WiserBAN

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FRAUNHOFER Fraunhofer-Gesellschaft zur Foerderung der Angewandten Forschung E.V.

VTT Valtion Teknillinen Tutkimuskeskus

TUB Technische Universitat Berlin

UNIBO Alma Mater Studiorum-Universita di Bologna

SORIN Sorin CRM SAS

EPCOS EPCOS SAS

MED-EL MED-EL Elektromedizinische Geraete GmbH

DE-SAT Siemens Audiologische Technik GmbH

DEBIOTECH Debiotech S.A.

SG SignalGenerix Ltd

TALOS RTD TALOS Ltd

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Executive Summary

This deliverable is the final report on the results obtained on antenna-human body interaction, around-the-body propagation in the scope of task T3.1 of the WiserBAN project.

Section 1 introduces the context of the channel modelling activity in the project. In Section 2 a state-of-the-art on body-centric channel model focused on, but not limited to, 2.4 GHz bands is presented. In particular it is shown that literature lacks of dynamic models for on-body, body-to-body and off-body channels. Most of results are in static conditions or are not suited to the WiserBAN project for what concerns the antenna employed, the node emplacement or the band.

The section 3 presents the test-beds employed for channel measurements in T3.1. Two different approaches have been retained: time domain and continuous wave measurements were performed by CEA in order to address dynamic channels, while CSEM performed frequency domain measurements on a phantom.

Section 4 presents the antennas employed for channel measurements and the results on antenna-body interaction. Planar and top-loaded monopoles have been used in order to characterize different polarization properties.

Section 5 presents the measurement campaigns carried out within T3.1, covering all the body-centric channels, i.e. on-body, off-body, body-to-body and in-body scenarios.

Section 6 presents the results on on-body dynamic channel considering different antennas, movement and environments. Measurements were performed on both real human subjects at CEA and human phantom at CSEM.

Sections 7 and 8 present the off-body and body-to-body channel models respectively. The analysis is carried out with respect to the node emplacement and the antenna separation.

Finally section 9 investigates the link budget for the in-body communication. Two different links were addressed: the first considers both antennas in the human body, while a second one considers the channel between one implanted antenna and another antenna outside the human body.
1 Introduction to body-centric channel models

A good understanding of channel characteristics is of fundamental importance in order to design operative and reliable communication systems. Physical (PHY), Medium Access Control (MAC) and Upper Layers protocols are strictly connected to the knowledge of propagation mechanisms and channel models, and a number of studies have been performed in that direction for Body-centric communications.

As far as Body Area Networks (BANs) scenarios are concerned, it is possible to point out three types of channels that have to be investigated separately. They are characterized by specific features and the nodes involved in the communication are located in different places related to the human body. The channel models classification can be organized according to the antennas location around the body:

On-Body channel: in this case both end points of the communication link are placed on the human subject. The propagation takes place along or around the body by diffraction (creeping waves), by Line-of-Sight (LOS) path in specific scenarios such as a link between the waist and the wrist, and hybrid mechanisms (e.g. diffraction off of arms). The shadowing effect of the body could affect significantly the system performance.

In-Body channel: the propagation takes place between an implanted device and another that is positioned in or on the body itself (we can distinguish between in-in and in-on body communication). Human tissues and organs are extremely lossy materials leading to sever attenuation.

Body-to-Body or Off-Body channel: we refer to body-to-body channels when the communication takes place between at least two human subjects, wearing different BAN, free to move relatively to each other in the environment, whereas off-body channels occur when one of the end point of the communication link is represented by an external fixed device e.g. a gateway or a router. In these cases a free-space propagation component has also to be considered.

The WiserBAN project is focused on the development of an ultra-miniaturized and ultra low-power radio frequency (RF) microsystem for BAN, targeting primarily wearable and implanted devices for healthcare, biomedical and lifestyle applications. This deliverable presents a state-of-the-art of the body-centric channel models presented in literature and the results of the preliminary studies carried out in the WiserBAN project.
2 State of the art of channel models and antennas in BANs

A number of investigations have been carried out in the last years on body-centric channel, because of the increasing interest in BANs for a huge number of possible applications.

In particular in November 2007 the IEEE 802.15 Task Group 6, also known as IEEE 802.15.6, was formed in order to standardize BANs, which were not covered by any existing communication standard yet.

The intended standard, which should be released at the end of 2011, will define the PHY and MAC layers optimized for short-range transmissions in, on or around the human body. The purpose is to support a low complexity, low cost, ultra-low power and highly reliable wireless communication for use in close proximity to, or inside, a human body (but not limited to humans) to serve a variety of applications both medical/healthcare and non-medical.

The broad range of possible application fields in which BANs could be involved into, leads to an equally wide variety of system requirements that have to be met. The definition of a unique PHY layer has turned to be not a feasible solution; hence the IEEE802.15.6 standardisation group has proposed three different alternatives:

- narrowband centred at different frequencies,
- UWB and Human Body Communication (HBC).

Figure 1 graphically summarizes the spectrum allocation chart of all available frequencies for BAN applications, with the specification of the related country or region where they could be used.

The channel models presented by the “Channel Modelling Subgroup of IEEE802.15.6” generally characterize the path loss in different BAN scenarios, also taking into account possible shadowing effects due to the human body or obstacles near it and postures of the subject [1].

The human body is not an ideal medium for frequency wave transmission, considering that it is partially conductive and consists of materials of different characteristics. Moreover, depending on the operation frequency and the particular tissue considered, the body can also lead to high losses. This complexity and the specificity of the body shape make it extremely difficult to drive a simple path loss model for BAN.

As shown in Table 1, the standardisation group has identified a list of scenarios in which BAN IEEE802.15.6 compliant devices will operate, along with their description and the frequency band of interest:
The scenarios are determined based on the location of the nodes; according to their physical emplacement, three different types of nodes have been identified:

- **Implant node**: placed inside the human body, immediately below the skin or further deeper inside the body tissue.
- **Body Surface node**: placed on the surface of the human skin or at most 2cm away.
- **External node**: not in contact with human skin (between a few centimetres and up to 5 meters away from the body).

In Table 1 the scenarios are grouped into classes that can be represented by the same Channel Model (CM).

It is important to remark that the channel model for scenarios involving implanted devices is fundamentally different from the one characterizing body surface communications, for that reason the CMs could be divided into two subgroups: CM1 and CM2 for channel model involving at least one implant device, and CM3 along with CM4 for the Body Surface to Body Surface or to external nodes communications.

### Table 1: List of scenarios and their description

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
<th>Frequency Band</th>
<th>Channel Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Implant to Implant</td>
<td>402-405 MHz</td>
<td>CM1</td>
</tr>
<tr>
<td>S2</td>
<td>Implant to Body Surface</td>
<td>402-405 MHz</td>
<td>CM2</td>
</tr>
<tr>
<td>S3</td>
<td>Implant to External</td>
<td>402-405 MHz</td>
<td>CM2</td>
</tr>
<tr>
<td>S4</td>
<td>Body Surface to Body Surface (LOS)</td>
<td>13.5, 50, 400, 600, 900 MHz, 2.4, 3.1-10.6 GHz</td>
<td>CM3</td>
</tr>
<tr>
<td>S5</td>
<td>Body Surface to Body Surface (NLOS)</td>
<td>13.5, 50, 400, 600, 900 MHz, 2.4, 3.1-10.6 GHz</td>
<td>CM3</td>
</tr>
<tr>
<td>S6</td>
<td>Body Surface to External (LOS)</td>
<td>900 MHz, 2.4, 3.1-10.6 GHz</td>
<td>CM4</td>
</tr>
<tr>
<td>S7</td>
<td>Body Surface to External (NLOS)</td>
<td>900 MHz, 2.4, 3.1-10.6 GHz</td>
<td>CM4</td>
</tr>
</tbody>
</table>

Figure 2: IEEE Channel models

A graphical representation of the scenarios and the relative channel model is presented in Figure 2.

