

Received February 18, 2022, accepted March 17, 2022, date of publication March 31, 2022, date of current version April 11, 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3163859

Influence of User Mobility and Antenna Placement on System Loss in B2B Networks

MANUEL M. FERREIRA¹, (Member, IEEE), FILIPE D. CARDOSO¹, (Member, IEEE),
SŁAWOMIR J. AMBROZIAK², (Senior Member, IEEE),
AND LUIS M. CORREIA³, (Senior Member, IEEE)

¹ESTSetúbal, Polytechnic Institute of Setúbal and INESC-ID, 2914-508 Setúbal, Portugal

²Faculty of Electronics, Telecommunications and Informatics, Gdańsk University of Technology, 80-233 Gdańsk, Poland

³IST/INESC-ID, University of Lisbon, 1000-029 Lisbon, Portugal

Corresponding author: Filipe D. Cardoso (filipe.cardoso@estsetubal.ips.pt)

This work was supported by Intelligence-Enabling Radio Communications for Seamless Inclusive Interactions (INTERACT) through COST Action under Grant CA20120.

ABSTRACT In this paper, the influence of user mobility and on-body antenna placement on system loss in body-to-body communications in indoor and outdoor environments and different mobility scenarios is studied, based on system loss measurements at 2.45 GHz. The novelty of this work lies on the proposal of a classification model to characterise the effect of user mobility and path visibility on system loss, allowing to identify the best set of on-body antenna placements. To quantify the influence of visibility and mobility on the average system loss, a combined score is proposed, allowing to map system loss onto the degree of visibility and mobility that depends on the scenario being considered and on on-body antenna placements. Overall, a good agreement is observed between the proposed classification model and the average measured values of system loss, with the higher values of combined scores being associated with lower values of systems loss. For the cases under study, the average values of system loss are 61.6 dB for the cases of the antennas being positioned only on the front of the body and/or the head, and 64.5 dB if at least one of the antennas is placed on an arm.

INDEX TERMS Body Area Networks, body-to-body, user mobility, on-body antenna, path visibility, system loss.

I. INTRODUCTION

Wireless Body Area Networks, or simply Body Area Networks (BANs), are composed of a set of wireless devices attached to the human body [1], nowadays having a major role in many applications, such as the monitoring of vital signs, which is important for usage scenarios in medicine, sports, military, police, civil protection and even entertainment. The cooperative 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, is quite important for system design, since the location of the antennas on the body together with users' mobility will lead to quite diverse situations, concerning not only shadowing but also signal variability.

As mentioned in [2], B2B communications are extremely difficult to characterise, due to their specific characteristics.

The associate editor coordinating the review of this manuscript and approving it for publication was Wei Feng¹.

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

Several studies on B2B channel characterisation can be found in literature, namely based on measurements at the 2.4 GHz band. S.L. Cotton *et al.* [3] conducted measurements in a car parking outdoor environment, with antennas on the chest and the back of users in several mobility conditions, showing received power results, and these measurements were taken by S.L. Cotton [4] to analyse models for shadowing. R. Rosini *et al.* [5] 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 [6], extracting path loss and shadowing and multipath fading models as well.

The measurements performed by S.J. Ambroziak *et al.* [7] were done at both indoor and outdoor environments, for a number of antennas placements larger than the previous ones, involving several mobility scenarios, leading to an analysis of system loss, in terms of average and standard deviation.

F.D. Cardoso *et al.* [8] addressed propagation inside circular metallic structures and propose a channel model assessed with measurements at 2.45 GHz in a passenger ferry discotheque with a circular shape. The measurement campaign focused on system loss measurements in the link between a transmitting antenna located on a human body in different locations and a receiving one positioned off-body. Different walking scenarios have been considered, allowing to perform the analysis of system loss for various conditions and on-body antenna placements. In [9], F.D. Cardoso *et al.* present a wide-band characterisation of the propagation channel in circular metallic indoor environments, and an analytical model for the mean and the average delay spread, based on the results from [8].

In [10], M.E.H. El Azhari *et al.* 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 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).

Recently, F.D. Cardoso *et al.* [2] have analysed the B2B radio channel at 2.45 GHz, in indoor and outdoor environments and different mobility scenarios, for different on-body antenna configurations. For each environment, three mobility scenarios were measured and analysed, i.e., Approach, Departure and Parallel, corresponding to typical situations of day-to-day people's mobility. The on-body antenna configurations for both transmitter (Tx) and receiver (Rx) were right and left sides of the head, front side of the torso, front side of the waist and external sides of both arms at the wrist.

The novelty of the current paper lies on the extension of the analysis in [2], in order to identify the best set of on-body antenna placements by taking certain factors into account, such as the degree of visibility and mobility, as well as the stability of the propagation channel during the whole path.

The paper is organised as follows. The measurement environments setup and scenarios are briefly described in Section II. An analysis of measurement results in different scenarios is presented in Section III. The effect of user mobility and antennas is addressed in Section IV, together with the relationship between the measured value of system loss and visibility, and mobility conditions; also, a classification model for the choice of the on-body antenna location is proposed. A discussion on the choice of the best on-body antenna placement is presented in Section V. Conclusions are drawn in Section VI.

II. MEASUREMENT SCENARIOS, VISIBILITY AND MOBILITY

A. DESCRIPTION OF SCENARIOS

As detailed in [2], measurements were performed in indoor and outdoor environments. The indoor environment was a corridor in one of the buildings of the Gdańsk University of Technology and the outdoor one was in the square in front of the previous building. The measurements were carried out by avoiding the influence of other people or objects (e.g., cars) moving in the outdoor environment.

The measurement campaign has already been detailed in [7] and [11]. The measurements were made at 2.45 GHz with a variable sample period (with an average of 150 ms and a standard deviation of 50 ms).

Both users wore a patch antenna with the same characteristics. Six different on-body antenna placements were considered, Fig. 1: 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).

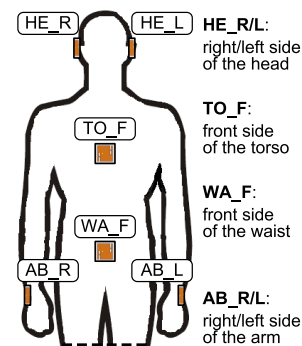


FIGURE 1. Placements of the on-body Tx/Rx antennas.

The antenna has a gain of 6.6 dBi, a radiation efficiency of 80.2 % and input return loss of 12.35 dB. The half-power beamwidths (HPBW) in the E- and H-planes are 85° and 95°, respectively. As referred in [2], due to the low radiation into the body, its presence does not lead to significant distortion of the given antenna parameters, Fig. 2 [12], [13].

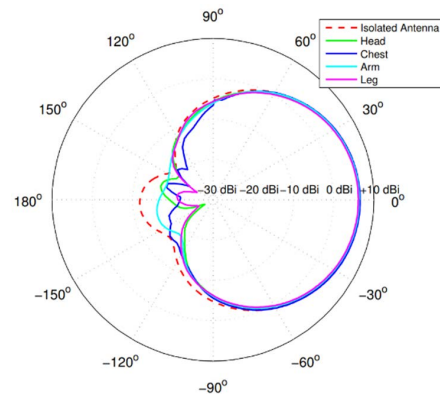


FIGURE 2. Antenna radiation pattern in the E-plane [12].

