presents simulated results for MIMO characteristic parameters.

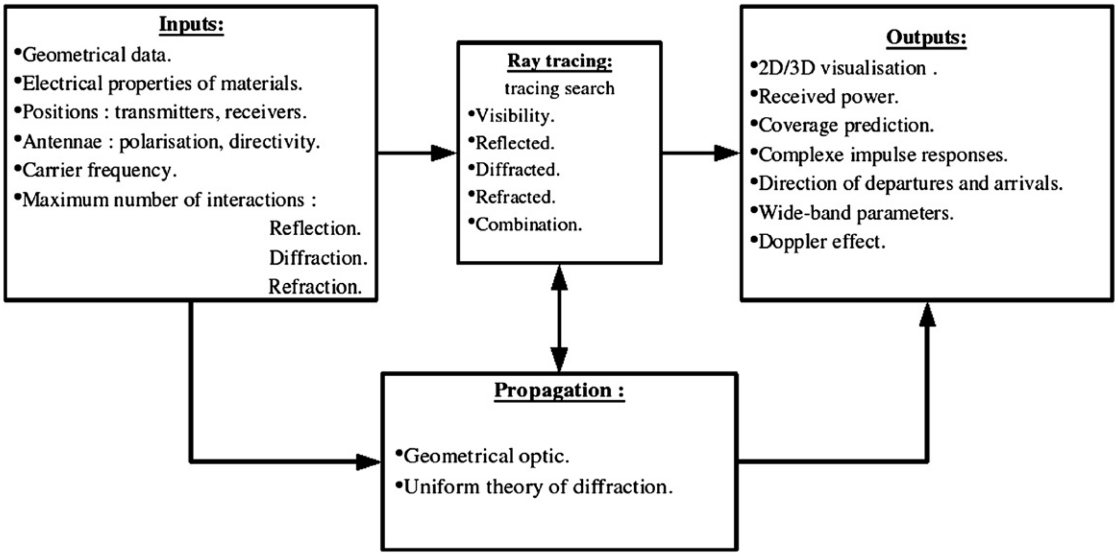

Fig. 1. Summary chart of wave propagation simulation.

2. Modelling and characterisation of a MIMO channel

2.1. *Modelling of a MIMO channel*

In wireless communication, a received signal is the result of a multi path phenomenon. This is due to electromagnetic interactions (reflection, diffraction and refraction) between an electromagnetic wave and obstacles in the environment. Each received path is characterised by a specific loss, polarisation, propagation delay and direction of arrival. The received signal derives from the sum of all the paths.

To simulate this multi-path mechanism, a wave propagation simulator was developed in the SIC[1] laboratory [8]. This allows a deterministic prediction of radio channel behaviour. It associates an optimised 3D ray-tracing technique to an asymptotic frequency method, which is based on the Geometrical Optic (GO) and the Uniform Theory of Diffraction (UTD). Fig. 1 shows input and output information of the wave propagation simulator. The inputs concern information about the environment (geometrical and electrical properties), antennae (position, radiation pattern, polarisation, carrier frequency) and electromagnetic interactions. The output information consists of the Complex Impulse Response (CIR) of the channel, the Direction of Departure (DOD) and Arrival (DOA) of the ray angle in azimuth and elevation planes. These data are considered in order to arrive at the full characterisation of the MIMO radio channel.

2.2. *Characterisation of a MIMO channel*

From the previous wave propagation simulator output data, channel characterisation software, likewise developed in the laboratory [10], allows the calculation and visualisation of characteristic functions and parameters of the SISO and MIMO channels. In this section, the MIMO channel parameters are the focus and relate to correlations between MIMO sub radio links and the ergodic capacity. These two parameters are based on the channel transfer matrix defined in the following subsection.