This section presents a state-of-the-art of body-centric channel including the IEEE models and the main works presented in literature. Before entering into the details of each model that will be presented and that constitutes the basic background for further investigation and modelling attempts in the WiserBAN context, it is necessary to underline that all these models are far from
giving an exhaustive characterization of the propagation channel for BAN scenarios. Each of them lacks in taking into account more than one source of variability, such as population (human subjects), postures and movements, antenna and frequency variability, and only few studies consider the time varying characteristics of the channel.

It would be also very difficult to compare the results presented in these works because there is no standardized measurement protocol that could be used as a reference and often the data have been collected for too specific scenarios, loosing in this way the desirable generality that a model should present.

2.1 On-body channel

First investigations on on-body propagation have been carried out in 2002-2003 [2], [3], although contributions concerning related questions (such as the strong influence of the body on antennas, beam shadowing by persons, etc.) have been published since the late 90s. In Europe, contributions have been provided by ETH Zurich [4], IMEC (NL), ULB (Brussels) and UCL (Louvain) [5], [6], [7], [9], the University of Birmingham and Queen Mary University of London [10], and Queen’s University of Belfast [12], [13]. Worldwide, contributions have come from Japan, Korea, Singapore, Australia and the USA.

The considered frequency bands are typically around 400, 600, 900 MHz, 2.45 GHz and 3-10 GHz for Ultra Wideband (UWB).

In next sections the most significant results and conclusions about proposed models characterizing the BAN channel will be described.

2.1.1 Standardized channel models: path loss and first order characteristics

The propagation mechanisms on (and/or around) the human body are very specific, mainly combining free space propagation, diffraction (creeping waves) and off reflections (from the environment), resulting in particular channels (as compared to “usual” ones such as indoor, urban, etc.).

One of the main parameters in channel modelling is the mean path loss and the shadowing and fading characteristics.

The conventional approach for modelling the Path Loss (PL), precisely as a function of the distance PL(d), is still widely used, although it is questionable.

Different kinds of models are proposed in the literature and all of them are for example retained in the IEEE 802.15.6 proposal.

- Power law model [14]

\[ PL(d) = a \cdot \log(d) + b + N \]  

where \( a \) and \( b \) are parameters of the model and \( N \) is a normally distributed variable, centred and with standard deviation \( \sigma_N \) (see Table 2). It is used for both Narrowband and UWB channels.

Note that variants, in particular dual-slope models, are also proposed in the literature. This path loss model, namely CM3A in the IEEE 802.15.6, is based on measurements that cover the frequency interval of 2.4-2.5GHz. Details of the measurement set up, derivation and data analysis can be found in [14].
• $a$ and $b$: Coefficients of linear fitting
• $d$: Tx-Rx distance in mm.
• $N$: Normally distributed variable with standard deviation $\sigma_N$

**Exponential model**

Exponential model following the simple form:

$$PL(d)_{[\text{dB}]} = P_0 + \gamma \cdot (d - d_0)$$  \hspace{2cm} (2)

is proposed essentially for the UWB channel; it is used e.g. in [15] for the propagation along or around torso in an anechoic chamber environment

**“Saturation” model** [16]

This kind of model is “hybrid” in the sense that it merges a local propagation model (on-body to on-body, or “on-on”) and the influence of the environment (typically Multi-Paths Components – MPCs – reflecting off of the walls) resulting in an exponential part for “short distances” (on-on mechanism) and a “plateau” for larger distances, accounting for a “saturation” behaviour of the PL in indoor premises whose MPCs reflecting off the room become dominant (saturation due to “environmental MPCs”). It has been proposed for Narrowband channels at 915 MHz and 2.4 GHz.

The corresponding formula (which is really ambiguous as written for example in the table of §8.2.5 B of [1]) should be read:

$$PL(d_{[\text{cm}]}\text{[dB]} = -10 \cdot \log\left(10^{P_0/10} e^{-M_0 d_{[\text{cm}]}/\text{4.34343}} + 10^{P_1/10}\right) + \sigma_P n_P$$  \hspace{2cm} (3)

where $P_0$, $P_1$, and $M_0$ are parameters of the model, $n_P$ is a unit variance centred normal random variable and $\sigma_P$ is the PL standard deviation (relative to mean).

This model, namely CM3B, is based on measurements at 2.45GHz. Details of the measurement set up, derivation and data analysis can be found in [16]. The path loss follows an exponential decay around the perimeter of the body. It flattens out for large distances due to the contribution of multipath components from indoor environment. Table 3 presents the model and corresponding parameters.

<table>
<thead>
<tr>
<th>Path loss model</th>
<th>Hospital Room</th>
<th>Anechoic Chamber</th>
</tr>
</thead>
<tbody>
<tr>
<td>$PL(d)<em>{[\text{dB}]} = a \cdot \log</em>{10}(d) + b + N$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a$</td>
<td>6.6</td>
<td>29.3</td>
</tr>
<tr>
<td>$b$</td>
<td>36.1</td>
<td>-16.8</td>
</tr>
<tr>
<td>$\sigma_N$</td>
<td>3.80</td>
<td>6.89</td>
</tr>
</tbody>
</table>

Table 2: CM3 A model parameters
Table 3: CM3 B model parameters

- **P₀**: The average loss close to the antenna
- **M₀**: The average decay rate in dB/cm for the surface wave travelling around the perimeter of the body
- **P₁**: The average attenuation of components in an indoor environment radiated away from the body and reflected back towards the receiving antenna
- **σₚ**: The log-normal variance in dB around the mean, representing the variations measured at different body and room locations. This parameter will depend on variations in the body curvature, tissue properties and antenna radiation properties at different body locations.
- **nₚ**: Zero mean and unit variance Gaussian random variable

The small scale fading is represented by a Ricean distribution with K factor that decreases as the path loss increases. The delay spread is normally distributed. Table 4 and Table 5 summarize the model and the corresponding parameters.

Table 4: Small scale fading in CM3 B model

<table>
<thead>
<tr>
<th>Small-scale fading</th>
<th>K_{\text{db}} = K_0 - m_k P_{\text{db}} + \sigma_k n_k</th>
</tr>
</thead>
<tbody>
<tr>
<td>K₀ [dB]</td>
<td>30.6</td>
</tr>
<tr>
<td>m_k [dB]</td>
<td>0.43</td>
</tr>
<tr>
<td>σ_k [dB]</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Table 5: Delay spread fading in CM3 B model

<table>
<thead>
<tr>
<th>Parameters of the mean value of the delay spread</th>
<th>t_{\text{mean}} [ns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance [cm]</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>45</td>
<td>16</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters of the 90% cumulative value of the delay spread</th>
<th>t_{\text{mean}} [ns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance [cm]</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>11</td>
</tr>
<tr>
<td>45</td>
<td>22</td>
</tr>
</tbody>
</table>

• “Scenario-based” models, [17][18]

In this more recent approach, application-dependent radio link “scenarios” are retained, e.g. belt to chest for ECGs (Electrocardiograms), and PLs are derived from measurements averaging various sources of variability (human subject, and/or “local positioning”, posture, unwanted movements, antennas, etc.). It has been proposed for both Narrowband and UWB channels.
The following path loss measurements have been performed at frequency of 2.36GHz for everyday activities such as walking around the office, working in the office, driving, at home, etc... and sleeping on a bed and in a bedroom. Details of the measurement set up, derivation and data analysis can be found in [17][18]. Table 6 summarizes the results.

