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Assessment of User Mobility's Influence on System Loss in Several Body-to-Body Scenarios

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Abstract — **In this paper, Body-to-Body communications in indoor and outdoor environments for different on-body antenna configurations and different mobility scenarios were studied, based on system loss measurements at 2.45 GHz. The main objective is to properly characterise the influence of the Transmitter-Receiver configuration on system loss and fast fading behaviour, the latter being modelled by the Rice Distribution. Globally, it is observed that there is no significant difference on the measured average system loss between indoor and outdoor environments, but a strong dependence is seen on the configuration of the antennas and on the mobility scenario. Concerning the Rice Factor, as expected, higher values were obtained in outdoor environments, due to the lower level of multipath, the difference to the indoor case being below 4 dB, depending on the mobility environment and on the positioning of the antennas.**

Keywords—BAN, Body-to-Body, User Mobility, Radio Wave Propagation, System Loss, Rice Factor.

I. INTRODUCTION

Wireless Body Area Networks (WBANs), or simply Body Area Networks (BANs), refer to a wireless set of devices attached to the human body [1], nowadays having already a major role in some applications, such as in monitoring vital signs, which is important for usage scenarios in medicine, sports, military, police, civil protection and even entertainment. The collaborative work between BANs, and in particular in Body-to-Body (B2B) scenarios, has attracted a lot of attention, given the potential applications already envisaged for 5G and beyond. The characterisation of the channel in B2B scenarios, namely concerning path loss and fading, is quite important for system design, since the location of the antennas on the body together with the mobility of users will lead to quite diverse situations, concerning not only shadowing but also signal variability.

In fact, B2B communications are extremely difficult to characterise, due to their specific characteristics. The radio channel is strongly influenced by a number of aspects: the characteristics of the devices placed close to the body; the characteristics, placement and orientation of the antennas; the specifications of the radios and their frequencies; the environment surrounding users associated to applications; and the mobility of users, among many others. All these factors make the characterisation of B2B communications a complex process, leading to the need to have models for a large variety of cases.

One can already find in the literature several studies on B2B channel characterisation, namely based on measurements at the 2.4 GHz band. S.L. Cotton et al. [6] conducted measurements in a car parking outdoor environment, with antennas on the chest and back of users in several mobility conditions, showing received power results, and these measurements were taken by S.L. Cotton [3] to analyse models for shadowing. R. Rosini et al. [4] performed indoor measurements in a room with users moving in different ways for several antennas' placements, leading to path loss and multipath fading models. A similar approach was taken by F. Mani and R. D'Errico [5], extracting path loss and shadowing and multipath fading models as well.

The measurements performed by S.J. Ambroziak et al. [6] were done at both indoor and outdoor environments, and for a number of antennas placements larger than previous ones, involving several mobility scenarios, leading to an analysis of system loss, in terms of average and standard deviation; the same set of measurements was used by K. Turbic et al. [7] to analyse shadowing and multipath fading characteristics, in a global perspective, distinguishing the Line-of-Sight (LoS) cases (straight LoS, Quasi-LoS (QLoS) and Non-LoS (NLoS)). Recently, M.E.H. El Azhari et al. [8] used the scenario of a tunnel and users with antennas on the chest, extracting path loss and shadowing and multipath fading parameters for several static positions of the two users.

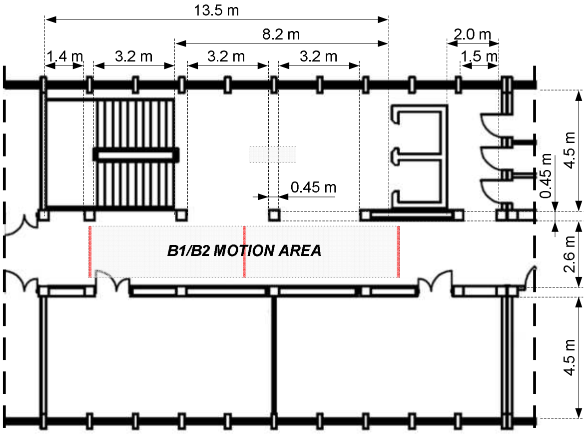
In general terms, these papers present path loss models based on the fitting of measurements, leading to an average decay rate with distance, and analyse the fitting of several statistical distributions (e.g., Log-Normal, Rayleigh, Rice and Nakagami). The current paper extends the analysis of [6] and [7], by taking the combinations of antennas positions and mobility scenarios to present a comparison of results for system loss and the Rice Factor (since previous works show that the Rice Distribution can properly describe the phenomena). The novelty of this paper lies on the consideration of both indoor and outdoor environments, and on the many combinations of antennas placements on the bodies, hence, enabling a comparison of results for the same antennas that has not been presented before.

