Characterisation of On-Body Communications at 2.45 GHz

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ABSTRACT

This work focuses on the characterisation of on-body communications using patch antennas at 2.45 GHz. An investigation on the effects of the body in the communication link is done, based on measurements, for a range of body postures and on-body links. Return reflection loss results show that, on average, the antenna performance is 0.6 dB worse than in free space, also presenting a small detuning (<5 MHz). A fitting to the Normal Distribution is proven to be acceptable. Up to 33 dB of dispersion of values is verified for path links with the same length, as a consequence of antenna mismatch, which can turn a *quasi*-line-of-sight link into a non-line-of-sight one, increasing path loss up to 15 dB.

Categories and Subject Descriptors

J.2 [**Computer Applications**]: Physical Sciences and Engineering – *engineering*

General Terms

Measurement.

Keywords

Body Area Networks. On-Body. Return Loss. Path Loss.

1. INTRODUCTION

Body Area Networks (BANs) [7] are the very last advance in "anywhere, anytime" communications. BANs engage body-worn wireless sensors with a wide range of promising applications in medicine (health care and patient monitoring), firemen/military forces outfits, advanced sports training, personal identification, navigation or multimedia entertainment, among others.

The characterisation of on-body links exhibits great dissimilarities to the models used in traditional wireless communication systems, such as the influence of the human body, the short distances between transmitting (Tx) and receiving (Rx) antennas, as well as the arbitrary orientation of antennas. Moreover, the characteristics of propagation channels for on-body communications are expected to differ according to the link-geometry variability. Variations in the channel are expected to occur due to body movement, being especially severe when antennas are mounted on the upper limbs (arms and hands). Even when standing or sitting, the body is subject to many small movements. In normal activities, movement is significant, becoming extreme during the playing of sports or similar activities. The main concern here is that the interaction antenna-body is an integral part of the channel, so that it is unrealistic to separate them. Nevertheless, it is important to look at the performance of the antenna near body tissues. Accordingly, the authors of [11] suggest that the antenna radiation pattern should no longer be deterministic, but, rather, a stochastic component of the link budget calculation for BANs. Such statistical model can be easily included in standards and in radio channel simulators.

Some attempts to model on-body links are found in the literature, parameters for the models being obtained from measurements (*e.g.*, [8], [2]). Well-designed measurements are a useful tool for dealing with whole the complex on-body channel, including user dynamics and realistic environments [1], drawbacks being their expensive and time consuming nature. Accordingly, this work is based on on-body propagation measurements.

In practice, it is of general consensus that the main propagation mechanism dominating line-of-sight (LOS) links in BANs is free space transmission. Hence, these links follow the usual power decay law, but are generally below it [8]. In the GHz range, the path loss exponent along the front of the body is between 2 and 3 [6], [12]. In [14], the authors observed that this exponent is almost the same along the front and the arm.

A common fault of most BAN studies is that many very different configurations (like LOS or non-LOS, near- or far-field links) are merged together in the same processing of results, [3]. The authors of [5] suggest that the great non-homogeneity of the body, and the variability given by people, lead to a new "scenario-based" approach for characterising on-body communications, depending on antennas' locations, movement, and the surrounding environment. The "scenario-based" approach models the on-body channels by setting specific conditions instead of giving a unique model for the whole human body ([1], [9]).

The novel aspect of this work is the adoption of this scenario-based perspective to the characterisation of on-body communications, together with the statistical approach for the parameterisation of the link budget calculation. This statistical analysis is done both for antenna performance and propagation channel, via the analysis of input reflection loss and received power (path loss). Although some works exist with statistical overviews ([4], [13]), this joint approach is not yet exploited in the literature.

The remainder of this paper is composed of three more sections. Section 2 defines the scenarios and measurement conditions, whereas Section 3 presents and discusses their results. The main conclusions are given in Section 4.

2. MEASUREMENT SCENARIOS

A measurement campaign was carried out in an anechoic chamber. Two similar simple patch antennas [10] were placed at 2 cm from the bodies of three human testers (a female and two males), radiating in one half of the hemisphere, with a 6.6 dBi gain and around 90º half power beam width. The patch antenna is illustrated in Figure 1.