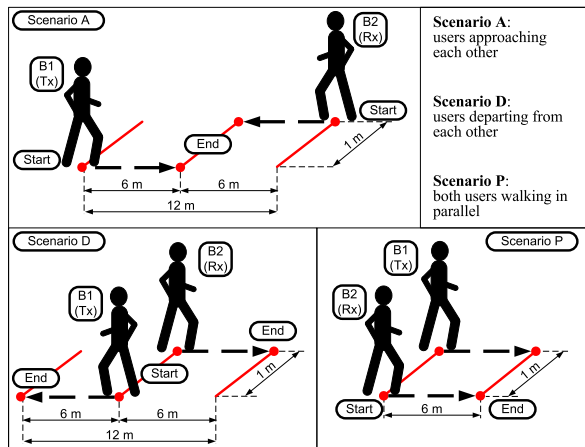


FIGURE 3. Investigated scenarios.

TABLE 1. 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						✓	

Three walking scenarios were considered, Fig. 3: Approach (A), Departure (D) and Parallel (P). In all scenarios, the walk routes of both B1 and B2 users 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 start line and stopped at the end line, while in Scenario D the situation was reversed, and in Scenario P both users walked in parallel for 6 m. For each Tx-Rx antenna configuration, scenario and environment, measurements were repeated 10 times.

Not all combinations of Tx-Rx antenna’s placement were considered, since some of them would be redundant, Table 1 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.

B. VISIBILITY AND PATH STABILITY

The antennas placement 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.

One can see that the configuration (HE_R-HE_L, Scenario P) corresponds to a “pure” Line-of-Sight (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”

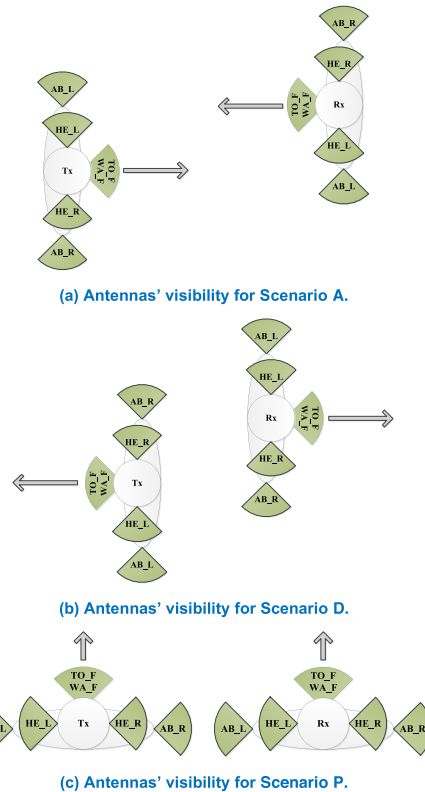


FIGURE 4. Visibility between Tx and Rx antennas for the three scenarios.

each other within HPBW when they are close to the end line. Also, cases exist where Non-LoS (NLoS) is very clear, such as (TO_F-TO_F, Scenario D), others where a mixture of LoS and Quasi-LoS (QLoS) exists during the path, such as (AB_R-AB_L, Scenario P) due to the lack of synchronism between arms during mobility, as well as Obstructed-LoS (OLOs).

As previously mentioned, and illustrated in Fig. 5, the visibility between antennas depends on the relative position of both Tx and Rx. For the given geometry, the project distance between Tx and Rx antennas along the paths, *d*, at which the antennas start to see each other out of their HPBW can be evaluated as

$$d = \frac{W}{\tan(\varphi)} \tag{1}$$

where:

- *W*: Tx/Rx path separation;
- 2φ : HPBW of the antennas.

Hence, the percentage of distance (or time, assuming that the Tx and Rx move at constant speed), relative to the whole path length, $2L$, for which the antennas are within the HPBW of each other, d_b , is given by

$$d_{b[\%]} = \left(1 - \frac{W}{2L \cdot \tan(\varphi)}\right) \times 100 \tag{2}$$

Considering the scenarios’ geometry in Fig. 3, for an angle of $\varphi = 42.5^\circ$ one gets $d_b = 91\%$; from now on, one refers to it as the long visibility path. Regarding the other case, which in this situation occurs only 9.0% of the time, one refers to it as

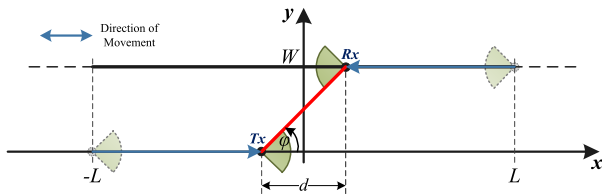


FIGURE 5. Long and low visibility paths, scenario A.

the short visibility one. From the system loss viewpoint, long and short visibility paths correspond to the situations in which the antennas are “seeing” each other within the HPBW or not, respectively, hence, being associated with lower or higher values of system loss.

It should be noted that the definition of long and short visibility paths does not apply to scenario P, since both Tx and Rx keep the same relative position during the whole path. For the values of L and W being considered and antennas with $\varphi > 45.4^\circ$, which is the most usual situation in this type of communication systems, one gets $d_b > 80\%$. Thus, to classify the degree of visibility between Tx and Rx antennas one considers the geometry of the long visibility path (i.e., 91% of the whole path for Scenarios A and D).

The cases shown in Fig. 6 illustrate the different situations in terms of visibility, as a function of the antennas’ alignment and body obstruction, where one considers the link to be within the HPBW (inHPBW) or outside it (outHPBW), in the latter one still having two cases: inside the outwards hemisphere (outHem), i.e., the one containing the main lobe where the antenna radiates outside the body; inside the inwards hemisphere (inHem), i.e., the one within which the antenna radiates into the body, which creates additional obstruction to the link. The relative positions of Tx and Rx antennas are classified into six categories, according to link between them: LoS, QLoS, OLoS and NLoS, the intermediate two being further differentiated between a strong “s” and a weak “w” signal strength. Table 2 shows the result of this classification, where background colours are used to enable an easier reading of the information. There is a symmetry between Tx and Rx in all these cases.

According to this classification, the visibility conditions for the given scenarios and antennas placement are indicated in Table 3.