As observed, the dominant factor affecting fading in the channel appears to be the movement of the test subject. This is to be expected, as movement causes the separation and orientation of the antennas to change.

<table>
<thead>
<tr>
<th>Action</th>
<th>Chest</th>
<th>Right Wrist</th>
<th>Left Wrist</th>
<th>Right Ankle</th>
<th>Left Ankle</th>
<th>Back</th>
<th>Back</th>
<th>Right Wrist</th>
<th>Right Ankle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standing</td>
<td>65.3</td>
<td>44.5</td>
<td>74.7</td>
<td>60.9</td>
<td>70.7</td>
<td>75.3</td>
<td>73</td>
<td>70.5</td>
<td>66.3</td>
</tr>
<tr>
<td>Walking</td>
<td>59.1</td>
<td>47.3</td>
<td>59.8</td>
<td>53.9</td>
<td>58.5</td>
<td>67.4</td>
<td>72</td>
<td>64.9</td>
<td>62.4</td>
</tr>
<tr>
<td>Running</td>
<td>55.9</td>
<td>36.3</td>
<td>52.5</td>
<td>55</td>
<td>59</td>
<td>68.5</td>
<td>71.7</td>
<td>57.4</td>
<td>63.3</td>
</tr>
</tbody>
</table>

Table 6: CM3 C model parameter

- $P_{tx}$: Transmitted power
- $P_{rx}$: The RMS received power
- $G_{amplifiers}$: Amplifier gain
- $L_{cable}$: Cable loss

The first-order statistics fits to everyday and sleeping on-body channel gain data, where the data has been normalized to mean of each link data set. The gamma distribution is the best fitting distribution type for this data, apart from overall sets, non-normalized, which is lognormal.

The shadowing term, i.e. the stochastic term added to the PL model (expressed in dB) and accounting for its variance, is generally assessed as a centred normal variable with standard deviation $\sigma_N$, resulting in the “classical” log-normal behaviour. A small parametric analysis of the antenna-body spacing $\delta$ effect on the PL is provided in [1]. As expected, the PL exponent $n$ essentially does not depend on $\delta$ whereas the $PL_0$ does:

$$\frac{\partial n}{\partial \delta} \approx 0$$
$$\frac{\partial PL_0}{\partial \delta} < 0$$

This is due to the fact that $n$ depends only on the physical phenomena along the propagation path (creeping waves, absorption, diffraction, etc.) whereas $PL_0$ is “source dependent” (antenna type and coupling to the body). This trend is confirmed by several works.

### 2.1.2 Impulse response (IR) and small scale statistics

Although this model has been partially checked with a few measurements of “control”, it is worthwhile to point out that its initial version – and notably its structure – was extracted from electromagnetic simulations (with the anatomic model of the “Visual Human Project” over a reflecting ground) over a [2-6] GHz bandwidth. Moreover, antennas behaviour was completely excluded from the model.

This model is consequently more or less restricted to the anechoic chamber environment with ground echoes, which may be considered as a representation of an outdoor environment.

Contrary to conventional Rayleigh or Ricean models, amplitude distributions are found to be log normal and bin to bin correlated (mainly between adjacent ones).

The number of clusters is fixed (only 2 are considered, one for the “on-on” and another for the ground reflection), as long as the inter-cluster and inter-path arrival time.

Three scenarios – corresponding to the receiver position on the front, side and back of the body – are specified with different parameterizations.

Improvements to take into account the multi-path components (MPCs) originating from the surrounding environment have been proposed in [6], [7] and recalled in [19]. Components creeping around the body are generated according to the previous correlated log-normal model, whereas the MPCs coming from the environment are added using a SV model modified as follows: the original exponential decay model of the Power Delay Profile (PDP) is replaced by a dual slope exponential decay model, with slopes $\Gamma_1$ (dB/ns), then $\Gamma_2$ (dB/ns) after an empirically derived breakpoint of $T_1 = 40$ ns. Variation around this trend is log-normally distributed with a standard deviation $\sigma$. Intra-cluster exponential decay ($\gamma$) model is unchanged.

The cluster arrival time statistics of the measurements (office environment) are more closely fitted by a Weibull distribution (with shape parameter $\alpha$ and scale parameter $\beta$) than by the Poisson process of the “generic” (SV-based) model.

The small-scale fading statistics, extracted from the received energy in each bin, turned out to be either Nakagami-m or log-normal with almost the same confidence levels.

In addition, a large-scale statistics of the energy reflected back from the surrounding environment – corresponding to the exploration of various locations in a room – is found to follow a lognormal distribution; the first empirical moments (lognormal mean $\mu_{\text{off,\ dB}}$ and standard deviation $\sigma_{\text{off,\ dB}}$) are obtained as ML estimates of the distribution of the integrated energy received after the arrival time of the diffracted MPCs (creeping waves around the body) and normalized to the transmitted energy.

Note that, comparing these figures with the path loss of the IEEE 802.15.4a BAN model, it appears that, for the scenarios were the antennas are placed on the same side of the body, the contribution of the surrounding environment is almost insignificant (ground reflection excluded), whereas it can be the reverse when antennas are placed on both sides. Due to the shadowing effect of the body, $\mu_{\text{off,\ dB}}$ varies typically from about -70 dB for the “front scenario” (antennas on the same side) to about -80 dB for the “back” one.

**Summary of the IEEE 802.15.6 model**

The PDP model – proposed by NICT – is a classical single cluster tapped delay line/ Poisson process model, with:
\[ h(\tau) = \sum_{\ell=0}^{L-1} a_\ell \exp(j\varphi_\ell)\delta(\tau - \tau_\ell) \] (5)

where, \(a_\ell, \tau_\ell, \varphi_\ell\), are respectively the amplitude, arrival time and phase for \(\lambda\)-th path.

The phase \(\varphi_\ell\) is modelled as a uniformly distributed random variable (r.v.) (over \([0, 2\pi]\)).

The path amplitude \(a_\ell\) is modelled by an exponential decay \(\Gamma\) with a Ricean factor \(\gamma_0\), which reads:

\[ (a_\ell)_{\text{dB}} = \begin{cases} 0 & \ell = 0 \\ \gamma_0 + 10\log(\exp(-\tau_\ell / \Gamma) + S) & \ell > 0 \end{cases} \] (6)

where \(S\) is a stochastic term modelled by a log-normal distribution with zero-mean and standard deviation of \(\sigma_S\). The path arrival time \(\tau_\ell\) is modelled by a Poisson distribution, which is given by:

\[ p(\tau_\ell | \ell - 1) = \lambda \exp[-\lambda(\tau_\ell - \tau_{\ell-1})] \] (7)

where \(\lambda\) is the path arrival rate. The number of the arrival paths \(L\) is modelled by a Poisson distribution, which reads:

\[ P(L) = \frac{\overline{L}^L \exp(\overline{L})}{L!} \] (8)

where \(\overline{L}\) is the average of \(L\).