This paper presents an analysis of B2B communications based on a set of measurements at 2.45 GHz in both indoor and outdoor environments, six different antenna placements in each body and three mobility patterns. The focus of this analysis is on the measured system loss and Rice Factor, K, in all these scenarios, conclusions being drawn from the analysis of propagation and antennas characteristics.

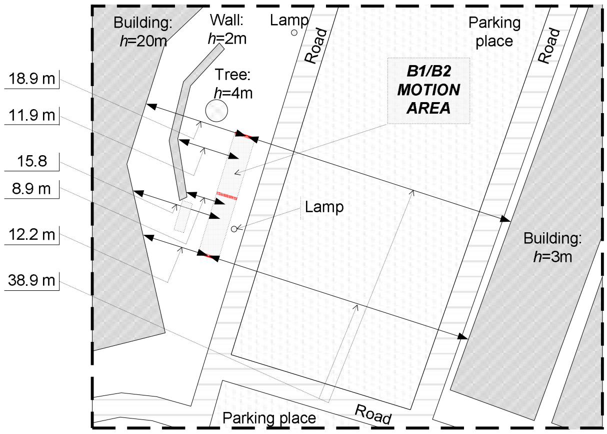
The paper is organised as follows. The measurement environments setup and scenarios are briefly described in Section II. Propagation aspects in different scenarios are discussed in Section III. In Section IV, measurement results are presented and discussed. Conclusions are drawn in Section V.

II. DESCRIPTION OF MEASUREMENTS

Measurements were performed in two environments, indoor and outdoor, Fig. 1. The indoor environment was a corridor in one of the buildings of the Gdańsk University of Technology (GUT), users moving next to a staircase and elevators, and measurement equipment being hidden behind a pillar. The outdoor environment was a part of the square just in front of the previous building, users moving at the distance of several metres from surrounding buildings, walls and other obstacles, including a metal lamp post in the proximity. All measurements were carried out during weekends, therefore, the influence of other people in the measurement area or cars in the parking area can be neglected.



(a) layout of indoor environment.



(b) layout of outdoor environment.

Fig. 1. Layouts of indoor and outdoor measurement environments.

The measurement campaign has already been described in detail in [6] and [7], and only an outline of the important information is provided in this section. The transmitting (Tx) section consisted of a vector signal generator SMU200A operating at 2.45 GHz and the receiving (Rx) one of a programmable spectrum analyser MS2724B, controlled by a computer. The measurements were done asynchronously (due to the setup's limitations), with a variable sample period (with an average of 150 ms and a standard deviation of 50 ms).

Both users were wearing a patch antenna with the same characteristics. From the several on-body antenna placements typical in BANs, the following six were considered, Fig. 2: right and left sides of the head (HE_R/L), front side of the torso (TO_F), front side of the waist (WA_F), and external sides of the right and left arms, at the wrist (AB_R/L). The antenna gain is 6.6 dBi, and the half-power beamwidths (HPBW) in the E- and H-planes are 85° and 95°, respectively. The total antenna radiation efficiency at the resonant frequency (i.e., 2.44 GHz) is 80.2% and the input return loss is -12.4 dB [9]; due to the low radiation into the body [9], its presence does not lead to significant distortion of the foregoing antenna parameters [10].

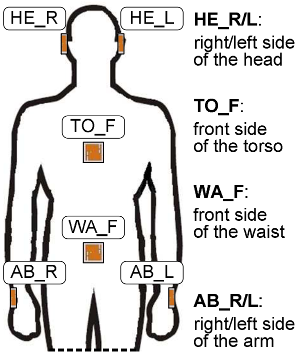


Fig. 2. Placements of the on-body Tx/Rx antennas.