2.2.1. *Channel transfer matrix*

The channel transfer matrix, H is a $N_t * N_r$ narrow band matrix. N_t and N_r are respectively the numbers of transmitter and receiver antennae. The expression of H is shown in (1):

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[1] SIC: Signal Image Communications.

$$H=\begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1N_t} \\ h_{21} & h_{22} & \cdots & h_{2N_t} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_r1} & h_{N_r2} & \cdots & h_{N_rN_t} \end{bmatrix} \tag{1}$$

Each element h_{ij} $(i, j \in [1, N_r; 1, N_t])$ of this matrix, calculated for each radio link, is a complex narrow band coefficient. It results from the contributions of all paths which make up the channel complex impulse response of a given radio link (i, j). Thus, h_{ij} is given by (2):

$$h_{ij}=\sum_{n=1}^{N} a_n \mathrm{e}^{-j\theta_n} \tag{2}$$

where N designates the total number of paths; a_n and θ_n are the magnitude and phase of the nth path.

2.2.2. Correlation

The first important characteristic parameter that measures the effects of the description is the correlation [11]. More precisely, a correlation matrix of dimensions equal to $(N_t * N_r)^2$ is analysed. Each element of the matrix is defined by (3):

$$X/Y=\frac{\operatorname{cov}(X,Y)}{\sqrt{\operatorname{var}(X).\operatorname{var}(Y)}} \tag{3}$$

where X and Y are the h_{ij} of H, with var(.) and cov(., .) being, respectively, the variance and covariance operators.

2.2.3. Capacity

Ergodic capacity is the second important characteristic parameter. It evaluates the performance of MIMO channels by quantifying the maximum information able to be transmitted by the propagation channel without error [12,13]. This parameter, expressed in Bit/s/Hz is defined by (4) or (5) so long as the power of the transmitter antennae is equal:

$$C_{\mathrm{MIMO}}=E\left\{\log_2\left(\det\left(I_{N_t}+\frac{\rho}{N_t}.\left(HH^H\right)\right)\right)\right\} \quad \text{for } N_r \leqslant N_t \tag{4}$$

$$C_{\mathrm{MIMO}}=E\left\{\log_2\left(\det\left(I_{N_t}+\frac{\rho}{N_t}.\left(H^H.H\right)\right)\right)\right\} \quad \text{for } N_r > N_t \tag{5}$$

where ρ is SNR (Signal Noise Ratio), I_{N_t} is an $N_t * N_t$ identity matrix, $E\{.\}$ is the expectation and $(.)^H$ is the Hermitian operator.

2.3. Semi-deterministic characterisation

The evaluation of MIMO channel characteristic parameters is obtained via the association (cf. Fig. 2) of the wave propagation simulator and the channel characterisation software.

These types of software are used in order to perform a semi-deterministic study. They are thus applied to a set of a MIMO sub radio links randomly defined. Note that this study has had to respect the stationary assumptions (WSSUS). As a consequence, the spatial variation of the antennae has been limited to small areas. Thus, the semi-deterministic study performed thanks to this association of software permitted the channel mean characteristic parameters (cf. Sections 2.2.2 and 2.2.3) to be obtained.

3. Environment modelling

To obtain varied results, two unfurnished indoor environments, differing in their dimensions and shape, are studied. The first one is a floor (cf. Fig. 3); with a surface area of 750 m^2. The second one is a hall (cf. Fig. 4) which measures 1200 m^2.

For these two environments, the impact of geometrical and electrical description on MIMO channel characterisation is investigated. In order to define this impact, three levels of description have been adopted. Fig. 5 illustrates these