The parameters values extracted by model fitting from measurements are listed below:
\(\gamma_0 = -4.6\) dB, \(\Gamma = 59.7\) ns, \(\sigma_S = 5.02\) dB, \(\lambda = 1.85\) ns\(^{-1}\) and \(\overline{L} = 38.1\) for the hospital room environment.

### 2.1.3 Time-variant channel models

Despite the huge number of scientific contributions on BAN channel existing in literature, only few works address the issue of time-variant channel modelling, whereas most others focus on static or quasi-static scenarios. Obviously, the human body mobility should be taken into account in order to accurately describe the radio channel characteristics and design cooperative protocols for BANs applications. However, the characterization of these phenomena presents some technical difficulties in performing measurements. The path losses that have to be measured are generally very high (more than 70-80 dB), because of strong shadowing effect produced by the human body. This means that measurement test-beds with a reasonable signal dynamic must be employed. That is why frequency domain measurements are often performed by means of Vector Network Analyser (VNAs) to characterize BAN channel [21], [22], [23]. Quasi-static measurement campaigns employing VNA have been performed by Fort in the UWB by focusing on the arm movement. The authors found a log-normal distribution for the path loss fluctuations around the mean value at three different antenna locations on torso. No distinction between the slow and the fast fading components is considered, and the frequency dependence of the path loss is not included.

Narrowband quasi-static measurements at 2.45 GHz have been performed in anechoic chamber by highlighting the effect of body posture [21], [22]; again a log-normal distribution variation of path gain around its means value has been proved, without any separation of the small and large fading component. A similar pseudo-dynamic measurement method has been applied in [24] to reproduce the human walking motion.
The measurement test-bed for on-body channel measurements at 868 MHz employed by Scanlon and Cotton presents some interesting features since different sensors on body are able to collect RSSI values, avoiding in that way cable parasitic effects [25]. The main drawback of this measurement setup is that no phase information is given, so that it is not possible to evaluate the channel dispersion characteristics. Nakagami and Rice distributions with high K-factor have been found to best fit fading distribution for respectively standing and moving scenarios. The same team also performed some measurements at 2.45 GHz with a TX on waist and receiver on different positions on body [26], [27], [28]. In [26] the authors propose a Nakagami-m distribution to model the fading channel characteristics. In stationary scenario high k value of the Nakagami distribution suggests the existence of a predominant component.

Measurements by NICT have employed a channel sounder at 4.5 GHz [29]. The transmitting antenna was placed on the navel, while the receiving one was on different positions on body. The scenarios measured in anechoic chamber were: standing position, walking on the spot, and up-down movement. The authors propose three different distributions of the relative path gain. Normal or log-normal distribution seem the best suited distributions for static or little movement scenarios, while the Weibull distribution can be employed in larger human body movements.

An important work in on-body narrowband channel characterization has been carried out by NICTA in [17]. This work focuses on two frequencies relevant for the ISM band: 820 MHz and 2.36 GHz. The human subject was asked to perform three different actions: standing still, walking on the spot and running on the spot. The receiving antenna is placed on the right hip or chest, while the transmitting antennas were located on different body positions. The analysis carried out shows that a unique distribution is not suitable to describe all the scenarios for the three different body movements, moreover the authors pointed out the dependency of different fading characteristics on the carrier frequency and movement. Despite the fact that different statistical behaviours have been pointed out according to the scenario, the results presented in [17] have been integrated in the final IEEE 802.15.6 report [1] by merging all the scenarios together.

The same team has also performed some investigations on the stability and temporal correlation of the dynamic BAN channel, introducing a new parameter called channel variation factor, calculated as the ratio between the standard deviation and the square root of mean received power [30].

Recently real-time channel measurements have been exploited in order to define a channel model which keeps space-time correlation properties, in fact this kind of knowledge is mandatory to define the possibility for use of cooperative approaches in BANs [31], [32].

In [33] a specific scenario at 2.45 GHz is investigated to model the fading correlation between two antennas as a function of the distance d. With respect to the scenarios specification in IEEE 802.15.4a, sensors are distributed horizontally on the front abdomen at a given level of the torso. The measurements are conducted in a quasi-anechoic environment in the walking mode (torso is kept standing still without actual walking while the arms periodically move forward and backward). The fading distribution in BAN follows a lognormal distribution.
The measurement results show consistent relationships between correlation coefficient and the distance difference. An average linear approximation to model the fading correlation variation is proposed for the front abdomen body area:

\[ \rho = 1 - 0.043 \, d[\text{cm}] \] (9)

with a shared propagation distance of 12cm between the transmitting and the receiving antennas.

The measurement protocol presents the following parameters:
- Sampling rate: 1kHz,
- Observation time: 20s,
- Body movements. Natural arm swinging (around 1.2s/cycle),
- Perimeter of abdomen: 86cm,
- Torso’s height: 183cm,
- Torso’s weight: 80kg,
- Front body region: a span of 20cm from the centre to left/right side.

In [34], a front/back scenario is analysed with the help of a human body model based on an ellipsoid representing the torso trunk. Two cylinders representing the arms are added with a swinging movement alternatively forward and backward in a periodical pattern. There are three propagation paths: propagation paths reflected by left/right arms and propagation path around body trunk. For the NLOS case, the reflected propagation paths are combined by the tangent free-space propagation path from the arm centre to the ellipse and the creeping waves from the tangent point to the destination.

It is observed that the fading correlation obtained at the back side of torso trunk has steep drops at given distances. This could be due to the body surface shape change at some position of the back side of torso trunk. The paper also demonstrates that even if there are only three MPCs for each channel, their different phase contribution to the channel can still affect the channel correlation under regular body movements.

One of the latest measurement campaign performed in order to investigate the characteristics of time-variant BAN channel at 2.45GHz has been carried out at CEA-Leti and the results are presented in [35]. The measurement campaign has been realised in both anechoic chamber and indoor environment involving different human subjects, who stood still just changing the arm position, walked in straight line and ran on the spot. The results extend to the WiserBAN project will be presented in Section 5 and 6.

2.1.4 Analytical models

Since 2007 the UCL (Université Catholique de Louvain) in Belgium, together with other different European research teams, has been performing several studies on the physical propagation mechanisms concerning on-body transmissions [36], [37], [38], [39]. In order to derive a model which leads to a deeper insight into expected propagation trends and which takes into account the proper effect produced by the human body itself (i.e. shape, tissue composition, etc.), Maxwell equations have been directly solved. The human body has been modelled as an infinite lossy cylinder, and the presence of different sources of excitation has been considered: infinite line source with different phase velocities, evanescent and propagating modes of the plane wave and point source.
The models derived have been validated through the comparison of the results with data acquired through specific measurement campaigns. Interesting studies performed on the realisation of an analytic BAN channel propagation model are presented in [40], [41] where the creeping waves theory is used in the prediction of the surface wave attenuation on curved surfaces (i.e. head and waist).