Three typical walking scenarios were considered, Fig. 3: Approach (A), Departure (D) and Parallel (P). In all scenarios, the walk routes of both users B1 and B2 were parallel, separated by 1 m, and walking for 6 m at the same time, so their speed was approximately the same as well. In Scenario A, users started at 6 m from the end line and stopped at the end line, while in Scenario D, the situation was reversed, and in Scenario P both users walked parallel to each other for 6 m. For each Tx-Rx antenna configuration, scenario and environment, measurements were repeated 10 times.

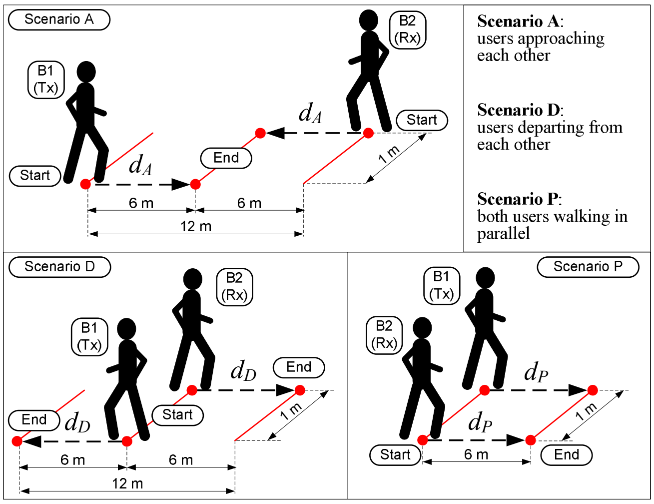


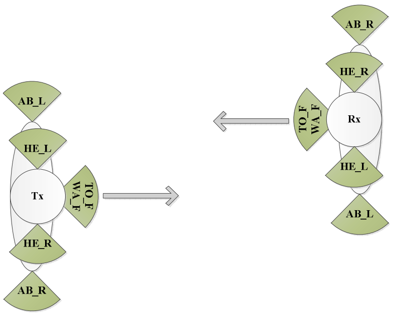
Fig. 3. Investigated scenarios.

Not all combinations of Tx-Rx antenna's placement were considered, since some of them would be redundant, Table I showing the measured 21 antenna placement configurations. One refers to the placement of the antennas according to the antennas pair Tx-Rx, e.g., HE_R-TO_F stands for the Tx antenna placed on the right side of the head and the Rx one at the front of the torso.

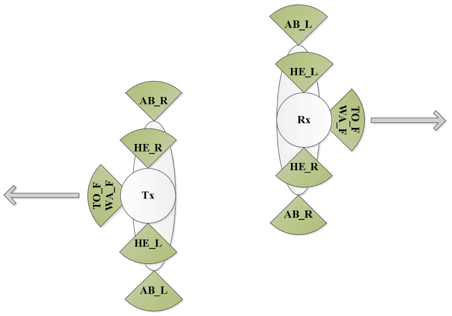
TABLE I. TX AND RX ANTENNA CONFIGURATIONS.

		Tx Antenna					
		TO_F	HE_L	HE_R	AB_L	AB_R	WA_F
Rx Antenna	TO_F	✓	✓	✓	✓	✓	✓
	HE_L		✓	✓	✓	✓	✓
	HE_R			✓	✓	✓	✓
	AB_L				✓	✓	✓
	AB_R					✓	✓
	WA_F						✓

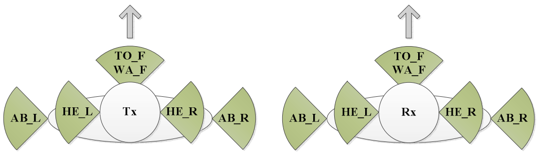
The placement of the antennas has quite an impact on signal behaviour, since the several configurations can lead to a variety of cases regarding the visibility between Tx and Rx antennas during the whole displacement, and, in addition, whether they are within the HPBW of each other. Fig. 4 shows the schematic of antennas' visibility for all cases.



(a) Antennas' visibility for Scenario A.



(b) Antennas' visibility for Scenario D.



(c) Antennas' visibility for Scenario P.

Fig. 4. Visibility between Tx and Rx antennas for the three scenarios.