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The Tx for the different communications was the patch located in the arm. The Rx patch was sequentially placed on the arm, chest and leg, creating different on-body links, which were measured for the basic standing and sitting postures, as well as for a military posture (a promising BAN application), Figure 2. The different arm poses in the standing positions characterise the arms movement taken in different snapshots. The same idea is used in the sitting posture. The military position represents a soldier in two surveillance postures, carrying a firearm.

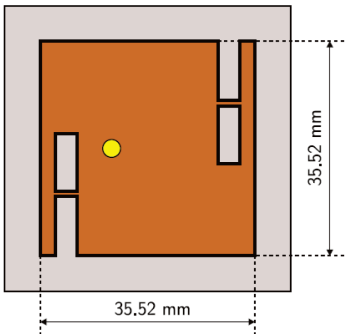


Figure 1. Patch antenna [10].

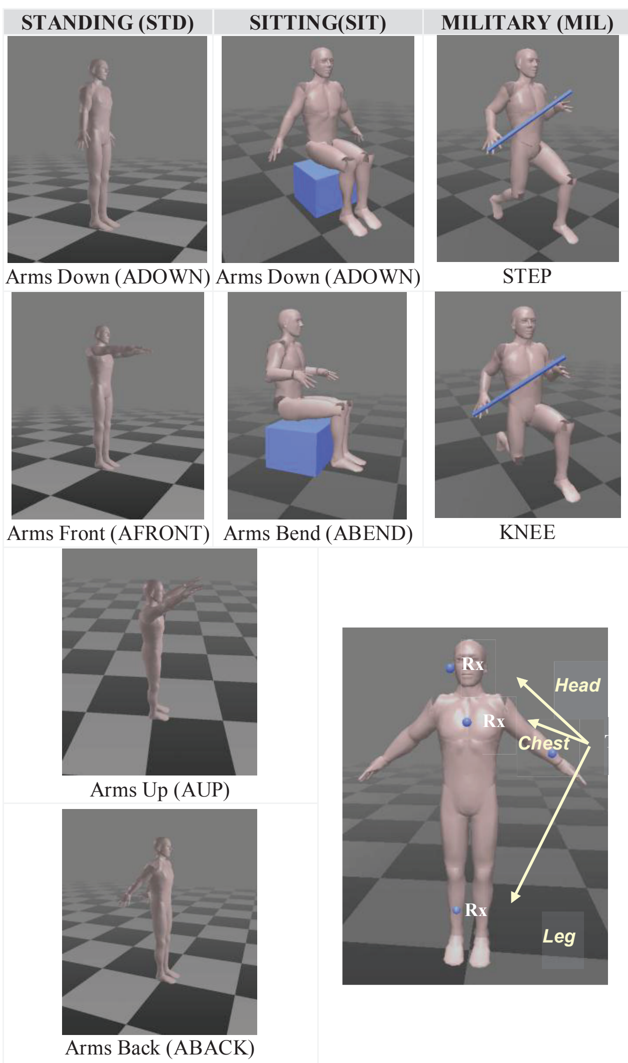


Figure 2. Measurement Scenarios.

The transmitting power (P_t) was set to 0 dBm, within the [2.4, 2.5] GHz band, with a 250 kHz step. Both Tx and Rx antennas were connected to the two ports of a vector network analyser (Agilent E8361A), used to measure the *s*-matrix, with a data acquisition rate of 100 samples per measurement (acceptable rate for statistical studies).

A systematised matrix of connections was created, identifying quasi-LOS (QLOS) or non-LOS (NLOS) links, Table 1. The QLOS condition is applied whenever the antennas do not have any obstacle between them, but takes into account that they are not aligned with each other in the maximum gain direction.