Gupta and Abhayapala present an analytical electromagnetic channel model for BAN [42]. Specifically, the dyadic Green’s function for a cylindrical human body model is used. Four possible cases are considered, where the transmitter and receiver are either inside or outside the body. An exact analytical expression is derived for the case where both transmitter and receiver are outside the body.

2.2 In-body channel models

The most common EM link used for implanted devices in the human body is the inductive link. One of the use cases explored within MicraBAN is an inductively coupled cochlear implant. The implant incorporates a relatively small coil inside the silicone housing of the implant. In the middle of the coil a permanent magnet is placed in order to mechanically support and align an external coil, which is placed on the temporal bone outside the head. The inductive coupling between the collinear coils is used as a communication channel. The main drawbacks of the inductive link are the relatively low frequency limits and the available bandwidth, which consequently result in a low data rate.

The European Telecommunication Standards Institute (ETSI) [43] is an official European Standards Organization also recommending the standardization of the Medical Implant Communication Systems (MICS). A technical report from ETSI is providing a survey on applicability and feasibility study for low power MICS operating around 2.45 GHz [44]. A work presented in [45] has characterized the amount of power absorbed by the body tissues of a wireless source implanted in a bladder. Regardless of the antenna type the gain at 402 MHz and 868 MHz varied from -14 to -20dBi depending from the different body typed models used in the simulations [45].

The major complication for the MICS is that their antenna is placed in the human body, which is a lossy medium. The energy of the EM wave dissipates and attenuates considerably when the wave front reaches the surface of the body. A study in [46] on in-body propagation through tissues in 403 MHz and 2.4 GHz confirms that the in-body propagation loss is much higher than that of on-body propagation at 2.4 GHz. As measured in [46], relative path gain at a distance of 10 cm for 2.4 GHz is about -40 dB for on-body channel and about -80 dB for the in-body channels. To overcome such drawback the authors introduce a concept placing an on-body device coordinating the communication for the MICS. Such body surface coordinator has more resources and is relatively more powerful as compared to the medical implants.

In-body channel models are also included in the IEEE document but they refer only to the frequency interval between 402 MHz and 405 MHz. On the other hand, WiserBAN project aims at using the 2.45GHz ISM band also for implant nodes; this will require different kinds of studies for a proper model of these channels. Anyway, it will be given a briefly insight of the IEEE802.15.6 models for the in-body scenarios CM2 Scenario S2 (Implant to Body Surface) and CM2 Scenario S3 (Implant to external), that could be interesting in WiserBAN applications. Concerning Implant to Body Surface CM2 (Scenario S2) for 402-405 MHz, since physical measurement and
experimental study inside human body are not feasible [47], a 3D simulation & visualization scheme was used to study the propagation characteristics in the Medical Implant Communications Service (MICS) band (402-405MHz). The human body model used in this study includes (frequency dependent) dielectric properties of 300+ parts in a male human body with a maximum resolution of 2mm. The implant antenna used in this study is a multi-thread loop antenna with the following characteristics [48]:

• Size: 8.2 x 8.1 x 1 mm
• Metallic Layer: Copper, t=0.036 mm
• Substrate: D51 (NTK), =30, tanθ= 0.000038, and t=1mm
• The metallic layer is covered by RH-5, ε_r=1.0006, tanθ = 0, t =1mm

Parameters of a statistical path loss model have been extracted which fit the following equation.

\[ PL(d) = PL(d_0) + 10n\log_{10}(d/d_0) + S \]  \hspace{1cm} (10)

Where \( S \sim N(0, \sigma) \) and \( d_0 = 50\text{mm} \)

The parameters corresponding to this channel model are expressed in the Table 7. Details of the model derivation can be found in [49], [50].

<table>
<thead>
<tr>
<th>Implant to Body Surface</th>
<th>( PL(d_0)(dB) )</th>
<th>( n )</th>
<th>( \sigma (dB) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep Tissue</td>
<td>47.14</td>
<td>4.26</td>
<td>7.85</td>
</tr>
<tr>
<td>Near Surface</td>
<td>49.81</td>
<td>4.22</td>
<td>6.81</td>
</tr>
</tbody>
</table>

Table 7: CM2 channel model parameters

The Implant to external CM2 Scenario S3 scenario can be approximated by considering a combination of scenarios S2 and S6 (or S7). In the simple case of an environment where there is neither object nor obstacle, a free-space path loss can be added to CM2 to account for the additional loss that the implant signal will go through once it leaves the body. This usually occurs after around 10cm away from the body surface.

On the other hand, if there are objects within the 5 meter distance of the human body, a channel model for scenarios S6 or S7 (at 400 MHz) can account for the impact of these objects. Therefore, such model can be added to CM2 to emulate scenario S3. (Remark: the path loss model for S6 (or S7) in this case should not include the on-body transmitter antenna gain).

### 2.3 Body-to-body and Off-Body channels

Even if a lot of efforts have been put on the study of propagation dynamics and channel characteristics for on-body communications, body-to-body (or inter-body) as well as off-body channels have been little investigated. Hereafter a general overview on the proposed channel models for these scenarios will be given.
2.3.1 Body-to-Body communications

Some research teams realized different measurement campaigns in order to collect data to characterize the *inter-body* channel. In particular, S.L. Cotton and W.G. Scanlon from the Queen University of Belfast performed the statistical description of the dynamic body to body communications at 2.45GHz. They considered a scenario representative of indoor sweep and search operations for fire and rescue personnel where four subjects move in a building, one of them held the transmitter device while the other three played the role of the receivers ([51], [52]). The authors demonstrate (see Figure 3) that the k-µ distribution is able to provide a good fit to the distribution of small-scale fading for all the considered links, in comparison to other statistics such as Nakagami, Lognormal, Rice and Weibull.

![Figure 3: Fading distribution in body-to-body channel](image)

Considering also the low cross correlation and comparable mean signal levels characterizing the received signals, the idea of employing spatial diversity to improve channel performance could be an interesting option. Similar conclusions on diversity are presented in [53] and [54] even if measurements have been carried out wideband at the carrier frequency of 5.5GHz in an indoor environment. Considering the classical distance-dependent path loss model, the authors propose an inter-BAN channel model where the shadowing is best described by a Log-normal distribution and the path loss exponent results to be always smaller than 2.

Another statistical description of the inter-BAN channel is given in [55] and [56]. The authors investigated propagation characteristics in the frequency band centred at 2.45 GHz and 5.8 GHz through an extensive measurement campaign involving two subjects (one with the transmit antenna and the other equipped with the receiving devices) in an office environment. The users were positioned at different distances between each others, performing various random activities with random body orientations. Variations of the channel path gain was found to follow a gamma distribution with mean and variance values following a power law in respect to the distance between the two BANs, the rate of decrease resulted to be almost independent of the considered frequency, while more related on the device on-body position.
Moreover, the short-term fading turned to be described by a Rican distribution with K-parameter depending more on the on-body position of the antenna than on the distance, while the long-term fading followed either a gamma distribution (when the distance between the subjects remains constant) or a lognormal one (if the distance also changes randomly). For this distribution, the mean and the variance decrease with the distance following a power law with a rate of decrease almost independent from the frequency band but strictly related to the antenna position.

Investigations on the UWB have been performed by the Institute for Infocomm Research of Singapore [57]. Collecting data in an anechoic chamber environment for two subjects standing at various distances with different body orientations, the authors found that the path loss, calculated through the classical distance-dependent formula, was strongly related to the devices on-body emplacement as well as to the relative position of the human bodies.

