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A Statistical Assessment of Anthropomorphic Characteristics Impacts on WBAN Communications

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Abstract— In Wireless Body Area Networks (WBAN), the subject characteristics (morphology, including gender, posture and movement) are among the main sources of the channel variability. The objective of this communication is to highlight statistically the influence of the anthropomorphic characteristics on the on-body channel. To do it, we have simulated five radio links on five homogeneous men subjects with different morphological characteristics. Experimental results obtained for some radio links have been used to support the relevance of the simulations. Within the framework of this first semi-quantitative approach, this communication is limited to the modeling of the Path Loss as a function of two quantitative morphological parameters that are the Body Mass Index (considering different body heights and fatness) and the Waist Circumference. The objective is to identify the main trends and to extract "semi-quantitative" models giving the orders of magnitude of the variability for each radio link. The latter typically ranges from 4 to 10.6 dB for the phantoms considered (except for a link for which the variations are limited to approximately 2 dB). This analysis is motivated by the importance of the variability obtained.

Index Terms— WBAN, channel modeling, indoor on-body channel, statistical study, antennas, anthropomorphic characteristics.

I. INTRODUCTION

The channel in WBAN has been studied for more than two decades. However, important aspects remain to be explored more deeply. Indeed, one of the peculiarities of WBAN lies in the numerous sources of variability, among which, the "subject's characteristics" (movement, including involuntary, posture and morphology). Considering the human body composition (of about 70% of water), it is a strong electromagnetic (EM) scatterer. It is at the origin of significant attenuations due to specific propagation mechanisms along and around the body. The proximity effect of the body on the antennas may also have a strong influence on the behavior of the terminals [1–4].

To our knowledge, the influence of the subject's morphology on the WBAN channel has been little studied. Apart from an article which considers Path Loss (PL) modeling in a quantitative way [5], the majority of studies deals with this source of variability in a very partial and qualitative manner [2] and [6–8].

In the literature, when the anthropomorphic variability is statistically considered the subjects are often similar with close morphology characteristics (typically young men, rather thin and of medium height) [8–10]. In the latter publications, on the one hand there is no specific statistical study of the

influence of morphology and on the other hand, although the results are based on measurement campaigns with human subjects, the considered "morphological variability" is not really representative of the real population.

The objective of this communication is to propose a more quantitative modeling of the morphological variability on WBAN communications than what has been done so far, by highlighting the average trends and the orders of magnitude of its influence. To do this, we have simplified the problem by considering homogeneous phantoms because the techniques of deformation of inhomogeneous phantoms remain complex and are still the subject of research (in particular when certain constraints such as conservation of mass are mandatory, as is the case for the "interior EM problems" such as the SAR estimation). This is notably the case when it comes to modifying the posture of a phantom, but it is even more complicated when the objective is to play on the corpulence, because it is necessary to modify the very structure of the body model. Morphed models based on MRI (Magnetic Resonance Imaging) data (by anatomical transformation) are starting to be available (e.g. IT'IS foundation, the Virtual Population suit [12]) but the number of models accessible remains limited and does not offer the same flexibility as the image synthesis, which explains our approach. Nevertheless, this will be the subject of further work in order to calibrate the results obtained with our methodology. The underlying assumption is that for external EM problems as is the case here, it is the geometric effects that are dominant in the morphological variability (at least in most cases).

The morphological variability is assessed here by considering two anthropometric indicators, namely the Body Mass Index (BMI) and the Waist Circumference (WaC). Thus, we based this 1st semi-quantitative approach on these parameters which describe the input variability and limited our analysis of their influence on the WBAN channel to the PL which is the most important observable.

The simulations were carried out with five homogeneous models of men having the same static posture, obtained from one "reference model" by deformations thanks to image synthesis softwares (DAZ Studio 3D[®] and Blender[®]). The *scenario-based approach* is preferred as it is considered more appropriate because it avoids mixing data of radio links (RLs) of very different types for comparable distances [13]. Five RLs are studied in this paper: Hip-to-Chest (H2C), Hip-to-Wrist (H2W), Hip-to-Biceps (H2B), Hip-to-Ear (H2E) and

Hip-to-Toes (H2T). The transmitter (Hip) is located on the left side of the subject while the receivers are on his right side. The comparison of part of the simulations with measurements carried out previously [4] on a whole body phantom made it possible to check their consistency with the latter, and therefore their relevance.