One can see that the configuration (HE_R-HE_L, Scenario P) corresponds to a "pure" LoS (with the antennas "seeing" each other in the direction of maximum gain) during the whole displacement, while in (TO_F-TO_F, Scenario A), although there is indeed LoS between the two antennas during the entire path, they do not "see" each other within the HPBW when they are close to the end line (which corresponds to a QLoS situation). Also, cases exist where NLoS is very clear, such as (TO_F-TO_F, Scenario D), and others where a mixture of LoS and QLoS exists during the path, such as (AB_R-AB_L, Scenario P) due to the lack of synchronism between the arms during mobility.

Considering the scenarios geometry (see Fig. 3), the path distance corresponding to an angle of 45° (i.e., roughly half of the HPBW) between the two bodies is 0.5 m from the centre line, i.e., $d_A = 5.5$ m and $d_D = 0.5$ m.

III. ANALYSIS OF MEASUREMENT RESULTS

A. *Data Processing and Analysis*

The measurements registered the received power for the various situations. From these data, the system loss, L_S (the relationship between the power supplied to the input terminal of the Tx antenna and the one available at the output terminal of the Rx antenna, [11]) was easily obtained regarding the average and the standard deviation by using Matlab®, which was also used to obtain the estimate of the Rice Factor, K [12], via the appropriate fitting functions. The figures below concerning system loss show the average values in columns, and the range of plus/minus a standard deviation around the averages in bars.

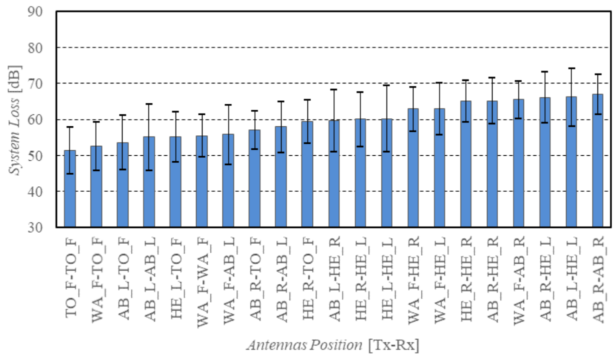
In this analysis of the measurement results, one focuses on the dependence of the system loss and the Rice Factor on the different antenna placement configurations and mobility environments (Scenarios A, D and P) for both indoors and outdoors, and the comparison among them.

As mentioned before, the cases shown in Table I correspond to quite different situations in terms of LoS characterisation and antennas' visibility. Since the system loss corresponds to the combined effect of path loss with antennas' radiation patterns, the analysis of results addresses these aspects, combined with the relative mobility of the locations to the body, i.e., while TO_F, WA_F and HE_R/L can be considered relatively static to the body, AB_R/L are quite dynamic.

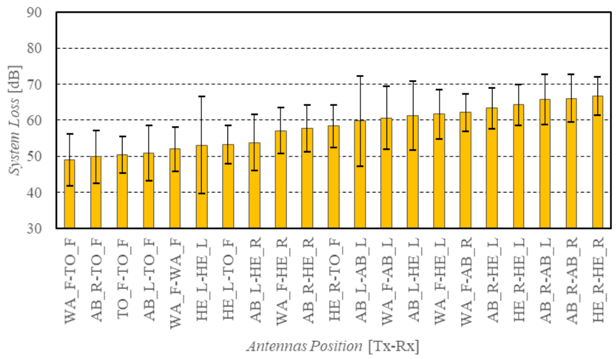
B. *System Loss Analysis*

1) *Approach Scenario*

Scenario A is the one with the largest mixture of different cases in LoS characterisation and antennas' visibility, the results for system loss being shown in Fig. 5, in ascending order for the average.



(a) Indoors.



(b) Outdoors.

Fig. 5. System loss (average and standard deviation) in Scenario A.

For indoors, Fig. 5.a, as expected, the lowest averages (below 53.6 dB) are observed for LoS cases, TO_F-TO_F and WA_F-TO_F, as well as for high visibility QLoS, AB_L-TO_F, while the highest ones (above 66.2 dB) occur for the NLOS or low visibility QLoS ones, AB_R-AB_R and AB_L-HE_L. The highest standard deviation cases (above 9.2 dB) correspond to the visible QLoS, AB_L-AB_L and HE_L-HE_L, showing the importance of both body mobility (not only the mobility of a person him/herself, but also of a persons' arms and legs) and antenna "mutual" visibility on system loss; the lowest standard deviation cases (below 5.3 dB) occur for WA_F-AB_R and AB_R-TO_F, i.e., in low visibility QLoS to NLoS.