Table 1. Matrix of connections

	Head	Chest	Leg
MIL_STEP	NLOS	QLOS	NLOS
MIL_KNEE	NLOS	QLOS	NLOS
STD_ADOWN	NLOS	NLOS	NLOS
STD_AFRONT	QLOS	QLOS	NLOS
STD_AUP	QLOS	QLOS	NLOS
STD_ABACK	NLOS	NLOS	QLOS
SIT_ADOWN	NLOS	NLOS	NLOS
SIT_ABEND	QLOS	QLOS	NLOS

Although the same postures were reproduced by human testers, their anatomical differences determine the length of the links, Figure 3. Note that these distances were obtained through an ordinary flexible distance meter, which has measured the shortest path between the patches. Due to the short distances involved, the standard technique of using phase shift to measure the length of the link was not use. In general, link distances are higher for the male testers than for the female one, as the male volunteers are taller than the woman. For most of the postures in the leg link, the largest one, the Tx and Rx are in NLOS. For the chest and the head links, the position of the arms determines whether or not there is QLOS.

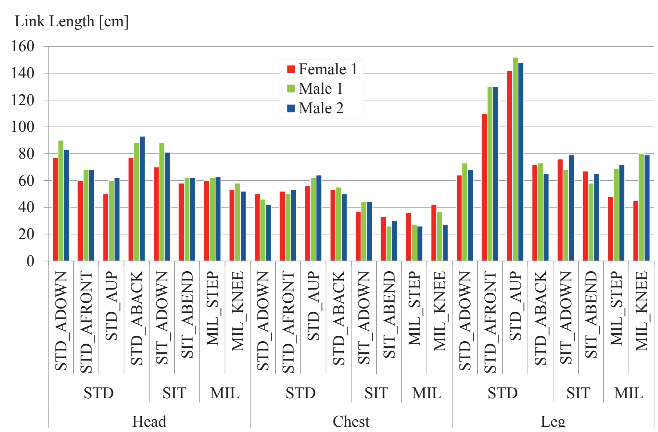


Figure 3. Length of on-body links.

3. RESULTS AND DISCUSSION

The analysis of measurements is based on the extracted *s*-parameters, namely on the input reflection loss, s_{11} (or Γ_{in}) and on the transmission, s_{12}.

The analysis of Γ_{in} is important for the link budget, as it quantifies the reflection or mismatch losses caused by the presence of the body. This parameter was measured for the different on-body links, its mean value was extracted and compared with the one obtained for the isolated patch, Figure 4.

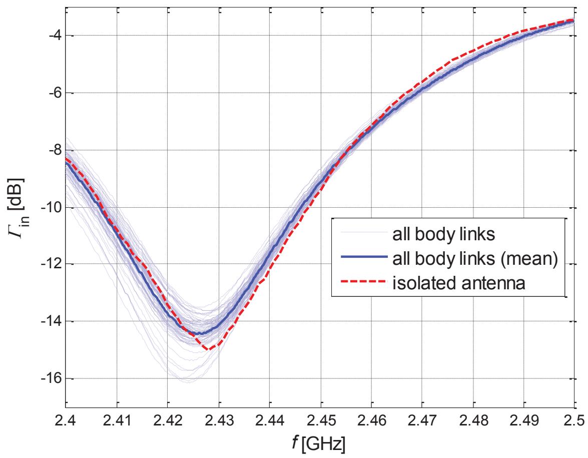


Figure 4. Input reflection coefficient (overview).

Results show that the input reflection coefficient is affected by the presence of the body. On average, the antenna performance on the body is 0.6 dB worse than in free space, which is reflected in a decrease of less than 1% on antenna reflection efficiency. Additionally, there is a small detuning from free space resonance, less than 5 MHz and whose practical effect is the increase of standard deviation. At 2.45 GHz, the curves for the different links are almost coincident, with $\Gamma_{in} < -8$ dB, meaning that almost 85% of the input power is transmitted, which is in agreement with the specifications for short distance communications.

Figure 5 and Figure 6 display, for the different poses, the comparison of the average return loss and its respective standard deviation, $\mu_{\Gamma_{in}}$ and $\sigma_{\Gamma_{in}}$.

The military and sitting poses present a slight worst performance when compared to the standing posture (about 0.5 dB poorer). This effect might be a consequence of the arm rotation, causing antenna misalignment, and of the influence of nearby objects (*e.g.*, the presence of the chair in the sitting position). Conversely, the standing posture presents a higher standard deviation for Γ_{in}, compared to the other postures, as seen in Figure 6. It also shows that the standard deviation of Γ_{in} is especially sensitive near the resonant frequency.