It must be noted that the use of highly directive antennas is not addressed, since they are not appropriate to be used for BAN applications, like the ones being studied here, due to the level of mobility of the body itself, specially arms and legs, but also head and torso, thus, leading to a mix of LoS and NLoS situations due to the misalignment caused by the body movement. Still, the proposed approach can be used but different conditions will be observed for the long and short visibility paths, e.g., for scenario A, as illustrated in Fig. 4, the long visibility path will be mainly corresponding to a situation of outHPBW as opposite to inHPBW, hence, higher values of system loss will be observed. In any case each situation must be analysed and proper tables with the visibility

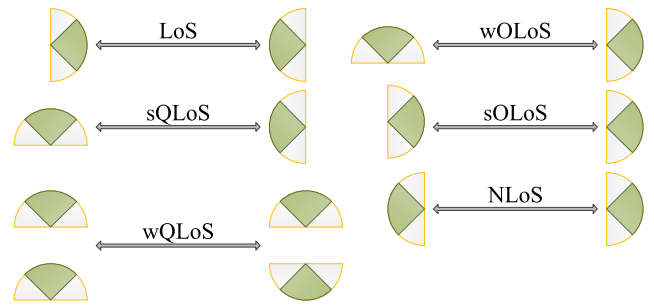


FIGURE 6. Visibility characterisation.

TABLE 2. Visibility classification between Tx and Rx according to the antennas radiation patterns.

Visibility		Tx			
		outHem		inHem	
Rx	outHem	inHPBW	LoS	sQLoS	sOLoS
	inHem	outHPBW	sQLoS	wQLoS	wOLoS
		outHPBW	sOLoS	wOLoS	NLoS

conditions must be derived, depending on the antenna characteristics and scenario under consideration.

C. MOBILITY

System loss depends not only on the visibility conditions but also on the mobility of different parts of the body, e.g., head, torso/waist and arms. For example, while TO_F, WA_F and HE_R/L can be considered relatively static to the body, AB_R/L are quite dynamic.

To characterise mobility as a function of antenna’s position, three categories were considered: High (H), Medium (M) and Low (L), as defined in Table 4. In short, the links between antennas on the head, torso or waist can be considered with a Low mobility, while those between arms are of High mobility, mixed ones being considered Medium.

III. MEASUREMENT RESULTS

A. DATA PROCESSING

The measurements registered the received power, from which the system loss (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, [14]) was easily obtained, the average and the standard deviation being then calculated by using Matlab®.

For illustration, an example of the comparison between measured system loss and theoretical one (obtained with the free-space path-loss model, with an exponent of 1.7, together with the influence of the antennas’ radiation pattern) is illustrated in Fig. 7. One can observe that a good agreement is obtained both for indoor and outdoor environments. Also, the influence of visibility can be clearly identified, with the short visibility path (the lower values, being observed for 9% of the path) corresponding to distances up to 1 m. For larger distances, the long visibility path, here classified as a wQLoS situation, the system loss increases with distance, also because the HPBW of the antennas get more misaligned.

TABLE 3. Visibility classification as a function of antennas' position, for the long visibility path.

(a) Scenario A.

Visibility		Tx					
		TO F	WA F	HE L	HE R	AB L	AB R
Rx	TO F	LoS	LoS	sQLoS	sQLoS	sQLoS	sQLoS
	WA F	LoS	LoS	sQLoS	sQLoS	sQLoS	sQLoS
	HE L	sQLoS	sQLoS	wQLoS	wQLoS	wQLoS	wQLoS
	HE R	sQLoS	sQLoS	wQLoS	wQLoS	wQLoS	wQLoS
	AB L	sQLoS	sQLoS	wQLoS	wQLoS	wQLoS	wQLoS
	AB R	sQLoS	sQLoS	wQLoS	wQLoS	wQLoS	wQLoS

(b) Scenario D.

Visibility		Tx					
		TO F	WA F	HE L	HE R	AB L	AB R
Rx	TO F	NLoS	NLoS	wOLoS	wOLoS	wOLoS	wOLoS
	WA F	NLoS	NLoS	wOLoS	wOLoS	wOLoS	wOLoS
	HE L	wOLoS	wOLoS	wQLoS	wQLoS	wQLoS	wQLoS
	HE R	wOLoS	wOLoS	wQLoS	wQLoS	wQLoS	wQLoS
	AB L	wOLoS	wOLoS	wQLoS	wQLoS	wQLoS	wQLoS
	AB R	wOLoS	wOLoS	wQLoS	wQLoS	wQLoS	wQLoS

(c) Scenario P.

Visibility		Tx					
		TO F	WA F	HE L	HE R	AB L	AB R
Rx	TO F	wQLoS	wQLoS	wOLoS	sQLoS	wOLoS	sQLoS
	WA F	wQLoS	wQLoS	wOLoS	sQLoS	wOLoS	sQLoS
	HE L	sQLoS	sQLoS	sOLoS	LoS	sOLoS	LoS
	HE R	wOLoS	wOLoS	NLoS	sOLoS	NLoS	sOLoS
	AB L	sQLoS	sQLoS	sOLoS	LoS	sOLoS	LoS
	AB R	wOLoS	wOLoS	NLoS	sOLoS	NLoS	sOLoS

TABLE 4. Mobility classification.

Mobility		Tx					
		TO F	WA F	HE L	HE R	AB L	AB R
Rx	TO F	L	L	L	L	M	M
	WA F	L	L	L	L	M	M
	HE L	L	L	L	L	M	M
	HE R	L	L	L	L	M	M
	AB L	M	M	M	M	H	H
	AB R	M	M	M	M	H	H

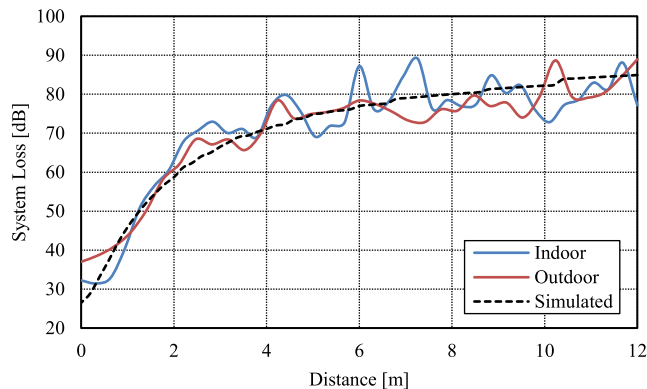
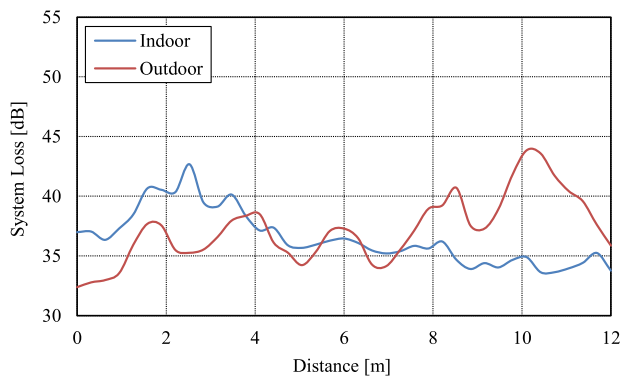


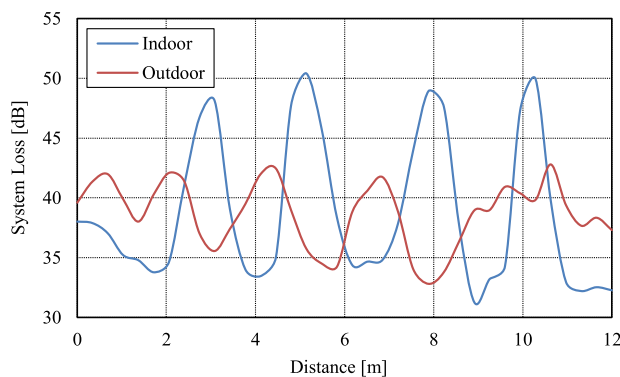
FIGURE 7. Comparison between measurements and simulation in scenario D, AB_R-AB_R configuration.