For outdoors, Fig. 5.b, similarly to the indoor environment, WA_F-TO_F, TO_F-TO_F and AB_L-TO_F are the cases with lowest averages (below 50.8 dB). The proximity of the metallic lamp post on the right side of the Tx trajectory (see Fig. 1) may explain the low average value for the AB_R-TO_F configuration, due to strong reflections. The highest averages (above 66.1 dB) occur for the clear NLoS cases, i.e., AB_R-AB_R and HE_R-HE_R. The highest standard deviation cases (above 12.5 dB) occur again for AB_L-AB_L and HE_L-HE_L, while the lowest (below 5.2 dB) also includes WA_F-AB_R in addition to TO_F-TO_F (a clear LoS).

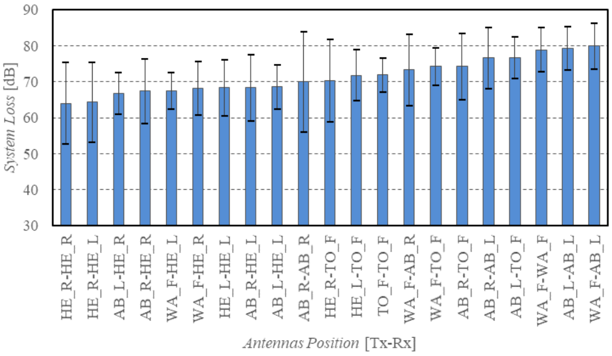
Concerning the difference between the indoor and the outdoor environments, no significant distinction is observed, but there are trends worthwhile exploring. The indoor average system loss is in the range [51.4, 67.0] dB while the outdoor one is [49.1, 66.7] dB, with global average values of 59.8 dB and 58.0 dB, respectively, the difference being 1.8 dB; since Scenario A is the one with the largest variety of cases regarding LoS characterisation and antennas' visibility, one can expect that the surrounding environment may not have a strong influence on these global averages. As far as the standard deviations are concerned, the ranges are [5.2, 9.3] dB and [5.1, 13.4] dB, for indoors and outdoors respectively, with corresponding global average values of 7.0 dB and 7.2 dB; these values confirm the previous statement on the average ones.

2) *Departure Scenario*

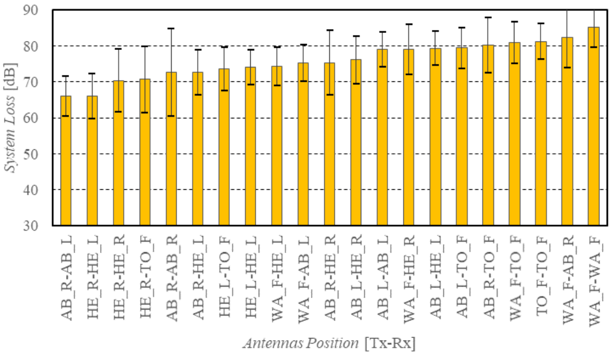
Scenario D is the one where there are no LoS situations during the whole path, but just a few cases at the beginning of the mobility, the majority being NLoS with some in QLoS with low visibility, Fig. 6.

Concerning the configurations, one can see that, in both indoor and outdoor environments, HE_R-HE_R and HE_R-HE_L present the lowest averages: while HE_R-HE_R corresponds a high visibility QLoS, HE_R-HE_L is a case of NLoS, where the low losses can be justified by reflections on nearby walls; the impact of walls may be the reason for a similar low average loss in the AB_R-AB_L case for outdoors. As expected, configurations in clear NLOS from body obstruction have the highest average losses, e.g., WA_F-WA_F, TO_F-TO_F and WA_F-TO_F, as well as other cases, such WA_F-AB_L and WA_F-AB_R.

In both indoors and outdoors, the lowest standard deviations occur for the cases where the average loss is the highest, and the highest for the high visibility QLoS with the highest mobility, i.e., AB_R-AB_R. These results reinforce the ideas presented for Scenario A on the importance of both body mobility and antenna "mutual" visibility on system loss in B2B communications, confirming that system design in applicability scenarios should look into these aspects.