The s_{12} parameter quantifies the received power, P_{rx}. Figure 7 displays P_{rx} for each posture, separating the links. The few number of volunteers does not assure enough statistical confidence for some configurations, motivating an analysis based on the range of changes of P_{rx}. Table 2 presents an overview of the average $\mu_{P_{rx}}$, its standard deviation $\sigma_{P_{rx}}$ and the maximum variation within the same distance $\Delta_{P_{rx}}$ ($\Delta_{P_{rx}} = P_{rx_{max}} - P_{rx_{min}}$).

Results show that the received power in the chest link is higher than in the head or leg ones, with values at least 18, 7 and 11 dB higher, for the military, standing and sitting postures, respectively. This observation, more than being related to the slight small links lengths, is associated to the visibility and stability between Tx and Rx antennas. The plots of Figure 7 also show that there are different paths that have approximately the same length, but have tens of dB of difference. For the military posture, the spread of values goes up to 15 dB for the same distance (*e.g.*, head and chest links). The act of knee's flexion can produce variations up to 7 dB in the chest link. For the standing position, there is a larger dispersion of values (*e.g.*, 33 dB for the leg link). Within the chest link, it is observed that the arm movement (back, down, front, up) leads to a standard deviation of 8 dB. Regarding the sitting posture, the higher dispersion of values at the same distance is for the arm to head link (34 dB). The arm movement (bend, down) leads to a standard deviation of 7 dB in the chest link.

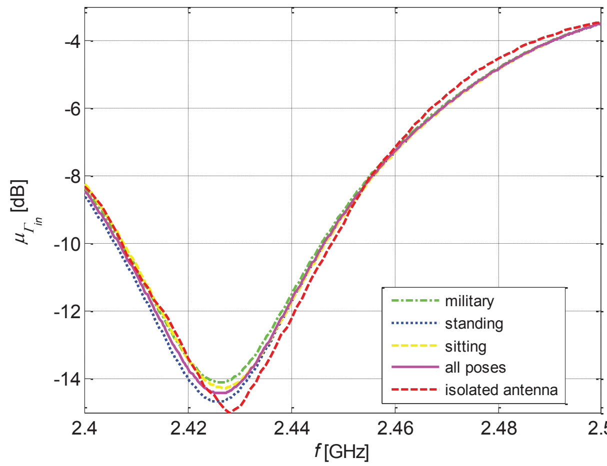


Figure 5. Input reflection coefficient (average).

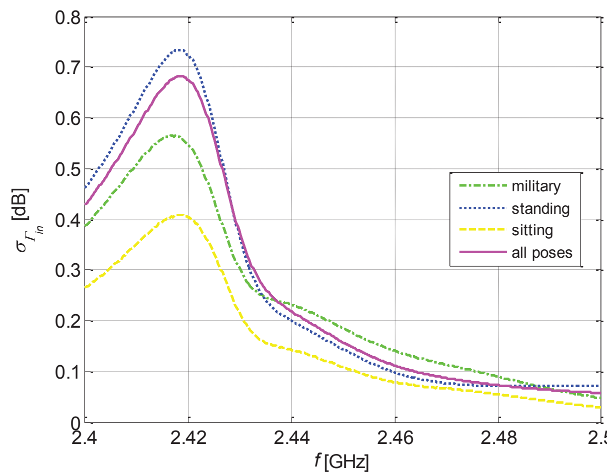
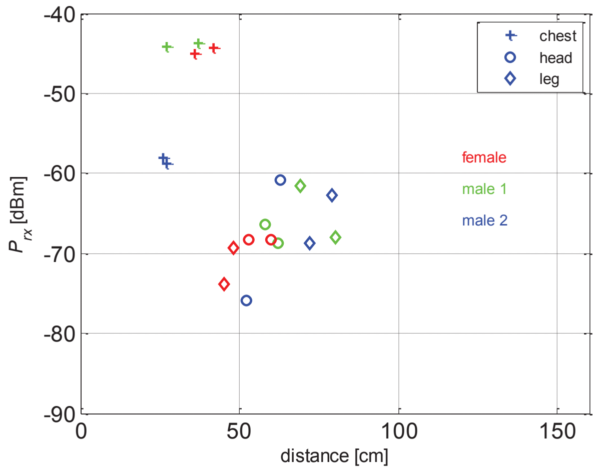
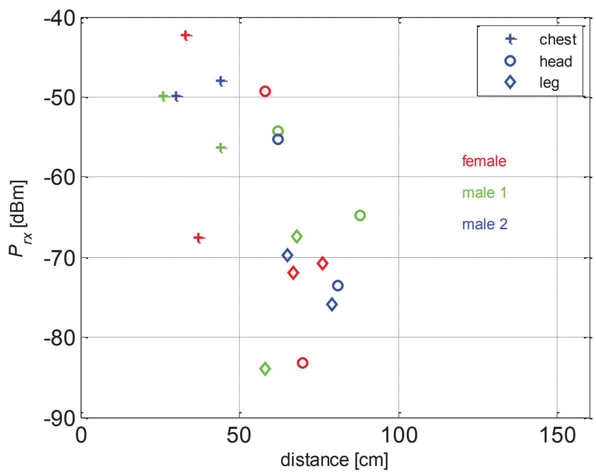