Unlike the approach adopted in [5] in which the PL is modeled in distance (based only on the results of simulations) and the effect of morphology is taken into account in the PL exponent (as function of the height and waist size), our approach is *scenario-based*, and the PL is directly modeled as a function of anthropometric parameters (either the BMI or the WaC), for each considered RL. Eventually, the originality of the methodology lies also in the joint use of experimental data, and electromagnetic and Ray Tracing (RT) simulations. The EM simulations are partly validated by comparison with measurements of the mean PL of the *on-body cluster* PL^{On} , and of the Mean Realized Gain MRG ($MRG(\theta, \varphi) = \frac{1}{B} \int_{f_{min}}^{f_{max}} G_r(f, \theta, \varphi) df$) [4] averaged over a solid angle around the azimuthal plane.

The phantom characteristics and the propagation mechanisms in the vicinity of the body are recalled in section II. Section III is devoted to the methodology and the elaboration of the Experimental Design, and statistical results are exposed in section IV; finally conclusions and perspectives are drawn in section V.

II. CHARACTERISTICS OF PHANTOMS AND PROPAGATION MECHANISMS

Human tissues are highly dispersive dielectric and conductive materials, of relative permittivity $\epsilon_r = \epsilon_r' - j \epsilon_r''$, comprising dielectric and ionic losses. Although human tissues are commonly modeled with a Cole-Cole model of order 4, the complexity is reduced in our approach in which homogeneous phantoms are considered. The permittivity used in the EM simulations follows a dispersive law (over the chosen band of interest $B = [3.1, 4.8]$ GHz, i.e. the 1st UWB band [14]) obtained from previous measurements realized on a homogeneous whole body phantom whose nickname is “Kevin” (Fig. 3) [15].

The propagation mechanisms in the vicinity of the body are recalled hereafter [6]:

- Propagation along the body (Norton/surface waves),
- Diffraction around the body (Creeping waves) [13],
- Reflections from the body (e.g arms) and the surrounding environment (wall, ceiling, floor, furniture...).

III. METHODOLOGY, EXPERIMENTAL DESIGN AND SIMULATIONS VALIDATION

A. Phantom models and Experimental Design

The models which are extracted from simulations come from the Channel Transfer Functions (CTFs) of the *on-body cluster* (the path(s) along, around or close to the body) S_{21}^{On} and they are intended to be integrated in future work with previous research [4] taking into account the environment

S_{21}^{Env} . The resulting CTF H is calculated (or measured) as the S_{21} and therefore reads:

$$H = S_{21} = \frac{b_2}{a_1} = S_{21}^{On} + S_{21}^{Env} \quad (1)$$

Usually the CTF is spatially averaged on a small scale in order to eliminate interferences, but for computation time reasons this has not yet been done (but this work is ongoing). However, the small-scale fading is partly corrected by the frequency averaging performed.

Among the many sources of variability, only the RL and subjects evolve in the simulations and experimentations realized, the others are “fixed”. The antennas used are the MSA-BP (Multi-slot Antenna with a Screening Backplane), which are designed to be resilient to the body proximity effects ([4], [14] and [16]).

A small Experimental Design (ED) consisting in varying the morphology, the weight and the stature was defined as follows: a categorization based on three typical morphologies (*thin*, *normal* and *corpulent*) of men of height 177 cm, value close to the median stature of European men and in several other countries around the world [17] and [18]. In order to account for the BMI variability due to the stature, two other subjects of normal corpulence but of different heights (167 and 187 cm) are otherwise considered (TABLE I). As the homogeneous phantoms used are defined only by their geometry, no information regarding their BMI is available. This difficulty was overcome thanks to the strong linear correlation ($R^2 = 0.91$) observed between BMI and WaC [19] and [20], the latter being easily measurable geometrically. Finally, the weight of the phantoms can be immediately deduced from the BMI and height. However, despite the strong correlation between BMI and WaC, some variability remains. Therefore, we have decided to keep these two input parameters, resulting in two sets of models, which users can alternately choose according to their needs.