(a) Indoors.



(b) Outdoors.

Fig. 6. System loss (average and standard deviation) in Scenario D.

Average system losses range in [64.0, 79.9] dB for indoors and in [66.1, 85.1] dB for outdoors, with corresponding global average values of 71.5 dB and 75.9 dB, the difference being 4.4 dB. The higher values, compared with Scenario A ones (at least 10 dB), are clearly due to the lack of LoS cases in Scenario D and the higher number of cases in NLoS. The global difference between indoors and outdoors reflects the importance of the surrounding environments, i.e., of reflections in nearby objects, since in indoors there are many more reflections on walls, hence, having a major contribution for NLoS situations.

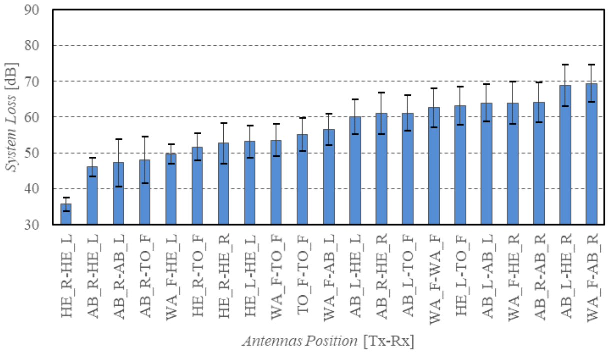
Standard deviations range in [4.7, 13.9] dB and [4.7, 12.2] dB, for indoors and outdoors, respectively, with corresponding global average values of 8.0 dB and 6.6 dB. Again, these results show the importance of reflections on system loss, with indoors presenting a non-negligible higher value.

3) *Parallel Scenario*

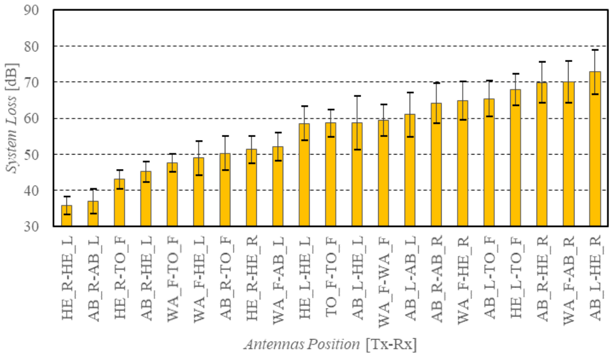
Scenario P is somehow the opposite to the previous one, in the sense that there are strong LoS links and a number of quite QLoS with high visibility, Fig. 7.

As expected, the configuration with the lowest average in both environments is the one with a clear LoS and very low relative mobility, i.e., HE_R-HE_L, with minor impact from the surroundings (35.6 dB and 35.8 dB for indoors and outdoors, respectively), also corresponding to the lowest standard deviations (2.0 dB and 2.4 dB, respectively). The effect of relative mobility (and of the surroundings, by the existence of reflections that appear in some instances) is observed by comparing the previous situation with AB_R-AB_L, where both arms are moving in a non-synchronised way between the two bodies: averages are 47.2 dB and 45.2 dB, for indoors and outdoors, respectively, and standard deviations are 6.6 dB and 2.8 dB, respectively; the difference between the averages in the two cases is around 10 dB or higher, just due to the effects aforementioned.

On the other hand, the cases with the highest averages are also the same in both environments, i.e., AB_L-HE_R and WA_F-AB-R, corresponding again to NLoS and QLoS with low visibility. The highest standard deviations (higher than 6.1 dB) are found in both environments for all LoS visibility cases: AB_R-AB_L and AB_R-TO_F for indoors, and AB_L-AB_L, AB_L-HE_R and AB_L-HE_L for outdoors, again supporting previous statements.



(a) Indoors.



(b) Outdoors.

Fig. 7. System loss (average and standard deviation) in Scenario P.