Figure 6. Input reflection coefficient (standard deviation).

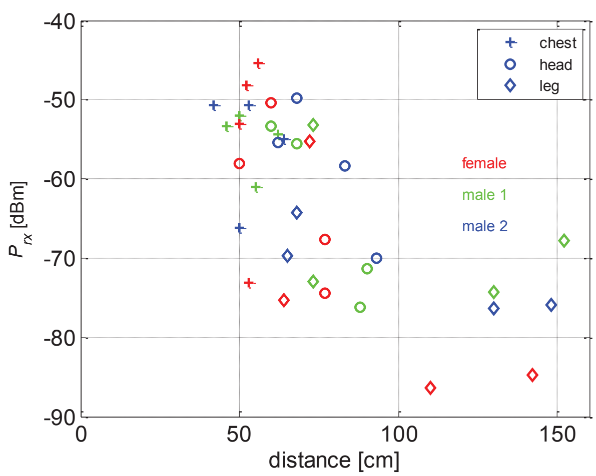
The considerable dispersion of values results from a mixture of different factors, such as the dielectric properties of the body and the posture. The amount of energy absorbed by the body depends on the position of the antenna and on the posture. Two individuals exactly in the same posture, having antennas in the same position, were likely to have similar results, ideally differing just because of the different body compositions. However, the differences in received power can be substantial, just because of, *e.g.*, hand rotation. This makes a radio channel that is considered as QLOS to become NLOS, increasing the path loss. Polarisation mismatch between Tx and Rx antennas changes according to the individuals, meaning that the power extracted by the antenna from the incoming signal will not be maximum due to polarisation loss.



a. Military Position



b. Sitting Position



c. Standing Position

Figure 7. Overview of P_{rx} results.

The cumulative distribution function (CDF) of P_{rx} is plotted in Figure 8 for the different poses. The plot confirms that the received power values are higher for the standing pose than for the military or sitting postures; for 50% of the cases, the received power is 15 dB higher than in the other poses. Taking the samples from all poses, the hypothesis that data follows a Normal Distribution was primarily tested using the χ^2 goodness-of-fit test, Table 3. Results for this distribution are very satisfactory, showing that, at a significance level of 5%, the hypothesis that data follows this distribution cannot be rejected, with 98% of probability p of observing the given statistic. The parameters for the distribution are estimated as mean of -62 dBm and standard deviation of 11 dB.