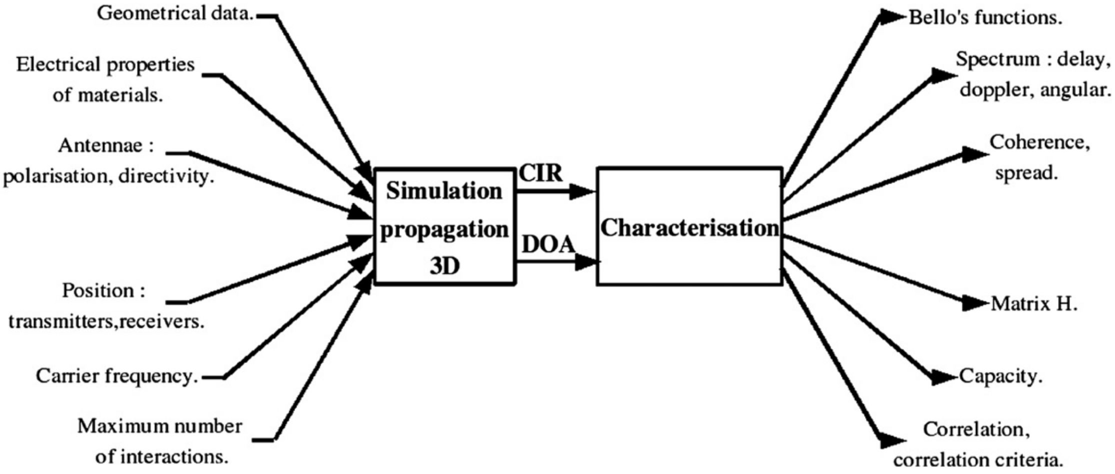


Fig. 2. Association between the wave propagation simulator and the characterisation software.

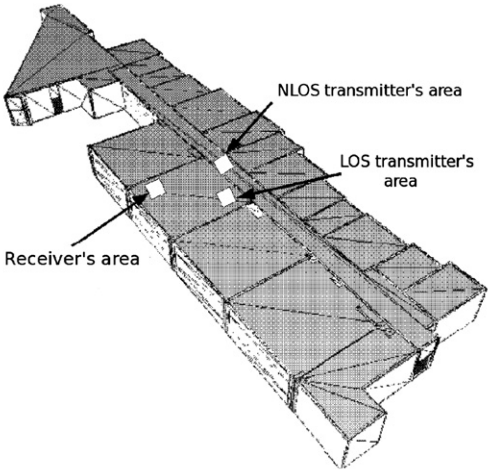


Fig. 3. Floor environment.

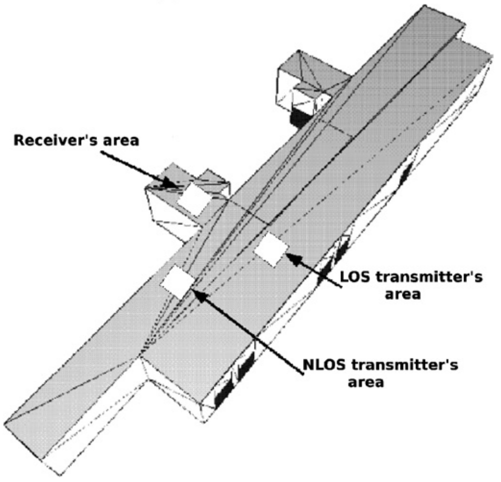
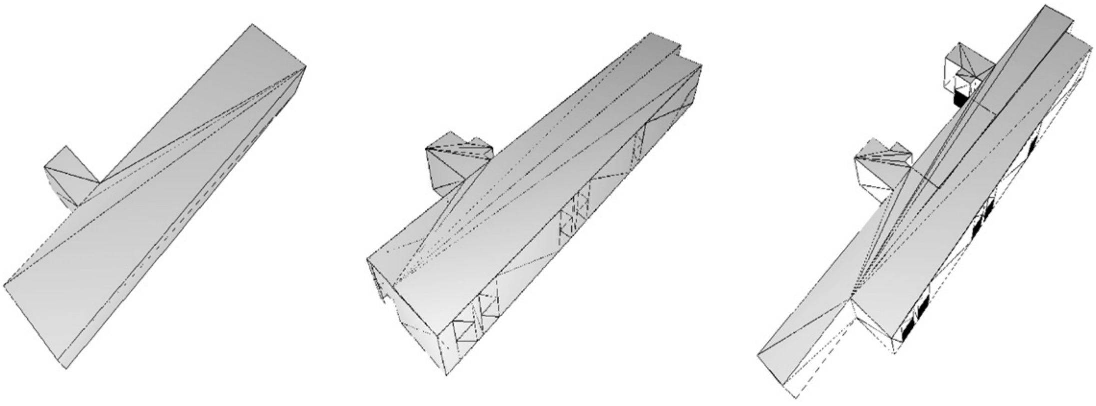


Fig. 4. Hall environment.