TABLE I. SUBJECTS PHYSICAL CHARACTERISTICS AND CATEGORIZATION

Subject ID	Height (cm)	Morphology	Weight (Kg)	BMI (Kg/m ²)	WaC (cm)
1	177	Thin	62	19.8	76
2	177	Normal	73.5	23.5	85
3	177	Corpulent	131	41.8	130
4	167	Normal	67	21.4	80
5	187	Normal	90	25.5	90

In [4], EM simulations with CST MICROWAVE STUDIO[®] (CST MWS) and experimentations in anechoic chamber have been driven for similar configurations, three RLs studied (H2C, H2W and H2T). For the experimentations with the phantom “Kevin”, a spatial sampling (comprising 5 micro-positions (μp) around the nominal one) has been performed for each RL in order to improve the results accuracy, by averaging the small scale fading in subsequent processing. For the simulations, a homogeneous numerical phantom (“Louis” of the Virtual Population suit, [12]) made of the same “material” (dispersive law measured on “Kevin”) and a morphology comparable to that of “Kevin” has been

selected (Fig. 3). The consistency between the simulations and the measurements has been assessed considering the Path Loss of the *on-body cluster* PL^{On} as:

$$PL^{On}(RL) = -10 \log \left(\langle \bar{G}^{On}(RL, \mu p) \rangle_{\mu p} \right) \quad (2)$$

The agreement between the results shown in TABLE II is very satisfactory. The results obtained with this methodology and evaluated with a key criterion make us confident about the use of simulations in addition to the experiments. This approach had been validated in a previous work [12] by comparison of the MRG simulated with the inhomogeneous phantom “Louis” and its homogenized version, the differences obtained being very moderate. The antennas used in this work were not resilient to body proximity effects, unlike the MSA-BPs; it is therefore assumed that the effects of inhomogeneity are less for the latter.

TABLE II. MEAN PL^{On} FOR CST SIMULATIONS AND MEASUREMENTS

PL^{On} (dB)	H2C	H2W	H2T
CST Simulations (“Louis”)	48.1	69.3	57.2
Anechoic Chamber Measurements (“Kevin”)	49.1	69.5	57.8

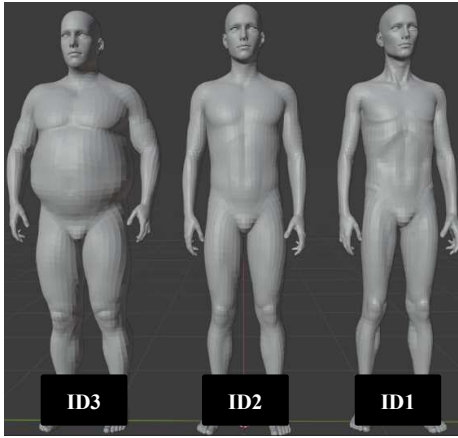


Fig. 1 Morphology aspect: Subjects designed with DAZ 3D and used for CST EM simulations.

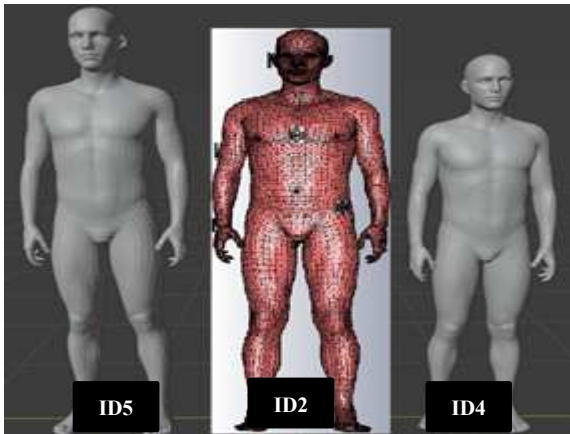


Fig. 2 Height aspect: Subjects designed with DAZ 3D and used for CST EM simulation. In the center model n°2 with antennas on the body.