An example of the influence of mobility is presented in Fig. 8, where two different situations for Scenario P are illustrated: Low (HE_R-HE_L) and High (AB_R-AB_L).

The periodic movement of the arms is clearly identified in the High mobility scenario, where the period is



(a) Low mobility, HE_R-HE_L.



(b) High mobility, AB_R-AB_L.

FIGURE 8. Examples of influence of mobility in scenario P.

approximately 2 s, which is in good agreement with usual walking conditions. The average system loss is not very distinct between the two mobility cases, i.e., 36.6 dB and 37.2 dB for indoor and outdoor environments in Low, and 38.8 dB and 38.7 dB for indoor and outdoor in High, respectively. However, as expected, the standard deviation is more sensitive to mobility, i.e., 2.3 dB and 2.8 dB for indoor and outdoor environments in Low, and 6.1 dB and 2.7 dB for indoor and outdoor in High, respectively; the higher influence of mobility indoors can be assigned to the presence of stronger reflections.

B. ANALYSIS OF MEASUREMENT DATA

This section addresses the dependence of system loss on the different antenna placements and scenarios; for conciseness, detailed results are presented only for indoors. A detailed analysis of the measurement results is presented in [2]. The figures show the average values in columns and the range of plus/minus a standard deviation in bars.

1) APPROACH SCENARIO

Scenario A is the one with the highest visibility between antennas, results being shown in Fig.9, in ascending order for the average, according to the visibility classification.

As expected, the lowest averages (below 54 dB) are observed for LoS cases (TO and WA cases), followed by sQLoS (a mixture of all cases), the highest ones (above

MOST WIEDZY Downloaded from mostwiedzy.pl

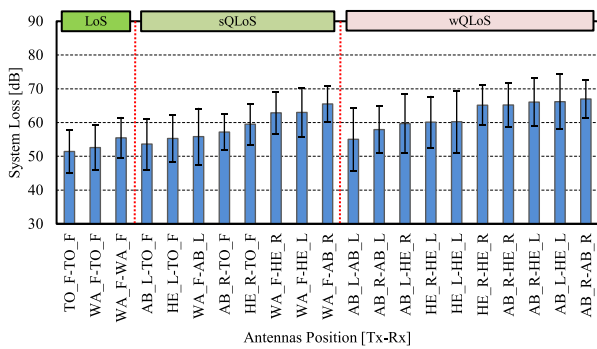


FIGURE 9. System loss (average and standard deviation) in scenario A, indoors.

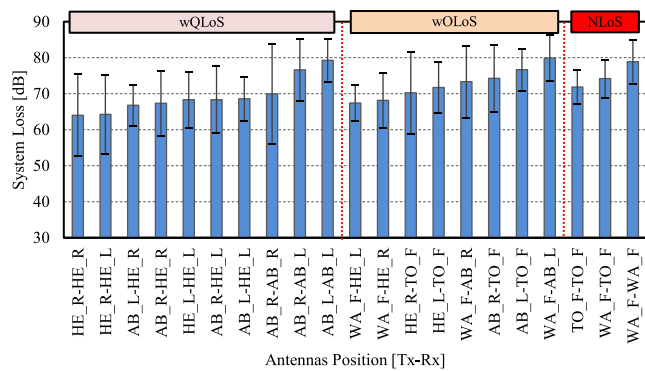


FIGURE 10. System loss (average and standard deviation) in scenario D, indoor.

66 dB) occurring for wQLoS (just AB and HE cases). The highest standard deviations (above 9 dB) occur for wQLoS (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 deviations (around 5 dB) occur for sQLoS (WA_F-AB_R and AB_R-TO_F).

As detailed in [2], no significant distinction is observed between indoor and outdoor environments, 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 within [49.1, 66.7] dB, global averages being 59.8 dB and 58.0 dB, respectively. Since this is the scenario with the highest visibility between antennas, one can expect that the surrounding environment will not have too much impact, hence, this small difference of 1.8 dB between the global averages. As far as 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 averages of 7.0 dB and 7.2 dB, confirming the previous statement on the impact of the surroundings.

2) DEPARTURE SCENARIO

Scenario D is the one where there are no LoS situations during the whole path, but just a few cases at its beginning, results being shown in Fig. 10.

The lowest average system losses occur for wQLoS (just AB and HE cases), where HE_R-HE_R and HE_R-HE_L are the lowest, most probably due to reflections on nearby walls), while the highest correspond to NLoS (just TO and WA cases), the other cases in wQLoS being in the middle (again, a mixture of all cases).

Lower standard deviations occur for the cases where the average system loss is higher, and higher ones are associated with wQLoS paths with the highest mobility (e.g., AB_R-AB_R). These results reinforce the idea 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 application scenarios should look into these aspects.

Average system losses range within [64.0, 79.9] dB for indoors and within [66.1, 85.1] dB for outdoors, with corresponding global averages of 71.5 dB and 75.9 dB. The higher values, compared with Scenario A ones (at least 10 dB), are clearly due to the lack of LoS. The global difference between indoors and outdoors, 4.4 dB, 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 within [4.7, 13.9] dB and [4.7, 12.2] dB for indoors and outdoors, respectively, with corresponding global averages 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 the more varied one, ranging from strong LoS links to NLoS ones, results being presented in Fig. 11.

As expected, the configuration with the lowest average system loss 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), also corresponding to the lowest standard deviations (2.0 dB). The effect of relative mobility can be clearly identified by comparing the previous situation (HE_R-HE_L) with AB_R-AB_L, where the arms are moving in a non-synchronised way between the two bodies, the average being 47.2 dB and the standard deviation 6.6 dB.

The cases with the highest averages are AB_L-HE_R and WA_F-AB-R, corresponding again to NLoS and wQLoS. The highest standard deviations (higher than 6.1 dB) are found for LoS and sQLoS visibility cases (AB_R-AB_L and AB_R-TO_F), respectively, supporting previous statements.

When comparing these results with the outdoor ones, it is observed that 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 averages of 56.5 dB and 56.4 dB, hence, the difference being negligible. 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

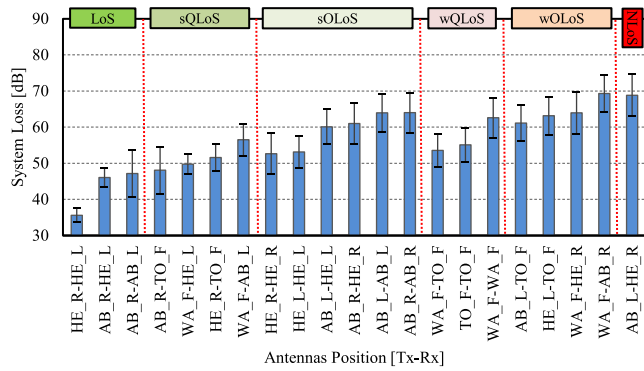


FIGURE 11. System loss (average and standard deviation) in scenario P, indoor.