(a) Level A (b) Level B (c) Level C

Fig. 5. Levels of description for the hall.

levels of description for the hall environment. The first, level A is the simplest (cf. Fig. 5(a)), being described in terms of two parallelepipeds whose walls are considered to be concrete. These two boxes represent the minimum level of description still allowing the investigation of LOS and NLOS configurations. The second level (level B, shown in Fig. 5(b)) is more complex: while dealing with the same boxes as in level A, there is a fuller geometrical description. Level B retains the electrical description of level A. As a result, a comparison between levels A and B highlights properties deriving from the geometrical description. Level C (illustrated in Fig. 5(c)) corresponds to the most accurate environment. It considers other boxes besides the two of level B and employs the same geometrical precision. At this level, all geometrical elements have their respective electrical properties. The comparison between level B and C shows the effect of electrical properties and the impact of external boxes on the characterisation.

4. Propagation simulation conditions

This section presents, on the one hand, the wave propagation simulator parameters and, on the other, the different configurations investigated.

4.1. Wave propagation simulator parameters

A carrier frequency of 5.18 GHz is chosen in accordance with Hyperlan 2 technology. The induced wavelength λ is thus approximately 6 cm. Transmitter and receiver antennae are dipolar and are placed 1.5 m above the ground. The wave propagation simulator was parametered in such a way that a maximum of two reflections, one diffraction and five refractions were allowed for each path. In fact, these parameters had emerged from previous studies [14] of indoor SISO cases based on comparisons between simulations and actual measurements.

It is helpful at this point to note that in the current characterisation, complex channel impulse responses are not normalised and that mutual coupling between antennae is not considered.

4.2. MIMO configurations

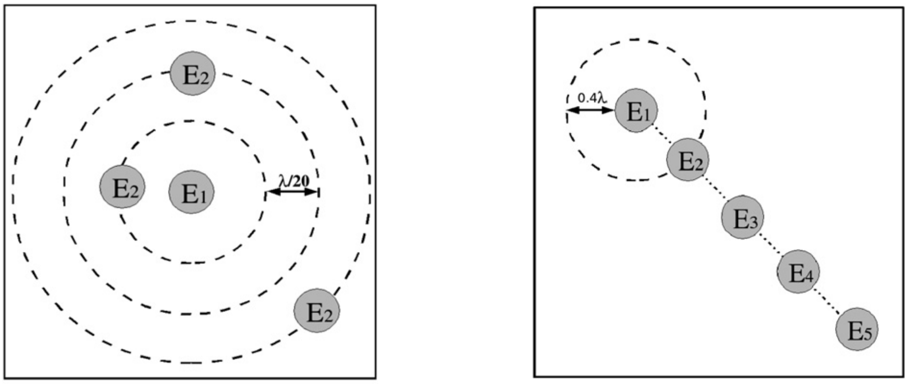
In all the simulations, more than 1400 antennae vary randomly according to a uniform law in zones of one square meter (cf. Figs. 3 and 4). In the floor environment, the mean radio link length is approximately 4 m, while in the hall environment this distance is 8 m. The areas are positioned in LOS and NLOS configurations and the simulation can be achieved with or without polarisation diversity. In the first case, all antennae are vertically polarised. In the second, polarisation diversity is obtained by inclining the antennae at angles of 45° and 135°.

For all the possible scenarios, the variation in the MIMO characteristic parameters is investigated in relation to:

- the spacing between antennae for a (2×2) MIMO transmission. At transmitter and receiver areas, two antennae are in the first place randomly positioned at a distance of $\lambda/20$. Afterwards, the spacing is augmented in a stepwise fashion to λ, each spatial step being $\lambda/20$ (cf. Fig. 6(a));
- the number of antennae. The number of transmitter and receiver antennae grows from one ((1×1) MIMO) to seven ((7×7) MIMO). The first two antennae are randomly positioned and the others follow the alignment of these two. The result is linear antenna arrays, the spacing between antennae being fixed at 0.4λ (cf. Fig. 6(b)). This generally corresponds to a minimum correlation [15].