Simulations have been performed on a computation server equipped with 256 Go of RAM and two GPU acceleration

units. The simulation of each realization (RL and subject) lasts about 10 hours which corresponds to a total of 250 hours for all the simulations, without considering the human time required for preparing the projects for each configuration, and for the subsequent processing.

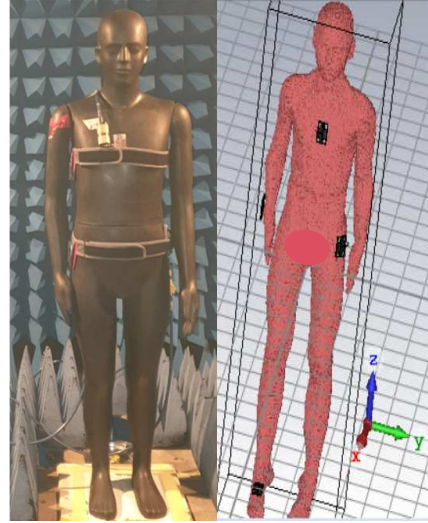


Fig. 3 Real whole body phantom “Kevin” (left) and homogenized numerical phantom “Louis” (right).

B. Simulations Validation

As introduced, two parameters have been used to assess and validate the relevance of the simulations i.e. the PL^{On} and the MRG. For the first one, the sameness between simulations and experimentations is described in TABLE II. For the second one, we note that whatever the subject the realized gain patterns are very close in the main lobe. Moreover, simulations of the horizontal component of the MRG averaged in θ around the azimuth ($MRG_{av,\phi}(\phi)$, cf. (3)) were compared with the measurements made with “Kevin” showing a satisfactory consistency for the antennas on chest (Fig. 4), and on hip and wrist (not shown).

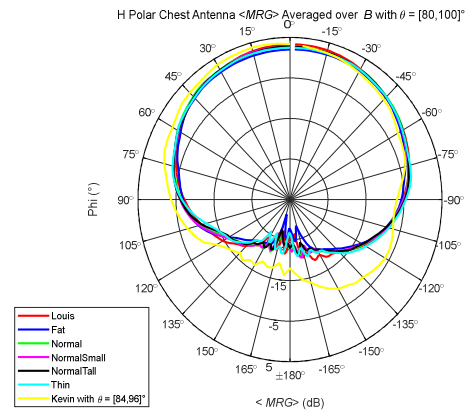


Fig. 4 $MRG_{av,\phi}$ (horizontal polarization) patterns in azimuth of the antenna on Chest for all the simulated subjects and measurements realized with “Kevin”.

As indicated above, the antennas used are resilient to the body proximity effects and it is confirmed in Fig. 5 and Fig. 6 with patterns of the *total* (including both polarizations)

Mean Realized Gain [12] averaged over the frequency band of interest B , and over elevations around the azimuthal plane with $\theta \in [\theta_{min}, \theta_{max}] = [80^\circ, 100^\circ]$, i.e. over $\Delta\theta = 20^\circ$, as:

$$MRG_{av}(\varphi) = \frac{1}{\Delta\theta} \int_{\theta_{min}}^{\theta_{max}} MRG(\theta, \varphi) d\theta \quad (3)$$

However, for the hip antenna (Fig. 7), it should be noted that the morphology of the corpulent subject has a significant effect on the radiation characteristics, most likely due to the pronounced curvature of the abdominal belt. For the other subjects, the MRG patterns are quite close in the main lobe.