Hanlen et al. performed some measurements focusing on coexistence problems when multiple BANs are co-located [58] and [59]. Since none of the networks has the right to stop the transmission of the others, they obviously mutually interfere, and this could lead to a severe degradation of the performances of the reference network. Collecting the RSSI values of all the investigated links (reference and interferer), the authors found that the interference signal power is dominated by factors which are not related to the distance but regard mostly subject movements, both local (e.g. arm swinging) and global (i.e. walking or running). Moreover, results show that Signal-to-Interference Ratio (SIR) could be low or even negative, since the interferers were often more powerful than the reference link because of the great shadowing effect of the human body that could lead to power absorption up to 60dB.

Authors also wondered if the reference and the interferer links were sufficiently independent, such that it would be possible to measure them separately and later combine them. The computation of correlation coefficients has revealed that the two signals are generally uncorrelated and also statistically independent when considered over large periods of time (order 100’s of seconds). Differently considering short intervals, the two channels may show correlation, in particular when the subject movement is not the main source of channel dynamic and hence it varies slowly. The answer to the initial question remains still open, since the correlation between interferers and reference signal is strongly related to the subject instantaneous activity.

Ray-Tracing methods have also been used recently in [60] for off-body and body-to-body communications. The 2D scenario considered in this work does not take into account the environment around the bodies and the latter are modelled as closed cylindrical surfaces with constitutive parameters chosen based on the “Muscle” model. This approach could represent a powerful building block in the perspective of modelling inter-BAN communications (i.e. at least the part which does not involve an interaction with the environment).

Differently from that, in [61] and [62] Cotton and Scanlon present a novel approach to simulating dynamic soldier-to-soldier signal propagation using jointly an animation-based technology, in order to take into account real body movements (Poser7 software tool), a computer generated environmental model (AutoCAD software package from Autodesk), and a commercial ray-launching engine to perform channel prediction. The reference scenario, in this case, was that of millimetre-wave (60GHz) soldier-to-soldier communication for counter-insurgency cordon and sweep operations. Authors
simulated the field of action and the realistic movement of a team of four soldiers to extract important channel metrics such as root mean square, angle of arrival and delay spread. In [63] the same team of researchers realised a simulated study of the co-channel inter-BAN interference at 2.45GHz and 60GHz. Using an accurate CAD model of an indoor location together with a human body model obtained through the use of Poser7 animation software and a full 3D ray-launching simulator tool, the authors found that on-body communications at 2.45GHz were heavily susceptible to interference caused by undesired signal reception from other nearby BANs, while operating at the 60GHz frequency generally provides mitigation of co-channel interference, allowing a greater number of networks to co-exist.

### 2.3.2 Off-Body communications

One of the first attempts in giving a complete insight on the off-body channel characteristics has been done by Ziri-Castro et al. in [64]. The authors presented a comparison between measured data and simulations of a narrowband 5.2GHz radio channel for two indoor scenarios (a corridor and an office). The measurements involved one fixed transmitter and one receiver placed on the hip of a subject walking towards (LOS conditions) and away (Non-LOS conditions) from the transmitting antenna, whereas the simulations were performed using a three-dimensional image-based propagation prediction technique. The use of a simulation tool seemed to be appropriate for LOS case but revealed some inaccuracies in NLOS situations. Statistical analysis on small-scale fading proved a good fitting with Rayleigh (signal level below the mean) or Lognormal (signal level above the mean) distribution for the corridor environment, whereas in the office case the Lognormal statistic turned to be the best one.

The research group at the Queen’s University of Belfast performed a set of experiments in order to extract a channel model for off-body communications at the frequency of 868MHz [65], [66], [67] and [68]. Measurements have been done considering several receiving antennas placed on the subject’s body, different environments (i.e. anechoic chamber, open office and hallway), LOS and NLOS conditions and a walking movement. Data analysis pointed out how both antenna positioning and human body movement play an extremely important role in indoor propagation characteristics for wearable systems. Moreover, it has been verified that Nakagami-m distribution provides the optimum fit for the majority of the off-body propagation channel investigated in both anechoic and indoor multipath environments. This distribution turned out to be suitable for the considered scenarios as, differently from other distribution like Rice or Rayleigh, it does not assume scattered components of equal amplitude. Level Crossing Rate (LCR) and Average Fade Duration (AFD) were also provided, which are well described by Nakagami second order statistics. In [68] the cross correlation level between fading experienced at different body locations was also evaluated, the low values found suggest the idea that a spatial diversity combining scheme could improve significantly the system performances.

A similar experiment is presented in [69], the authors perform a measurement campaign collecting real time channel responses at the carrier frequencies of 820MHz and 2.36 GHz for a subject equipped with two antennas and standing still in front of a
fixed RX antenna, just changing body orientation and the relative distance or performing a walk towards the receiving device. Different statistics have been compared in order to find the one that best describes the received signal amplitude; overall, the Lognormal distribution provides the most reliable fit for both the considered bands (see Figure 4).

![Figure 4: Fading distribution of off-body channel](image)

In order to evaluate the channel stability, the authors introduced a new parameter called channel variation factor and calculated as the ratio between the standard deviation and the root mean square power of a channel response sequence. Off-body BAN channel turned out to be quite stable, more at 802MHz than at 2.36GHz, with a coherence time reasonably of the order of tens of milliseconds; on-body device position also played a significant role in the channel temporal stability.

Considering the great advantages that the use of UWB could bring to the system performances in terms of reduction of multipath fading, possibility of reaching high data rates and decrease of the operative power, some researches have also been performed focusing on the characterization of the channel at these frequencies. Goulianos et al. from the University of Surrey [70], [71], [72], proposed to model the off-body communication channel with a multi-slope Path Loss equation obtained from the study of propagation mechanisms around the body (creeping waves) combined with the traditional distance-dependent Path Loss formula.

Based on the measured data, statistical channel parameters have been extracted with respect to both the radial coordinate $\rho$, denoting the distance between the transmitter and the body centre, and the body orientation angle $\Theta_A$, which is formed by the lines connecting the body centre to the transmitter and to the on-body antenna respectively. Mathematically the model could be expressed as:

$$L(\rho, \Theta_A) = \begin{cases} 
L_0(\rho) - n_0(\Theta_A)(\Theta_A - \Theta_0), & 0 \leq \Theta_A \leq \Theta_{AL}(\rho) \\
L(\Theta_{AL}) - n_0(\Theta_A)(\Theta_A - \Theta_{AL}(\rho)), & \Theta_{AL}(\rho) \leq \Theta_A \leq \Theta_{AS}(\rho) \\
L(\Theta_{AS}) - n_0(\Theta_A)(\Theta_A - \Theta_{AS}(\rho)), & \Theta_{AS}(\rho) \leq \Theta_A \leq \pi 
\end{cases}$$

(11)
Where $L_0(\rho)$ is expressed by:

$$L_0(\rho) = L_0(\rho_0) + 10n_0 \log_{10} \left( \frac{\rho}{\rho_0} \right)$$ \hspace{1cm} (12)$$

and $\Theta_{AL}$ and $\Theta_{AS}$ are the breaking point angles, that are defined as the angle after which the decay coefficient $n_0(\Theta_A)$ changes its arithmetic value. These angles indicate respectively the passage from the lit zone and from the shadow region of the transmitter.