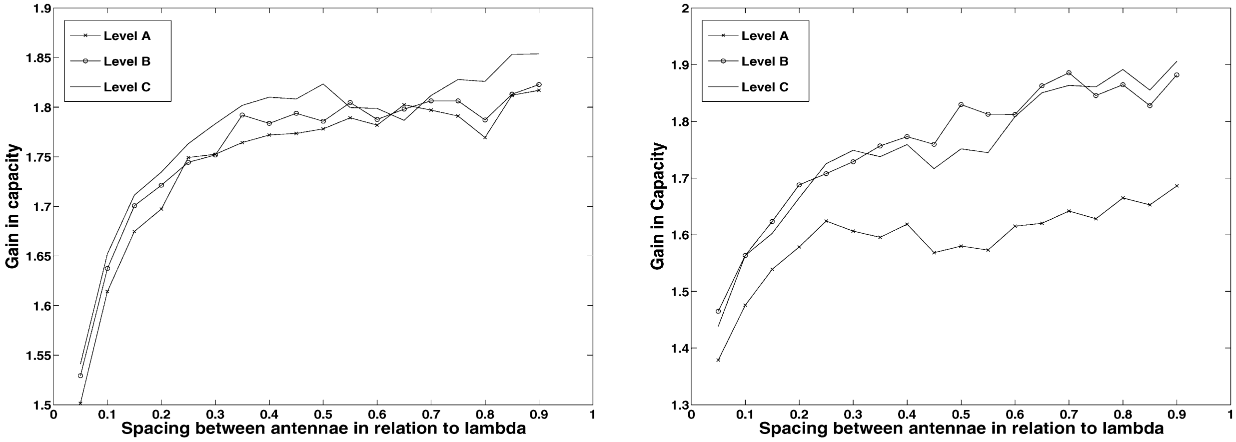
In the rest of this work the gain of capacity G_c is addressed. This gain results from the normalisation of the average capacities by considering the average capacities of the single transmission, single receiver antenna system (i.e., $N_t = N_r = 1$). Moreover, these equivalent SISO capacities are obtained for the higher level of description (level C). Consideration of G_c thus frees the investigation from needing to take account of transmission and reception constraints. These constraints include normalisation problems related to channel impulse responses, transmission power, reception amplification and SNR.

$$G_c = \frac{C_{\mathrm{MIMO}}}{E\{C_{\mathrm{SISO}}\}} \tag{6}$$



(a) Spacing antennae (b) Number antennae

Fig. 6. Antennae position pattern.



(a) Floor (b) Hall

Fig. 7. Variation of the gain in capacity in relation to the spacing between antennae in LOS without polarisation diversity.