TABLE 5. System loss, scenario A outdoors.

Mobility	Visibility	Cases	System Loss [dB]	Standard Deviation [dB]
L	LoS	WA_F-TO_F	49.06	7.23
M	sQLoS	AB_R-TO_F	49.88	7.29
L	LoS	TO_F-TO_F	50.40	5.06
M	sQLoS	AB_L-TO_F	50.82	7.69
L	LoS	WA_F-WA_F	51.97	6.09
L	wQLoS	HE_L-HE_L	53.12	13.42
L	sQLoS	HE_L-TO_F	53.26	5.31
M	wQLoS	AB_L-HE_R	53.77	7.79
L	sQLoS	WA_F-HE_R	57.13	6.42
M	wQLoS	AB_R-HE_R	57.72	6.51
L	sQLoS	HE_R-TO_F	58.37	5.90
H	wQLoS	AB_L-AB_L	59.81	12.50
M	sQLoS	WA_F-AB_L	60.64	8.75
M	wQLoS	AB_L-HE_L	61.25	9.61
L	sQLoS	WA_F-HE_L	61.70	6.82
M	sQLoS	WA_F-AB_R	62.13	5.12
M	wQLoS	AB_R-HE_L	63.41	5.66
L	wQLoS	HE_R-HE_L	64.26	5.64
H	wQLoS	AB_R-AB_L	65.81	7.00
H	wQLoS	AB_R-AB_R	66.13	6.60
L	wQLoS	HE_R-HE_R	66.70	5.24

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.

Regarding 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, reflecting the existence of clear LoS cases.

IV. SYSTEM LOSS DEPENDENCE OF VISIBILITY AND MOBILITY

In order to study the effect of user mobility and path visibility on system loss a classification model is proposed, allowing to characterise the different situations that can be found, and aiming at providing inputs for deriving a method for

the choice of the best antennas location for a given usage scenario, to minimise the global system loss.

A. ANALYSIS OF VISIBILITY AND MOBILITY

While visibility accounts for the higher or lower degree of alignment of the antennas together with the influence of body obstruction, mobility is classified according to the degree of relative movement of the body, e.g., arms, rather than the whole movement of a person him/herself.

To properly investigate the relation between the measured system losses and the observed visibility and mobility conditions, one has listed the values of system loss by increasing order, as illustrated in Table 5 for the case of Scenario A outdoors (all results can be found in [2]). Lower values are usually associated with higher visibility and low mobility conditions, e.g., WA_F-TO_F and TO_F-TO_F. Still, there are some exceptions resulting from the specific conditions of each scenario and the influence of the surrounding environment, both indoors and outdoors.

To assess the relationship between visibility and system losses, one has calculated averages and standard deviations for each scenario, by averaging all possible Tx and Rx antenna locations in each scenario, for both indoors and outdoors. The relationship between average system loss and visibility is presented in Fig. 12. It should be noted that not all visibility conditions are observed in all scenarios, as shown in Table 3. The general trend of increasing system loss when ranging from LoS to NLoS is observed, as is the difference among the three scenarios.

On the other hand, mobility is closely related to the standard deviation of system losses, as depicted in Fig. 13. For each scenario, the standard deviation increases with the degree of mobility, as expected.

In order to better understand the influence of visibility and mobility in indoor and outdoor environments, assuming that in a real situation users move in a mixture of environments and scenarios, in which visibility and mobility is not under control, one has calculated averages and standard deviation of system loss in both indoors and outdoors, for all three scenarios, Fig. 14 and Fig. 15.

System losses increase for weaker visibility conditions, both indoors and outdoors. Averages are higher indoors for higher visibility (LoS and sQLoS), but then tend to be opposite (higher for outdoors) when visibility becomes lower (the extreme being in NLoS). This can be explained by the influence of signal reflections in the environment, which are more significant indoors due to the presence of nearby walls and ceiling, namely in low visibility conditions.

Standard deviations observe a clear relationship with the degree of mobility, namely outdoors, i.e., increasing standard deviation with increasing mobility, as expected.

On the other hand, it is important to assess the influence of mobility on the average system loss, to understand if it should be considered as a parameter for quantifying link quality. Fig. 16 shows the average system losses in indoors and outdoors as a function of mobility, for all scenarios.

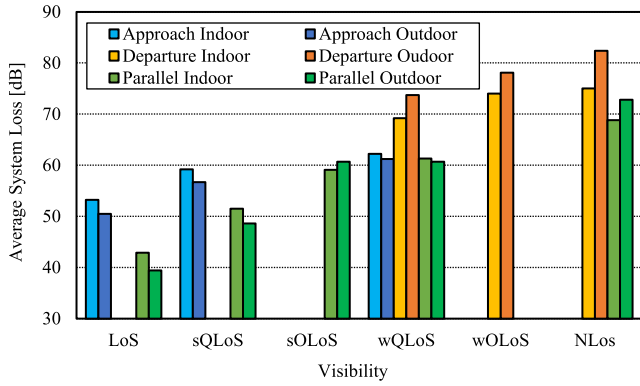


FIGURE 12. Average system loss in the different scenarios as a function of visibility.

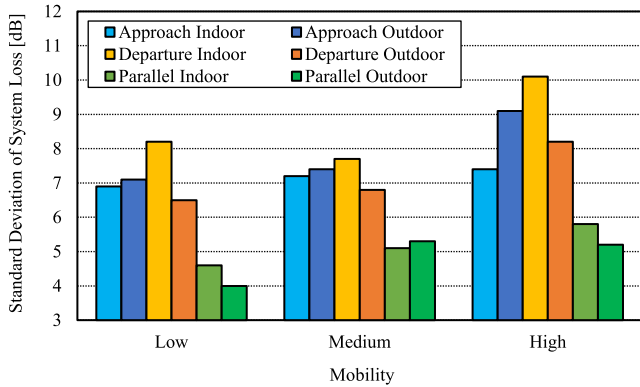


FIGURE 13. Standard deviation of the average system loss in different scenarios as a function of mobility.

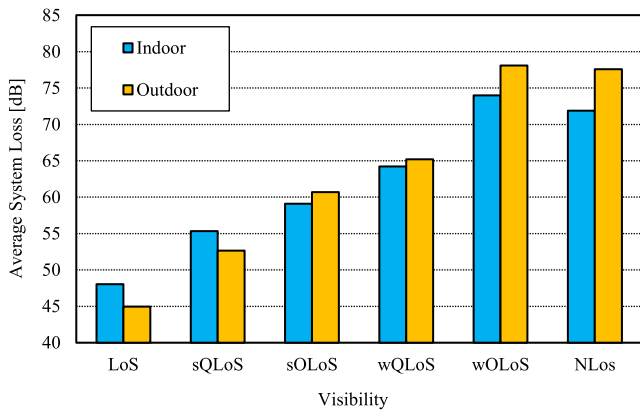


FIGURE 14. Average system loss as a function of visibility for all scenarios.