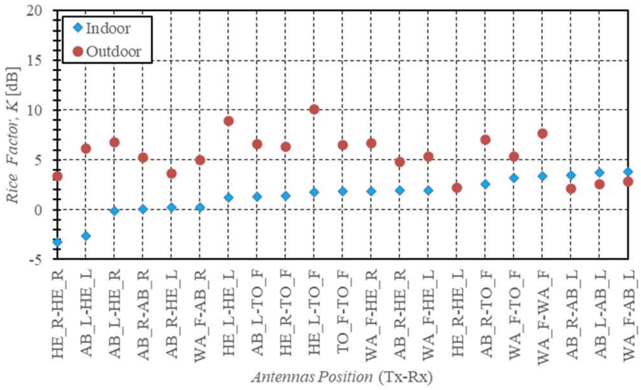
The range of variation for the average system loss is [35.6, 69.3] dB for indoors and [35.8, 72.8] dB for outdoors, with corresponding global average values of 56.5 dB and 56.4 dB, the difference being 0.1 dB. These averages are slightly lower than in the Scenario A case (around 2 dB), due to the existence of clear LoS cases in Scenario P. The negligible global difference between indoors and outdoors shows that the clear LoS cases minimise the importance of the surrounding environments, i.e., direct links between the pair of Tx-Rx antennas tend to minimise the importance of reflections in nearby objects.

For standard deviations, the ranges are [2.0, 6.6] dB and [2.4, 7.4] dB, for indoors and outdoors, respectively, with corresponding global average values of 4.9 dB and 4.5 dB, i.e., quite lower standard deviations, again reflecting the existence of clear LoS cases.

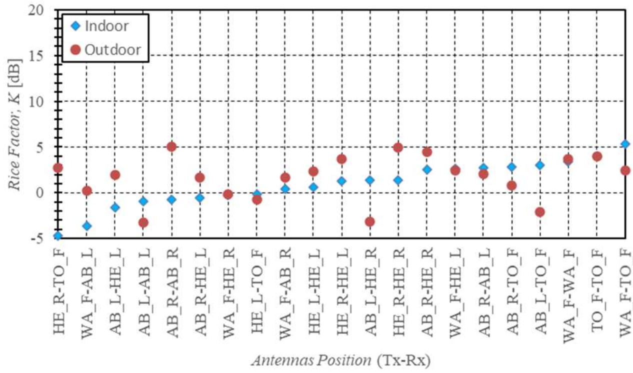
C. *Rice Factor Analysis*

The dependence of the Rice Factor, *K*, on the various configurations and scenarios is addressed in what follows, average values being presented in Fig. 8, sorted by increasing values of *K* in indoor environments.

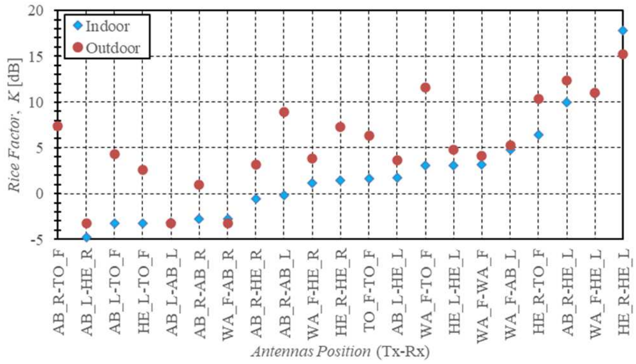
In Scenario A, where the largest mixture of different cases in LoS characterisation and antennas' visibility exists, there is a clear distinction between indoors and outdoors, the former presenting lower values in general, ranging in [-3.3, 3.8] dB while the latter ranges in [2.1, 10.0] dB, which means that multipath reflections do play a role, since they are more important indoors, leading to a less prominent direct signal, hence, a lower *K*. It is also interesting to notice that the lower values of *K* (where the direct signal is less important) do not occur for the same configurations between indoors and outdoors: in the former they are HE_R-HE_R (the most clear case of NLoS) and AB_L-HE_L (a low visibility QLoS), while for the latter they are AB_R-AB_L and HE_R-HE_L (cases of NLoS). The highest values of *K* do occur for LoS or high visibility QLoS, such as WA_F-AB_L and AB_L-AB_L for indoors, and HE_L-TO_F and HE_L-HE_L for outdoors, but again not being the same. Global averages are 1.4 dB and 5.5 dB for indoors and outdoors, respectively, the difference of 4.1 dB being a good measure of the surrounding environments on the importance of multipath.



(a) Scenario A.



(b) Scenario D.



(c) Scenario P.

Fig. 8. Average Rice Factors for all three scenarios.