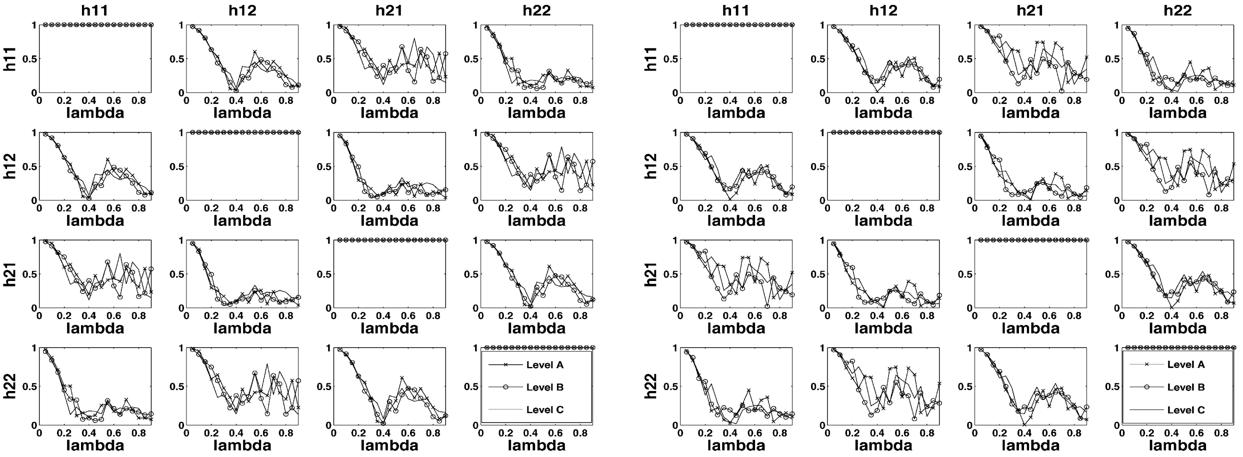
5. Results

5.1. Variation in characteristic parameters in relation to the spacing between antennae

This section presents the variation in the characteristic parameters (gain in capacity and correlation matrix) with respect to the spacing between antennae. The study is carried out in floor and hall environments defined using the three descriptive levels. It involves a (2×2) MIMO transmission in various configurations: LOS and NLOS; with or without polarisation diversity.

5.1.1. LOS configuration without polarisation diversity

In this subsection, transmitter and receiver antennae are in line of sight (LOS) and do not involve polarisation diversity. This means that complex impulse responses are composed of a set of paths, including the direct path. The first is the most powerful. Figs. 7(a) and (b) show the increased gain in capacity and highlights this in relation to the spacing between antennae. Whatever the level, this gain increases until roughly 0.4λ [15]. Fig. 7(a) shows that the evaluation of gain in capacity is not affected by the level of description. For the hall environment, however, there is a great difference between levels A and the other two. Thus, a geometrical description that is too simple cannot allow a pertinent evaluation of channel characteristic parameters.



(a) Floor

(b) Hall

Fig. 8. Variation of correlation in relation to the spacing between antennae in LOS configurations without polarisation diversity.

To complete these observations, the focus shifts to the correlation between MIMO sub radio links presented in Figs. 8(a) and (b). These characteristic parameters are evaluated in the same environments with the same conditions. The dimension of the correlation matrix is 4×4, with the consequence that, in the first diagonal we find all the auto-correlations (equal to one). Around this diagonal, the blocks represent inter-correlations, these being symmetrical on each side of the diagonal, because of the traditional matrix arrangement. The variation in the correlations is similar to that of a Bessel function, with minima at 0.4λ and 0.8λ, in line with previous studies [15].

Despite finding similar inter-correlation variation, different types of curves emerge:

- curves h_{11}/h_{12} and h_{21}/h_{22} involve complex impulse responses emanating from the same transmitter;
- curves h_{11}/h_{21} and h_{12}/h_{22} involve complex impulse responses arriving at the same receiver;
- curves h_{12}/h_{21} and h_{11}/h_{22} involve complex impulse responses that coming from both transmitters and going to both receivers.

As shown in Fig. 8(a), correlations vary in a similar way with respect to description levels. This similarity is supported by the results relating to capacity. However, for the hall environment (cf. Fig. 8(b)), inter-correlation characteristic variation at level A is different from that found at the other levels. This means that geometrical description (in this configuration) has an impact on channel characteristic parameters. This difference can be noted in curves h_{11}/h_{21} and h_{12}/h_{22}.

Examining these curves suggests that MIMO characterisation depends on a minimum of geometric description but seems to be insensitive to an electrical description (cf. comparison between levels B and C).

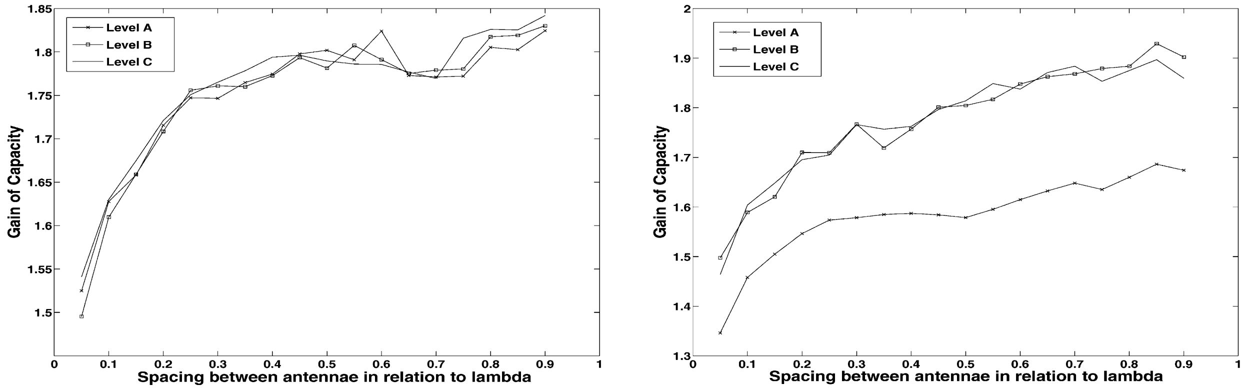
5.1.2. LOS configuration with polarisation diversity