For Low and Medium mobilities, average system losses do increase with mobility, but for High mobility this is no longer the case for outdoors. This behaviour is explained by the influence of some specific configurations in Scenario P, in which, besides the high mobility being observed, Tx and Rx antennas move close to each other during the whole path, i.e., for the four configurations corresponding to the antennas being positioned on the arms and/or the head they are always within the HPBW of each other.

Fig. 17 shows the average system losses in indoors and outdoors as a function of mobility, for Scenarios A and D. Now,

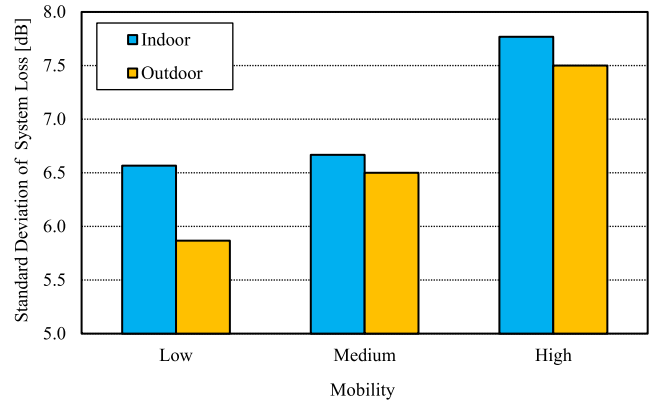


FIGURE 15. Standard deviation of system loss as a function of mobility for all scenarios.

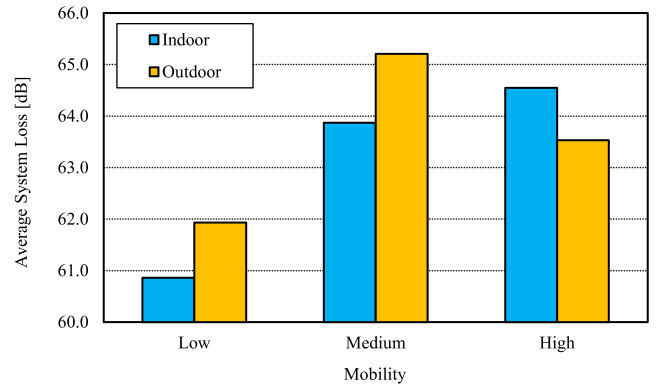


FIGURE 16. System loss as a function of mobility - all scenarios.

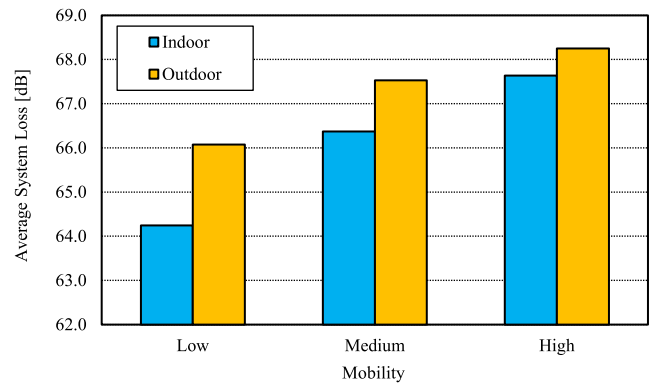


FIGURE 17. System loss as a function of mobility - only scenarios A and D.

the average system losses increase for increasing mobility in all cases, showing that the impact of mobility on system loss depends on the relative movement between the two bodies.

B. THE WEIGHTED SCORE MODEL

To quantify the influence of visibility and mobility on the average system loss, one proposes the combined score S_{MV} ,

$$S_{MV} = w_M \cdot S_M + w_V \cdot S_V \quad (3)$$

where:

- $w_{M,V}$: weights for mobility (M) and visibility (V) scores;

- S_M : score for mobility, being the same for all three scenarios (it only depends on the antenna positioning on the body);
- S_V : score for visibility, obtained as the average scores among the three scenarios,

$$S_V = p_A \cdot S_{VA} + p_D \cdot S_{VD} + p_P \cdot S_{VP} \quad (4)$$

where

- $p_{A,D,P}$: contribution parameters of Scenarios A, D and P for the mobility pattern in a given scenario;
- $S_{VA,VD,VP}$: score for visibility in each of the Scenarios A, D and P.

The values of S_M and $S_{VA,VD,VP}$ are defined as indicated in Table 6. The rationale, following the previous analysis of results, is to give a high score to a case with lower system loss, taking the analysis according to the data in Table 3.

In order to apply this model, one has to establish values for the weights and the contribution parameters, which strongly depend on the actual application scenario to be taken. Some example scenarios can be considered:

- in some sports, such as running in track and field, the athletes tend to be in a situation similar to Scenario P, with a high mobility;
- in other sports, such as basketball, the athletes tend to be in a very dynamic mixture of all scenarios (A, D and P), with a very high mobility;
- in military training, Scenario P tends to be the closer one, with a mobility that can vary from low to high;
- people walking in a street can be approximated by a mixture of all scenarios (A, D and P), with a mobility that can vary from low to high, and even being almost static (people stopping to talk or see a window shop);
- in an emergency situation, one can find in Scenarios A and D a good description of some cases, mobility ranging from low to high.

From this list, one can see that the values of $w_{M,V}$ and $p_{A,D,P}$ can really change from one application scenario to another.

The rationale to propose such a simple model is because in real scenarios, like the ones described before, there are so many uncertainties involved in the characterisation of mobility and visibility conditions that no significant added value is introduced by considering a more complex model that, thus, will decrease its significance, in the sense that it will get harder to understand and adapt to different situations.

In what follows, to highlight the impact of the several individual scores, one considered a uniform situation (but the analysis can obviously be done for other values), i.e., $w_M = w_V = 1/2$ and $p_A = p_D = p_P = 1/3$. The values obtained for S_{MV} are presented in Table 7.

The impact of visibility and mobility is very clear, as three distinct regions can be seen in the table, highlighted with different colours: the green region has the highest values of S_{MV} , between 0.6 and 0.8, corresponding to a high visibility and low mobility, in the cases where both antennas are placed

TABLE 6. Values of S_M , S_{VA} , S_{VD} and S_{VP} .

S_M			$S_{VA,VD,VP}$					
L	M	H	LoS	sQLoS	sOLoS	wQLoS	wOLoS	NLoS
1.0	0.5	0.0	1.0	0.8	0.6	0.4	0.2	0.0

TABLE 7. Value of S_{MV} .