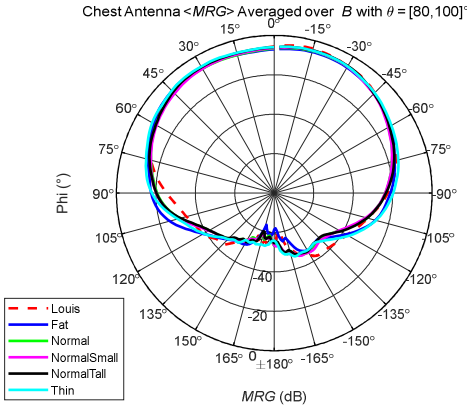


Fig. 5 Total MRG_{av} patterns in azimuth of the Chest antenna.

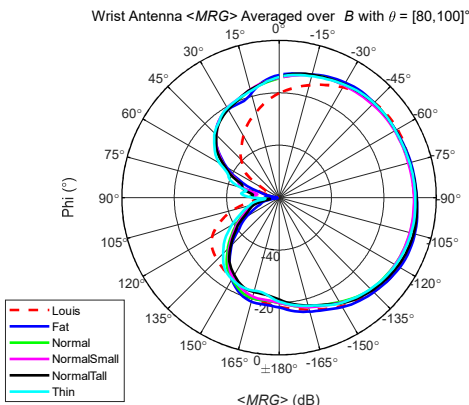


Fig. 6 Total MRG_{av} patterns in azimuth of the Wrist antenna.

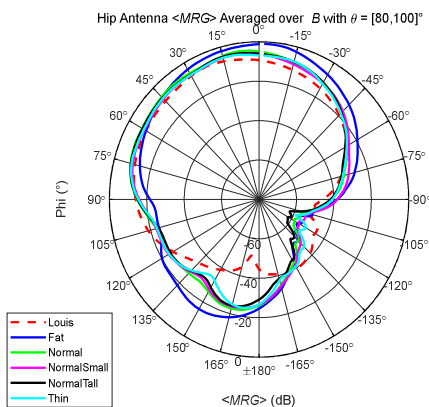


Fig. 7 Total MRG_{av} patterns in azimuth of the Hip antenna.

IV. STATISTICAL RESULTS

The parameter studied is the mean Path Loss of the *on-body cluster* PL^{On} for each RL. For that, the simulated CTF is power averaged over the frequency band of interest (using 1001 frequency points, i.e. with a frequency step of 1.7 MHz), i.e.:

$$\bar{G}^{On} = \frac{1}{B} \int_{f_{min}}^{f_{max}} |H^{On}(f)|^2 df \quad (4)$$

and:

$$PL^{On}(RL, Sub) = -10 \cdot \log_{10}(\bar{G}^{On}(RL, Sub)) \quad (5)$$

TABLE III. MEAN SIMULATED PL FOR EACH RADIO LINK

Subject ID	Height (cm)	H2C PL^{On} (dB)	H2W PL^{On} (dB)	H2B PL^{On} (dB)	H2E PL^{On} (dB)	H2T PL^{On} (dB)
4	167	48.3	71.4	72.2	72.5	60
2	177	49.2	72.1	73.2	75	60.9
5	187	50.5	72.3	76.2	77.9	61.4
1	177	50.2	68.4	75.8	76.2	60.3
3	177	52.5	74.9	81.3	83.1	62.2

These preliminary results show the main trends. First, as expected, for the subjects with different heights but of the same corpulence (green cells), we note that the PL^{On} increases with height moderately for all the RLs, with the exception of H2E for which a significant variation of about 5.5 dB is observed (orange cells). We can also observe that the corpulence has a greater effect than the size if we compare subjects 3 and 5 to subject 2, in particular for the H2B and H2E RLs. More finely, for each RL, we have modeled the average PL^{On} as illustrated in Fig. 8 and Fig. 9. The general trend suggests to adopt a simple linear regression model, i.e.:

$$PL^{On}(RL, \chi) = PL_{0,\chi}(RL) + \alpha_{\chi}(RL) \cdot \chi \quad (6)$$

or a quadratic regression model for the H2W RL as:

$$PL^{On}(RL, \chi) = PL_{0,\chi}(RL) + \alpha_{\chi}(RL) \cdot \chi + \beta_{\chi}(RL) \cdot \chi^2 \quad (7)$$

where χ is the “anthropometric indicator”, i.e. the WaC or the BMI, and $PL_{0,\chi}$, α_{χ} and β_{χ} are the model parameters obtained by linear or quadratic regression.