Picking up on the above results, an attempt is made to determine whether or not polarisation diversity increases the effects of environment modelling on MIMO characterisation. Figs. 9(a) and (b) show that the pattern of gains in capacity corroborates the findings relating to gains in capacity without polarisation diversity (cf. Figs. 7(a) and (b). Accordingly, comparison between the results in Sections 5.1.1 and 5.1.2 proves that impact of environment modelling on MIMO characterisation is the same, whatever the antenna polarisation in a LOS configuration.

It can be noted that the trend in the results shown in Sections 5.1.1 and 5.1.2 are similar. This is due to the definition of gain in capacity (normalisation of MIMO capacity by SISO capacity) being specified without recourse to units of measurement.

5.1.3. NLOS configuration without polarisation diversity

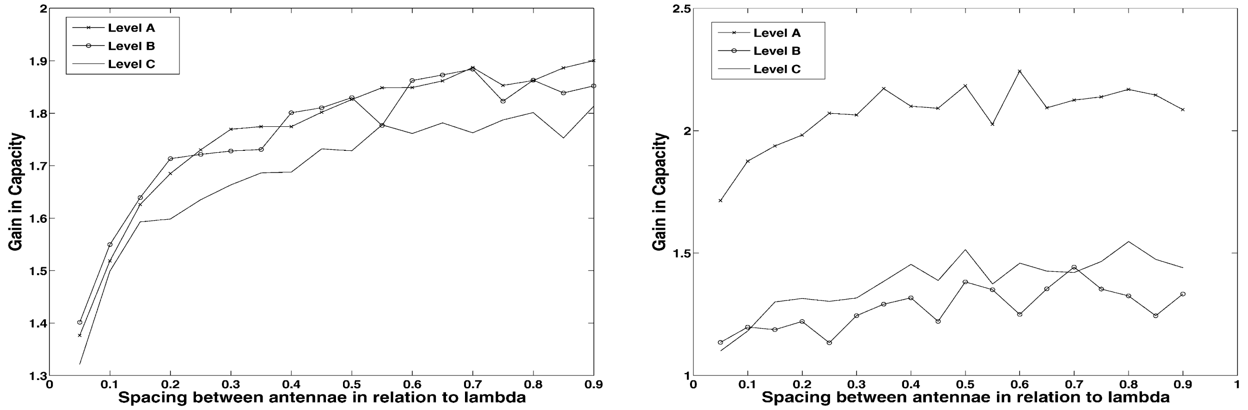
The main difference between the LOS and NLOS configurations is that, in the latter, there is no longer a direct path. A focus on this condition allows the influence of the direct path on environment modelling to emerge. The comparison



(a) Floor

(b) Hall

Fig. 9. Variation of the gains in capacity in relation to the spacing between antennae in a LOS configuration with polarisation diversity.



(a) Floor

(b) Hall

Fig. 10. Variation of the gain in capacity in relation to the spacing between antennae in a NLOS configuration without polarisation diversity.

between, on the one hand, Figs. 10(a) and (b) and, on the other, Figs. 7(a) and (b) points to similar characteristic trends. Nevertheless, in the NLOS configuration, the difference between the simplest geometrical description (level A) and the others is greater than in the LOS condition. However, characteristic parameters seem again to be insensitive to electrical description. This demonstrates that a direct path does not modify the effects of environment modelling. Supporting this, the same results are obtained with polarisation diversity.