S_{MV}		Tx					
		TO F	WA F	HE L	HE R	AB L	AB R
Rx	TO F	0.7	0.7	0.7	0.8	0.4	0.5
	WA F	0.7	0.7	0.7	0.8	0.4	0.5
	HE L	0.8	0.8	0.7	0.8	0.5	0.5
	HE R	0.7	0.7	0.6	0.7	0.4	0.5
	AB L	0.5	0.5	0.5	0.5	0.2	0.3
	AB R	0.4	0.4	0.4	0.5	0.1	0.2

TABLE 8. Values of S_{MV} and average system loss.

S_{MV} (Average System Loss [dB])		Tx		
		Front	Head	Arm
Rx	Front	0.7 (62.2)	0.7 (62.5)	0.5 (64.6)
	Head	0.7 (62.5)	0.7 (59.1)	0.5 (64.6)
	Arm	0.5 (64.6)	0.5 (64.6)	0.2 (64.0)

on the waist, torso or head; the red area shows low values of S_{MV} , between 0.1 and 0.3, corresponding to a low visibility and high mobility, in the cases where both antennas are placed on the arms; the intermediate region, in yellow, where S_{MV} takes values between 0.4 and 0.5, is the mixed situation.

These results show that antenna placements leading to lower system losses are those on the head or on the front of the body, no significant difference being observed between the left and right sides of the body. When averaging these results by considering both left and right sides of the body, and also waist and torso in the front of the body, one obtains the results presented in Table 8, where the values of the average system loss are also shown.

Overall, a good agreement is observed between the theoretical approach for the influence of mobility and visibility and the average of the measured system loss. It should be noted that higher scores, leading to better results, are expected when antennas are placed on the front of the body (waist or torso) or on the head with no distinction among them; still regarding the average system loss, a slightly better situation is obtained with both antennas being positioned on the head (around 3 dB), which may be explained by the existence of a more predominant LoS case.

The relative low value of system loss obtained for the case in which both antennas are placed on the arms (64.0 dB) is due to the fact that in scenario P there is a strong link among the antennas during the whole path for AB_R-AB_L, having a strong influence on the obtained result. If the average is taken only by considering Scenarios A and D, one gets 66.8 dB (roughly 2 dB higher than the “yellow” locations and reaching almost 7 dB compared to the best “green” one) which is in good agreement with the low S_{MV} score.

V. DISCUSSION ON THE CHOICE OF THE BEST ON-BODY ANTENNA PLACEMENT

In the real-life, people move in a diversity of scenarios that are not easily to characterise. One can mention situations such as people sitting together for a few hours to enjoy a concert in an auditorium or a similar one where people stand up, moving around and dancing, hence, having completely different patterns of movement and body mobility. People can be just walking in a street or on a square crowded of people, or they can be walking together watching the sea. All these situations result in a combination of mobility and visibility scenarios that are not easy to characterise.

In this paper, one proposes to model different visibility situations by considering only three different basic scenarios, i.e., Approach, Departure and Parallel. The modelling of real-life scenarios can be done by taking different values for the weights and the contribution parameters, as mentioned before. Rather than aiming at characterising all situations that can be found in real-life, the goal of this paper is to provide a model to identify the best on-body antenna locations for a given scenario. For the studied scenarios, it is found that a good agreement is observed between the proposed scoring strategy and the average system loss. Still, as already mentioned, further work is needed to properly characterise different real-life situations as a mixture of a finite set of environments.

Globally, it is observed that the best antennas' location is on the head and on the front of the body (waist or torso), but from the scenarios geometry one can expect that similar results are obtained with the antennas on the back.

VI. CONCLUSION

The main objective of this work, addressing body-to-body communications, was to characterise the influence of Tx-Rx antennas placement on the body and body mobility itself on system loss, since they are directly related to 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., Approach, Departure and 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.

A classification model to characterise the effect of user mobility and path visibility on system loss is proposed, allowing to characterise the different situations that can be found for the different scenarios being studied and any given position of Tx and Rx antennas.

To quantify the influence of visibility and mobility on the average system loss, a combined score is defined allowing to map the measured value of system loss to the degree of visibility and mobility that depends on the scenario being considered and on the on-body antenna placements. From the obtained results, a good agreement is observed between the proposed classification model and the average measured system loss, with the higher values of combined scores being associated with lower values of systems loss. For the cases under study, average values of system loss are 61.6 dB for the cases of the antennas being positioned only on the front of the body and/or the head, and 64.5 dB if at least one of the antennas is placed on an arm.

This work will be further developed in order to have recommendations for the location of antennas and a path loss model for BAN design, accounting for specific real-life use cases beyond the ones being addressed here.

REFERENCES

- [1] A. Reichman and J. Takada, Eds., "Body communications," in *Pervasive Mobile and Ambient Wireless Communications*, R. Verdone and A. Zanella, Eds. London, U.K.: Springer, 2012, pp. 609–660, doi: [10.1007/978-1-4471-2315-6_15](https://doi.org/10.1007/978-1-4471-2315-6_15).
- [2] M. M. Ferreira, F. D. Cardoso, S. J. Ambroziak, K. Turbic, and L. M. Correia, "Assessment of user mobility's influence on system loss in several body-to-body scenarios," in *Proc. IEEE 32nd Annu. Int. Symp. Pers., Indoor Mobile Radio Commun. (PIMRC)*, Helsinki, Finland, Sep. 2021, pp. 905–910.
- [3] S. L. Cotton, W. G. Scanlon, and A. McKernan, "Improving signal reliability in outdoor body-to-body communications using front and back positioned antenna diversity," in *Proc. 6th Eur. Conf. Antennas Propag. (EUCAP)*, Prague, Czech Republic, Mar. 2012, pp. 3393–3396, doi: [10.1109/EuCAP.2012.6206649](https://doi.org/10.1109/EuCAP.2012.6206649).
- [4] S. L. Cotton, "Shadowed fading in body-to-body communications channels in an outdoor environment at 2.45 GHz," in *Proc. IEEE-APS Top. Conf. Antennas Propag. Wireless Commun. (APWC)*, Palm Beach, Aruba, Aug. 2014, pp. 249–252, doi: [10.1109/APWC.2014.6905548](https://doi.org/10.1109/APWC.2014.6905548).
- [5] R. Rosini, R. Verdone, and R. D'Errico, "Body-to-body indoor channel modeling at 2.45 GHz," *IEEE Trans. Antennas Propag.*, vol. 62, no. 11, pp. 5807–5819, Nov. 2014, doi: [10.1109/TAP.2014.2352631](https://doi.org/10.1109/TAP.2014.2352631).
- [6] F. Mani and R. D'Errico, "A spatially aware channel model for body-to-body communications," *IEEE Trans. Antennas Propag.*, vol. 64, no. 8, pp. 3611–3618, Aug. 2016, doi: [10.1109/TAP.2016.2570260](https://doi.org/10.1109/TAP.2016.2570260).
- [7] S. J. Ambroziak, L. M. Correia, and K. Turbic, "Radio channel measurements in body-to-body communications in different scenarios," in *Proc. URSI Asia-Pacific Radio Sci. Conf. (URSI AP-RASC)*, Seoul, South Korea, Aug. 2016, pp. 1376–1379, doi: [10.1109/URSIAP-RASC.2016.7601348](https://doi.org/10.1109/URSIAP-RASC.2016.7601348).
- [8] F. D. Cardoso, P. T. Kosz, M. M. Ferreira, S. J. Ambroziak, and L. M. Correia, "Fast fading characterization for body area networks in circular metallic indoor environments," *IEEE Access*, vol. 8, pp. 43817–43825, 2020, doi: [10.1109/ACCESS.2020.2977425](https://doi.org/10.1109/ACCESS.2020.2977425).
- [9] F. D. Cardoso, M. M. Ferreira, S. J. Ambroziak, and L. M. Correia, "A wideband channel model for body area networks in circular metallic indoor environments," *IEEE Access*, vol. 9, pp. 73791–73798, 2021, doi: [10.1109/ACCESS.2021.3080933](https://doi.org/10.1109/ACCESS.2021.3080933).
- [10] M. E. H. El Azhari, L. Talbi, and M. Nedil, "Body-to-body channel characterization and modeling inside an underground mine," *IEEE Trans. Antennas Propag.*, vol. 68, no. 6, pp. 4799–4809, Jun. 2020, doi: [10.1109/TAP.2020.2969746](https://doi.org/10.1109/TAP.2020.2969746).
- [11] K. Turbic, S. J. Ambroziak, and L. M. Correia, "Fading characteristics for dynamic body-to-body channels in indoor and outdoor environments," in *Proc. 12th Eur. Conf. Antennas Propag. (EuCAP)*, London, U.K., 2018, p. '628, doi: [10.1049/cp.2018.0987](https://doi.org/10.1049/cp.2018.0987).
- [12] M. Mackowiak, C. Oliveira, and L. M. Correia, "Radiation pattern of wearable antennas: A statistical analysis of the influence of the human body," *Int. J. Wireless Inf. Netw.*, vol. 19, no. 3, pp. 209–218, Sep. 2012, doi: [10.1007/s10776-012-0188-y](https://doi.org/10.1007/s10776-012-0188-y).