Table 2. Overview of P_{rx} results

		head	chest	leg
Military	$\mu_{P_{rx}}$ [dBm]	-68	-49	-67
	$\sigma_{P_{rx}}$ [dB]	5	7	5
	$\Delta_{P_{rx}}$ [dB]	15	15	12
Standing	$\mu_{P_{rx}}$ [dBm]	-62	-55	-71
	$\sigma_{P_{rx}}$ [dB]	10	8	10
	$\Delta_{P_{rx}}$ [dB]	26	28	26
Sitting	$\mu_{P_{rx}}$ [dBm]	-63	-52	-73
	$\sigma_{P_{rx}}$ [dB]	13	9	6
	$\Delta_{P_{rx}}$ [dB]	34	25	17

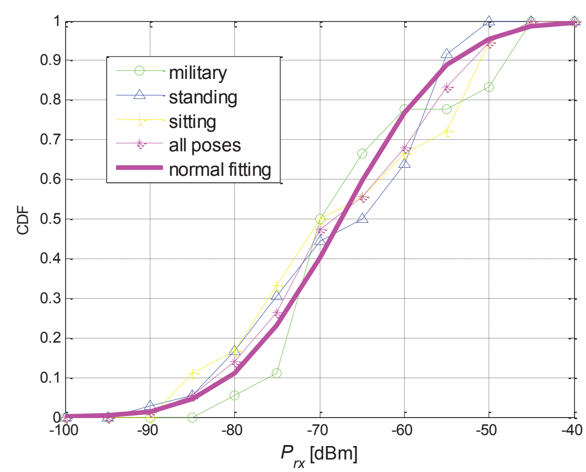


Figure 8. CDF of P_{rx} for the different poses.

Table 3. Results from Normal fitting (χ2 test)

		All Poses	NLOS	QLOS
***p*-value [%]**		98	96	95
χ^2 test		0.0008	0.0023	0.0045
χ^2 threshold	**95% confidence**	3.84		
	99% confidence	6.63		

Considering the matrix of connections, the CDF for NLOS and QLOS links is presented in Figure 9. These curves may also be successfully fitted by a Normal Distribution, at a significance level of 5%, with p equal to 96 and 95%, respectively for the NLOS and QLOS links (Table 3). Parameters for this distribution are a mean value in [-68, -51] dBm, and a standard deviation in [6, 9] dB, respectively for the NLOS and QLOS links. These results show that the change of the link nature originates a decay on P_{rx} of more than 15 dB, which can decide the connectivity.

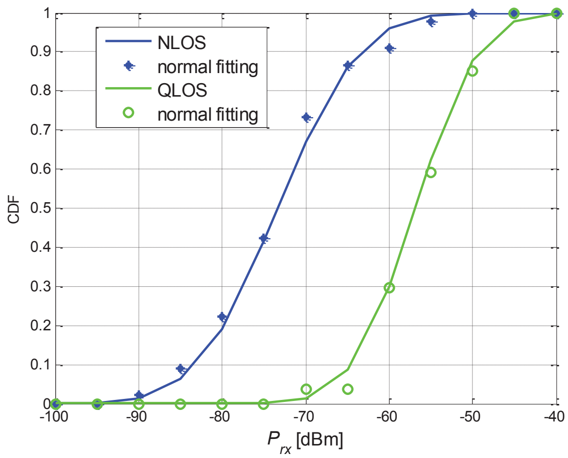


Figure 9. CDF of P_{rx} for QLOS/NLOS links.

Figure 10 presents the power decay with distance for all data points and also the range of variations within 3 cm distance intervals. The same power decays curves are shown in Figure 11, but here the NLOS/QOS sets are split.

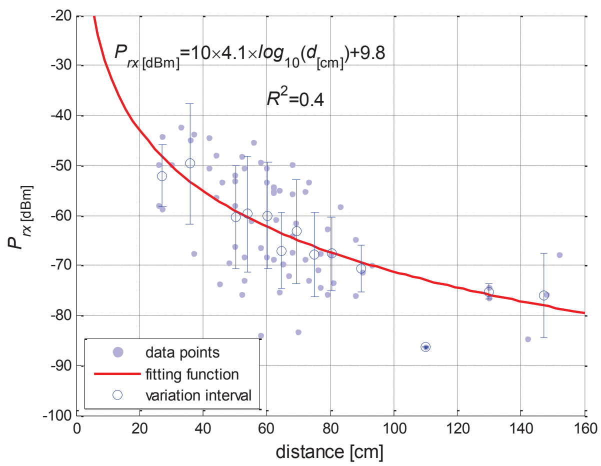


Figure 10. Power decay with distance for all data points.