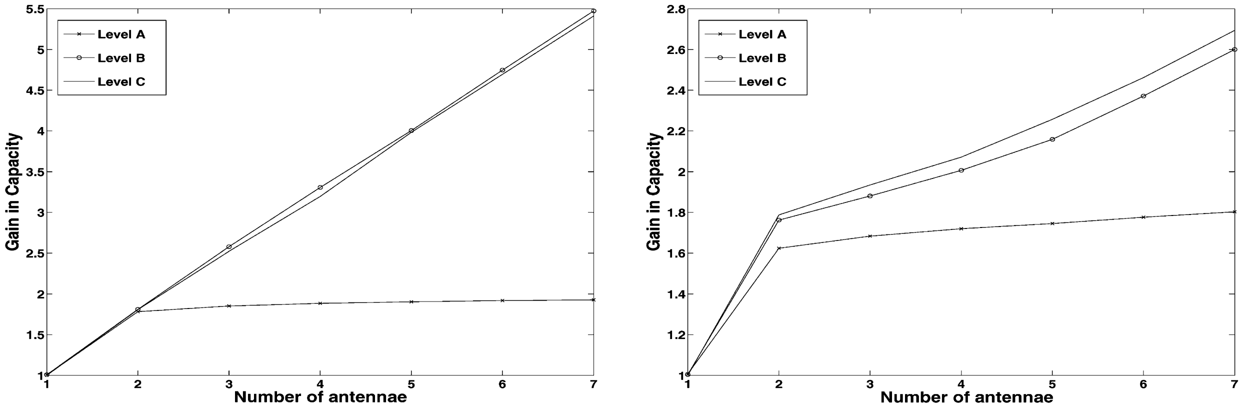
5.1.4. Summary

It has been shown that channel characteristic parameters are not sensitive to electrical description, whatever the configuration of the environment and whatever the polarisation. Furthermore, it is asserted that geometrical description has an impact on MIMO characterisation. This fact is amplified in the NLOS configuration because of the lack of a direct path.

Accordingly, level B would seem to be a satisfactory level of description for accomplishing an adequate characterisation of a MIMO channel. It is to be noted that this allows a gain in computation time over level C roughly to the order of two.

5.2. Variation of characteristic parameters in relation to the number of antennae

To build on the above findings, the following results evaluate gains in capacity in relation to the number of antennae (cf. Section 4.2) for a LOS case without polarisation diversity. Fig. 11(a) and (b) clearly show that a minimum level



(a) Floor (b) Hall

Fig. 11. Variation of gain in capacity in relation to the number of antennae in a LOS configuration without polarisation diversity (the element spacing is equal to 0.4λ).

of modelling is necessary as the number of antennae increases. In fact, where there are more than two transmitter and receiver antennae, the simplest modelling (level A) is not sufficient for a good evaluation of MIMO channel characteristic parameters. It thus appears that a geometric level of description is of major importance for MIMO characterisation. A minimum level of description is required to take into account the propagation of predominant paths. In spite of this, it is not necessary to consider all geometrical elements (i.e., all the boxes). In the end, an electrical description of materials has less impact on MIMO channel characterisation than a geometrical description.

6. Conclusions

This work has investigated environment modelling effects on MIMO channel characterisation. Our goal was to answer the question: what degree of accuracy is required to describe the indoor environment, both geometrically and electrically to arrive at an accurate MIMO channel characterisation involving a minimum of computation time?

To highlight modelling effects, correlation matrices and gain in capacity values were used. These characteristic parameters were investigated in relation to the spacing between antennae on the one hand, and the number of antennae on the other hand. Moreover, environment modelling effects were studied in LOS and NLOS cases, with or without polarisation diversity. All the cases studied revealed that MIMO characterisation is quasi-insensitive to the electrical properties of materials. However, geometrical description is a crucial parameter in achieving an accurate characterisation. Indeed, characteristic parameters vary strongly where environment modelling involves poor geometric description.

This fact is amplified in NLOS configurations. It is concluded that pertinent environment modelling requires a minimum level of description of geometric elements involved in propagation configurations. Also, materials can be described uniformly as having the electrical properties of concrete. It is consequently assumed that level B ensures an adequate level of accuracy, while offering a gain in computation time roughly of the order of two, when compared with level C.

Future work will consist in reinforcing these statistical results with further investigations of actual indoor environments.

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