- [13] M. Mackowiak, "Modelling MIMO systems in body area networks in outdoors," Ph.D. dissertation, IST-Univ. Lisbon, Lisbon, Portugal, 2013.
- [14] ITU-R, *The Concept of Transmission Loss for Radio Links*, Recommendation, document ITU-R P.341-7, Geneva, Switzerland, Aug. 2019 [Online]. Available: https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.341-7-201908-I!!PDF-E.pdf



and networks of excellence COST CA20120, COST CA15104, NEWCOM, and ICT/LEXNET. His research interests include wireless/mobile channel characterization and wireless sensor and body area networks.

MANUEL M. FERREIRA (Member, IEEE) received the Licenciado degree in electronics and telecommunications from the University of Aveiro and the M.Sc. degree in electrical and computer engineering from IST, Technical University of Lisbon. Since 1995, he has been with the Department of Electrical Engineering, ESTSetúbal, Polytechnic Institute of Setúbal, Portugal, where he is currently a Professor in telecommunications and electronics. He was involved in European projects



involved in European projects and networks of excellence COST 273, COST IC1004, COST CA15104, COST CA20120, IST/FLOWS, ICT/4WARD, ICT/EARTH, ICT/LEXNET, NEWCOM, and NEWCOM++. He was a Task Leader in energy efficiency in transmission techniques (EARTH) and dissemination and standardization (LEXNET) workgroups. He has authored papers in national and international conferences and journals, for which he has also served as a reviewer and a board member. He was a Secretary of the IEEE ComSoc Portuguese Chapter. His research interests include wireless/mobile channel characterization and modeling, body area networks, and mobile broadband systems.

FILIFE D. CARDOSO (Member, IEEE) received the Licenciado, M.Sc., and Ph.D. degrees in electrical and computer engineering from IST, Technical University of Lisbon. Since 1994, he has been with the Department of Electrical Engineering, ESTSetúbal, Polytechnic Institute of Setúbal, Portugal, where he is currently a Tenured Professor in telecommunications and the Head of the Electronics and Telecommunications Area. He is also a Researcher at INESC-ID, Lisbon. He was or is



He is the author or coauthor of many publications, including book, book chapters, articles, reports, and papers presented during international and domestic conferences. He participated and still participates in several projects related to special application of wireless techniques and three COST Actions (IC1004, CA15104, and CA20120). Currently, his main scope of research is radio channel modeling in body area networks. His research interests include wireless communication and radio wave propagation. He was a recipient of the Young Scientists Awards of URSI, in 2016 and 2011, the Eighth International Conference on Wireless and Mobile Communications Best Paper Award, in 2012, and many domestic awards. He is a Senior Member of URSI and a member of Gdańsk Scientific Society. He is also a member of the European Association on Antennas and Propagation (EurAAP) Delegate Assembly, Management Committee Member of the COST CA20120 Action and the Vice-Chair of Commission-F of the Polish National Committee of URSI. In previous years, he was a member of the Board of the Working Group on Propagation of EurAAP, Management Committee Substitute Member of the COST CA15104 Action, and the Chair of the Sub Working Group Internet of Things for Health within this action.

SŁAWOMIR J. AMBROZIAK (Senior Member, IEEE) was born in Poland, in 1982. He received the M.Sc., Ph.D., and D.Sc. degrees in radio communication from the Gdańsk University of Technology (GUT), Poland, in 2008, 2013, and 2020, respectively. Since 2008, he has been with the Department of Radiocommunication Systems and Networks, GUT, from 2008 to 2013, as a Research Assistant, from 2013 to 2020, as an Assistant Professor, and since 2020, as an Associate Profes-



regulator, besides other public and private entities, and has been in the Board of Directors of a Telecommunications Company. He has participated in 32 projects within European frameworks, having coordinated six and taken leadership responsibilities at various levels in many others, besides national ones. He has supervised over 220 M.Sc./Ph.D. students, having edited six books, contribute to European strategic documents, and authored over 500 papers in international and national journals and conferences, for which served also as a reviewer, an editor, and a board member. Internationally, he was a part of 37 Ph.D. juries, 74 research projects and institutions evaluation committees for funding agencies in 12 countries, and the European Commission and COST. He has been the Chairman of Conference of the Technical Program Committee and of the Steering Committee of 25 major conferences, besides other several duties. He was a National Delegate to the COST Domain Committee on ICT. He has launched and served as the Chairman for the IEEE Communications Society Portugal Chapter, besides being involved in several other duties in this society at the global level. He is an Honorary Professor of the Gdańsk University of Technology, Poland. He was a recipient of the 2021 EurAAP Propagation Award "for leadership in the field of propagation for wireless and mobile communications."

LUIS M. CORREIA (Senior Member, IEEE) was born in Portugal, in 1958. He received the Ph.D. degree in electrical and computer engineering from IST, University of Lisbon, in 1991. He is currently a Professor in telecommunications with the University of Lisbon, his work focused on wireless & mobile communications, with the research activities developed in the INESC-ID Institute. He has acted as a Consultant for the Portuguese telecommunications operators and

...