Power delay profile analysis and modelling were also performed.

Focusing on a real hospital environment in [73] the authors present a measurement campaign for stationary and mobile UWB off-body channels. Measurements were made using RF-over-fibre technology to eliminate unwanted electromagnetic effects associated to the use of co-axial cables. The results show that Received Signal Strength (RSS) values depend on whether transmitting and receiving antennas are in relative line of sight or non line-of-sight conditions. For mobile tests, both LOS and NLOS cases tend to have log-normally distributed fading with the latter having significantly lower mean signal strength. In stationary conditions, signal strength results also dependent on user orientation, with difference between standing and sitting in the same location.

In the IEEE 802.15.6 CM4 address the body surface to external scenarios. The following path loss measurements have been performed at frequency of 2.36GHz for sleeping position on a bed and in a bedroom. Details of the measurement set up, derivation and data analysis can be found in [74]. Table 8 summarizes the results.

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>LOS</th>
<th>NLOS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Standing</td>
<td>53.81</td>
<td>53.12</td>
</tr>
<tr>
<td>Walking</td>
<td>44.46</td>
<td>51.59</td>
</tr>
</tbody>
</table>

Table 8: CM4 channel model

The first-order statistics fit with off-body sleeping channel data, where the data has been normalized to mean of each link data set. The gamma distribution is the best fitting distribution type for this data, apart from overall sets, non-normalized, which is lognormal.

The second-order statistics fit with off-body sleeping channel data. Lognormal is the best fitting distribution type for channel outage distribution (linear magnitude values) for this data.

2.4 Antenna-body interaction

The dielectric properties of malignant tissues have been of interest for several reasons. The dielectric data are needed in microwave hyperthermia as a modality in cancer treatment as well as in developing the heterogeneous models simulating the electrical properties for implanted and placed on-body wireless sensor nodes and actuators. Another potential application includes microwave imaging [75]. At radio and microwave frequencies, the dielectric properties of biological matter are basically...
determined by the charging of the cell membrane through a combined impedance of the intra- and extracellular media [75]. They also depend on the chemical composition of the tissue [76]. In the WiserBAN project the EM properties of human body tissues are necessary to be defined for a proper modeling BAN propagation channel and antenna-body interaction for on-body and implantable wireless devices.

An ordinary body model has been presented in [77]. It comprises a plastic tank filled with a commercial body tissues simulating liquid (Figure 5 left). Such model has been verified numerically (Figure 5 right) and experimentally and it is an elegant solution for a fast estimation on antenna-body interaction without demanding much of computational recourses. For the practical experiments the use of a compact phantom model is desirable. It has been shown in [77] the minimum size of 220 mm × 220 mm × 110 mm is sufficient to emulate an electrically large body –size phantom at 868 MHz and 2.45 GHz frequency bands.

![Figure 5: Experimental setup (left) and equivalent EM simulation model (right) of the homogeneous phantom model presented in [77].](image)

The approach demonstrated in [77] does not take into account that the composition of the body tissues is substantially different for different body regions. In [78] an extended study was performed for any tissue composition that might occur at any location of the human body. A planar tissue model shown in Figure 6 was simulated using the finite-difference time domain method. This has considered the effect of possible tissue variations but not the uncertainties of the dielectric parameters of each layer in the model. However these uncertainties are relatively small compared to the variation between tissue types and the proposed model is a viable solution for SAR estimation.

![Figure 6: Layered planar tissue model presented in [78].](image)

### 2.4.1 Antennas for on-body applications

Considering the natural need to keep the dimension of the wireless sensor nodes as small as possible the requirements for the antenna system are very crucial in terms of available real estate. The most antennas for BAN application fall into the category of electrically small. Designing an electrically small antenna reduced in most cases to find the best possible compromise between antenna dimensions and radiation
characteristics. In extreme cases, the casing radiates most of the power whereas the actual antenna merely acts as a resonator to set the appropriate working frequency. An example illustrating this is shown in Figure 7 [79]. This a good example of an antenna integrated into a wrist watch as a part of the BAN sensor network. It consists of a PIFA antenna designed for a Bluetooth transceiver integrated in a wristwatch casing. A comprehensive survey of the work performed on electrically small antenna design was performed by the IST FP-6 networks of excellence ACE [80] and ACE2 [81], and has been summarized in a paper on small antenna design [82].

Figure 7: Miniature Bluetooth antenna (left), simulated current distribution on it (right).

Figure 8: CAD model of the finger-ring antenna.

For the case of wearable antennas for BAN, extra requirements can be added to the challenging small size and low profile characteristics. Besides, an antenna polarization which is normal to the body surface and which possess a low mutual influence by the human body, keeping high radiation efficiency and low SAR, is desirable. Different approaches can be found in literature, from the most extravagant wearable finger-ring antenna [83] at UWB (7.25GHz – 10.25GHz) (see Figure 8), to the classical PIFA or IFA solutions [84]. The latter introduces the new asset of a polymer ferrite sheet placed on the backside of the antenna, which reduces the body impact on the original antenna behaviour, masking the body absorption and improving the isolation between the antenna and its environment. Other approaches of textile patch antennas make use of large, flexible and electrically conductive ground planes to achieve the targeted low human body absorption. Nonetheless, these latter solutions can be considered more suitable for off-body systems, but less appealing for on-body systems like the ones targeted in the WiserBAN System-in-Package solution. An emerging technology for BAN antennas is the Cavity Slot Antenna. The PIFA-like behaviour of these radiating elements, together with its high integration level, makes it an appealing solution. Operating principles and expected performance in the vicinity of the human body are analysed and described in [85].
In the WiserBAN project, an antenna system able to co-habit within the System Package and in the vicinity of the human body will be investigated. The main focus will be on miniaturization, applying the different presented approaches, as well as on performance. Innovative printed antennas are considered as good candidates to meet the system requirements. Concerning the integration with the package, a smart antenna design is expected in order to overcome the challenging environment and be easily accommodated with the rest of the circuitry (see example in Figure 9). The importance of including full sensor details in determining and analysing the antenna performance was clearly proven in [86].

Over the last decade a special attention has been devoted to BAN antennas integrated into human outerwear such as textile antennas [87], [88] or even military UHF antennas for armored vests [89].

### 2.4.2 Implanted antennas

The implanted antennas should radiate being into an inhomogeneous lossy medium. In many cases it can be presented as a stratified medium with every stratum representing a particular biological tissue of a human body. An additional challenge lies in exactly modelling the biological tissues, as their properties vary from one individual to another. A general solution is to use average values for the body tissue model and to ensure the antenna performance with some margins encountering the parametric variation of the environment. A study [92] in characterizing a skin mimicking material has been done prior the design of a dual band implantable antenna [93], which was embedded in this skin mimicking material. The antenna in [92] and [93] are operating at ISM band (2.4-2.48 GHz).