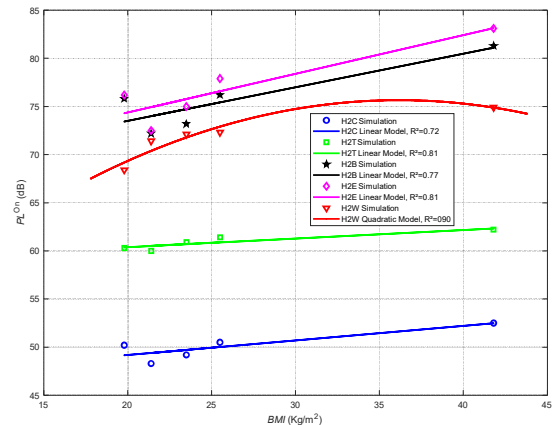


Fig. 8 PL^{On} function of BMI and regression models for all the RLs.

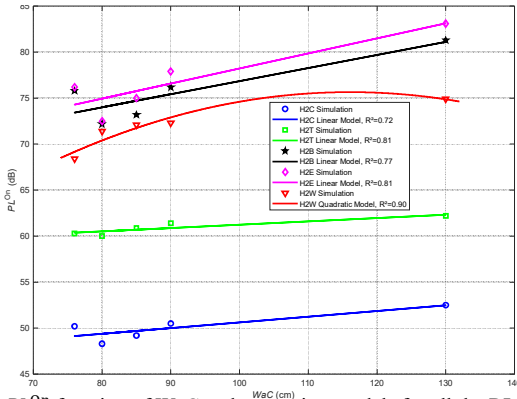


Fig. 9 PL^{0n} function of WaC and regression models for all the RLs.

TABLE IV. MODEL PARAMETERS

RL	Model	χ					
		BMI			WaC		
		$PL_{0,BMI}$	α_{BMI}	β_{BMI}	$PL_{0,WaC}$	α_{WaC}	β_{WaC}
H2C	Linear	46.15	0.15		44.47	0.06	
H2W	Quadratic	44.05	1.75	-0.02	21.22	0.94	-0.004
H2B	Linear	66.53	0.35		62.63	0.14	
H2E	Linear	66.19	0.40		61.83	0.16	
H2T	Linear	58.61	0.09		57.62	0.04	

The ‘goodness of fit’ given by the coefficient of determination R^2 is satisfying for each RL (Table V).

TABLE V. MODELS R^2 FOR EACH RL

RL	H2C	H2W	H2B	H2E	H2T
R^2	0.72	0.90	0.77	0.81	0.81

It is observed in TABLE III that the morphological effects can be interpreted according to three categories of RL. First, for vertical RLs where the propagation is mainly in LOS (Line Of Sight) or quasi-LOS conditions (e.g. H2C and H2T), one observes mainly moderate distance effects (related to height). Second, when the RL is horizontal (i.e. for H2W) combined waist curvature (diffraction/shadowing) and length effects are observed, irrespective of the height. Third, for the H2B and H2E RLs, the variations are the most significant (up to 10.6 dB) and caused by both distance – but this time related to the height – and corpulence effects.

V. CONCLUSIONS AND PERSPECTIVES

The obtained models give the trends and the orders of magnitude of the effect of some anthropometric characteristics on the Path Loss satisfactorily. Depending on RLs, the variations observed range from a few dB to more than 10 dB. The proposed PL models are, to our knowledge, the first to account for the morphological characteristics quantitatively (either with the BMI or the WaC) in the *scenario-based approach* context. In addition, our approach combining measurements with EM and RT simulations gives us confidence in the relevance and reliability of the results obtained. The use of deformable morphed phantoms offers the opportunity to model the morphological effects in an easier

and more “continuous way”. This study will be extended to a set of female models (work in progress). A validation with at least one inhomogeneous phantom is also planned. Finally, other channel parameters, such as the delay spread, could be investigated.

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