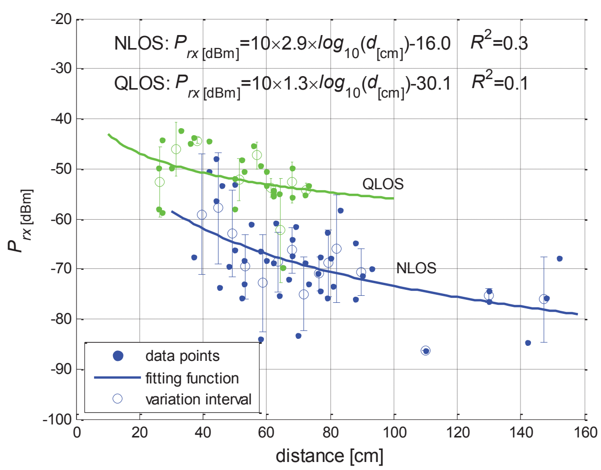


Figure 11. Power decay for NLOS/QLOS data points.

A first observation is that the standard deviation for all measurements is quite high, about 8 dB, with a maximum deviation of about 12 dB (corresponding to a NLOS link). On average, NLOS links present 3 dB more variations than QLOS ones, Table 4. This comes essentially from the fact that one are dealing with on-body measurements, with a chaotic channel performance, and supports the idea that a statistical, rather than deterministic, analysis of the on-body link budget is required.

Table 4. Analysis of P_{rx} results

	All Poses	NLOS	QLOS
$\Delta_{P_{rx}}$ [dB]	12	12	10
[dB]	8	7	4

Despite the wide spread of values, the usual average power decay model with distance was adjusted to the data, as seen in Figure 10 and Figure 11. A general poor correlation with this model is observed, with quite low R^2 values for all cases, but especially when points are split (NLOS/QOS sets). A polemical exponent of 1.3 was obtained for QLOS points, supporting a local guided propagation effect together with local (body) multipath and antenna coupling effects for short distance links. The decay exponent of 4.1 (obtained for all data points) is in agreement with other works for propagation in front of the torso [7], for anechoic chamber environment. Note that, higher decay exponents are expected in this environment, due to its non-reflecting nature. These results strengthen the need for a scenario-based approach, with a clear separation of on-body links.

4. CONCLUSIONS

On-body propagation measurements are presented under a scenario-based approach, using patch antennas at 2.45 GHz in an anechoic chamber. An investigation on the effects of the body in the received signal was taken for a range of body postures and on body links. A matrix of connections was established, distinguishing between QLOS and NLOS links.

Return reflection loss results show that, on average, the antenna performance on the body is 0.6 dB worse than on free space, meaning a decrease of less than 1% on its reflection efficiency. Moreover, there is a small detuning from free space resonance, quantified as less than 5 MHz.

It is observed that there are different paths that have approximately the same length, but have tens of dB of difference. This considerable dispersion is a combination of different factors, such as the dielectric properties of the different individuals and the body posture. The differences in path loss can be substantial, just because of, *e.g.*, hand rotation. This makes a radio channel that is considered QLOS to become NLOS, thus, increasing path loss as much as 15 dB (average results). Antenna misalignment is a dominant effect in on-body links and must be mitigated (*e.g.*, proper antenna design) and taken into account in link calculations for BANs, as connectivity should be assured, under the drawback that power is a limiting factor.

The Normal Distribution is seen to provide a good fit to received power. Anyway, a larger scale measurement campaign is required to gather statistical confidence. The scenario-based approach and the parametric evaluation carried out in this work should be enhanced in a future work, with some more realistic scenarios (further postures, multipath environment and body motion, for example), complex link classification (*e.g.*, create body segments, as front, back, side) and a complimentary study on packet success rates, for instance. Results from this work can later be used at system design level, *e.g.*, for quantifying fading margins.

5. ACKNOWLEDGMENTS

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