Scenario D, being the one without LoS configurations, presents, as expected, quite lower *K* values than the other two. The ranges are [-4.7, 5.3] dB and [-3.3, 5.0] dB, with global averages of 0.9 dB and 1.6 dB (difference of 0.7 dB), for indoors and outdoors, respectively. A few configurations have very similar values for both environments, showing that the level of multipath is similar between the environments in some cases.

Finally, for Scenario P, where there are strong LoS links and a number of QLoS cases with high visibility, there are also higher values of *K*, as expected (in Fig. 8.c, the value for AB_R-TO_F indoors is not presented, since it is quite low, -20.0 dB, potentially being a numerical outlier). The ranges of variation for indoors and outdoors are [-4.8, 17.9] dB and [-3.3, 15.2] dB, with global averages of 1.2 dB and 5.4 dB (difference of 4.2 dB), respectively.

The highest value of *K*, indicating a clear LoS situation (higher than 15 dB), occurs for HE_R-HE_L in both environments, as it would be expected, since this is the clear LoS and very low relative mobility case. Interestingly, the case for AB_R-AB_L presents values of *K* of -0.2 dB for indoors and 8.9 dB for outdoors, the difference being explained by the high relative mobility between the two antennas, which may lead to a much higher importance of the multipath coming from the surrounding environment. The consistently lower values of *K* for both environments occur for AB_L-HE_R, which corresponds to a clear case of NLoS.

A comparison of the global averages of *K* in both indoors and outdoors for the three scenarios is presented in Fig. 9.

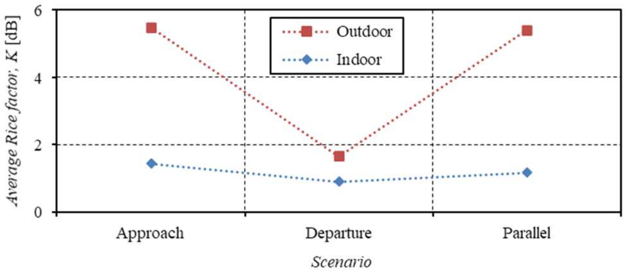


Fig. 9. Global averages of *K* in both environments in the three scenarios.

As expected, the global average of *K* is higher outdoors, where multipath reflections end up being less important, with differences between both environments higher than 4 dB for the scenarios where LoS cases exist, i.e., Scenarios A and P; on the opposite, for Scenario D, where only NLoS exists, the difference is not very significant (0.7 dB) and the global average is the lowest of all (0.9 dB). A final comment is that the values obtained for *K* are consistent with those available in the literature for similar conditions, e.g., [6]-[5].

IV. CONCLUSIONS

The main objective of this work, addressing Body-to-Body communications, namely the radio channel, was to properly characterise the influence of the Tx-Rx configuration between bodies on system loss and on the Rice Factor, since they are directly related to the link quality, hence, to the data rate that can be obtained.

The analysis of the radio channel, in indoor and outdoor environments and different mobility scenarios, for different on-body antenna configurations, is based on system loss measurements at 2.45 GHz. For each environment, three mobility scenarios were measured, i.e., A-Approach, D-Depart and P-Parallel, corresponding to typical situations of day-to-day people's mobility. The on-body antenna configurations for both Tx and Rx were right and left sides of the head (HE_R/L), front side of the torso (TO_F), front side of the waist (WA_F), and external sides of both arms at the wrist (AB_R/L). The indoor environment was a corridor in a building, while the outdoor one was a part of the square just in front of the previous building.

Globally, it is observed that results are coherent with theory and other works in literature. It is seen that multipath influence in indoors is higher than in outdoors, leading to system lower losses, with an average difference that can be higher than 4 dB. Regarding the value of *K*, lower values were obtained for indoors, the global difference being also higher than 4 dB compared to outdoors. It is clear that the position of the Tx and Rx antennas has a large influence on both system loss and Rice Factor, the range of variation among the various positions reaching more than 35 dB for the former.

This work is being further developed, by clustering the several cases and by decoupling the radiation patterns from the losses, so that an empirical model can be established from these measurements and analyses. The final goal is to have recommendations for the location of the antennas and a path loss model for BAN design, accounting for the specific use cases, i.e., environment and mobility, among others.

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