A practical example of an implantable antenna co-designed together with the whole implantable device was presented in [90], [91]. Figure 10 shows the sketch on the implantable device sealed in a biocompatible casing material. The choice of such biocompatible materials is limited and it is important to have them characterized at the targeted frequencies prior the design phase of the implantable antenna. [90]. The dimensions of the implant with an integrated antenna in Figure 10 are L = 32.1 mm and D = 10 mm. The lateral length of the conformal ground plane is h_g = 10.65 mm. The maximum gains of the antenna at 405 MHz and 2.473 GHz taking into account the body are -32.6 dBi and -20.1 dBi respectively. This would allow an adequate dual-band performance for a 2 m operating range.
A very small antenna having 10 mm substrate diameter is presented in [94]. It is used for a wireless capsule endoscope system. The antenna has 4.2% fractional bandwidth with the center frequency of 2.45 GHz. It was realized on a low loss PCB material and encapsulated in a biocompatible capsule for in vivo test. The raw data measured from a pig show that the loss along the wireless link is about -60dB. For a human body the link loss is expected to be lower. Another miniature PCB antenna with dimensions of $5 \times 4.8 \times 1$ mm was proposed in [95]. An alternative look to obtain a very small antenna capable to fit into an implantable micro device is described in [96]. The antenna comprises a cantilever MEMS resonators which is sensitive to low power magnetic fields at kHz – MHz frequency range. This antenna is chip size (roughly of $2 \times 2 \times 0.5$ mm) and suitable for implantable bio devices. This MEMS antenna is produced utilizing the same silicon processing steps similar to those used in RF chips production, which makes it possible to monolithically integrate it onto the same substrate with the radio ICs.

2.5 Conclusions and general considerations

As it could be seen from previous paragraphs, there is a high dispersion of the results presented in literature, notably as regards to Path Loss data and models both in a controlled environment (anechoic chamber) and in various indoor premises. This is due to the fact that BAN channel is characterised by a large variability with regards to population (human subjects), postures and movements (including involuntary micro-movements, breathing, internal fluxes, etc.), used antennas (including distance from the body and polarization), positioning on the body and surrounding environment.

The numerous sources of variability have not been investigated with a sufficiently funded and rigorous statistical approach: in particular, the collected statistical sets seem either too small or too specific.

The classical approach of the path loss depending on the distance in on-body channel could be questionable: in classical channels (indoor, urban, etc.) antennas are usually far away enough to be in their respective far field zones, and weakly perturbed by their environment. In these contexts, the power law model (function of the distance) is valuable and physically funded, and the constant term $PL_0$ is primarily fixed by the chosen reference distance and possibly the frequency. For the on-body channel, the physical interpretation of this term is completely different and depends on the energy absorbed by the body notably in the vicinity of the antennas, which is actually related
to the antenna total efficiency, not only in the usual sense (i.e. including return losses) but body included.

All these considerations have led to the conclusion that a scenario-based approach is far more appropriate and promising, as described for the experiences presented in the next sections.

Concerning body-to-body channel there is neither contribution nor literature at 2.45 GHz exploitable for WiserBAN scenarios and the off-body studies do not include the human mobility which is fundamental for a correct and realistic channel modelling.

In-body to on-body channel or external devices links are different scenarios which can be assumed as a sum of in-body propagation and free-space propagation. In these scenarios the main issue is the antenna efficiency in the body. As in the IEEE model a simplified approach can be to consider the antenna gain in the body as an extra-loss to the body to off-body channel.
3 Test-bed and procedures for channel and antenna characterization in BAN context

In task 3.1 there are two main paths of exploration related to the EM propagation in and around human body. The very first one is the antenna-body interaction. The vicinity effect of the human body in antenna performance, in terms of impedance matching, radiation pattern and efficiency will be studied for different antennas. These antennas will be designed and customized for several use-case scenarios identified by industrial partners in the WiserBAN project. The second exploration path will focus on channel characterization and modelling. CSEM will study the propagation channel and measurements in the frequency domain and CEA will characterize the channel for BAN in the time domain. In this Section we present the test beds that will be employed to characterize the channel and the antenna-body interaction.

3.1 Time-domain measurement setup at CEA

In this section the time-domain channel measurement test-bed available at CEA-Leti (Grenoble) will be described. Most of the investigations and models presented in literature (see Chapter 2) are based on static measurements. However, the radio link performances can be strongly affected by fading and/or shadowing due to the human body’s movements. Moreover, a Doppler frequency shift can occur in time-variant channels. The test-bed here presented has been specifically set up, in order to obtain a reliable characterization of the time-variant channel in BANs, by taking into account realistic scenarios. The time-domain channel test-bed is mainly composed by a pulse step generator, a wideband real-time digital oscilloscope, a power amplifier at transmitting side, and several low noise amplifiers at receiving side, in a sort of SIMO (Single Input Multiple Output) configuration (Figure 11). The idea is to collect simultaneously up to four channel impulse responses (CIRs), each one corresponding to a different location on body. RF cables and antennas are obviously part of the test-bed. A brief description of each element composing the test bed is given below.

Figure 11: Time domain channel measurement test-bed
**Transmitter side**

On transmitter side, a Pulse Generator Picosecond Pulse Lab 4050B (Figure 12) has been employed to generate a wide band signal. The instrument produces 10 V, 45 ps rise time pulses with 10 ns duration. The Generator Pulse Repetition Rate (GPRR) can be suitably tuned from 1 Hz to 1 MHz.

![Figure 12: Pulse Generator Picosecond Pulse Lab 4050B](image)

Two additional impulse forming networks allow to fit the desired pulse shape in the 2-9 GHz bandwidth (see Figure 13).

A Power Amplifier (PA) AMF-4B-030070-33P MITEQ® is used just behind the two forming filters, delivering 37dB gain (±3dB) in the frequency band of interest.

**Receiver side**

A wide band real-time Digital Oscilloscope Tektronix DSA71254B (Figure 14), is employed at the receiving side. The instrument can collect up to four channels simultaneously. Obviously this is an interesting feature for time-variant BAN channel measurements, allowing to gather received signals at different antenna positions on-body, while the subject is moving (e.g. walking, sitting down/standing up…). This is representative of realistic applications in which different on-body sensors send information to a central node at the same time.
The sampling rate of the instrument has been set to 12.5 GSps in order to get a resolution time step of 80 ps. The acquisition time window is fixed to 200 ns, which results into 2500 collected points for each CIR. As a consequence, scatters up to a distance of 30 meters can be detected.

In order to get a continuous collection of CIRs during an observation time $T_{obs}$ the digital oscilloscope works in “Fast Frame Mode”. The total observation time is given by the Generator Pulse Repetition Period ($GPRP$) and the number of collected pulses:

$$ T_{obs} = N_p \times GPRP $$  \hspace{1cm} (13)

Since averaging is not available in “Fast Frame Mode”, it is performed in post-processing resulting in a Pulse Repetition Period (PRP):

$$ PRP = N_{Avg} \times GPRP $$  \hspace{1cm} (14)

where $N_{Avg}$ is the averaging factor. As a consequence $N = N_p / N_{Avg}$ CIRs will be available (Figure 15). The choice of these parameters has to be done carefully in order to obtain the best trade-off in terms of signal dynamic and channel time variation: $PRP$ should be chosen small enough to consider the channel static between two consecutive CIRs and $N_{Avg}$ should be large enough to measure high Signal-to-Noise Ratio (SNR) CIRs.

**Figure 15: Time line of the data acquisition cycle at the receiver**
A Low Noise Amplifier (LNA) AFS42-00101000-20-10P-42 MITEQ® is used at each receiving channel, delivering 42 dB gain (± 2 dB) in the frequency band of interest. The LNA should be placed just behind the receiving antenna front-end in order to reduce the noise figure. However, since the LNAs are armoured in order to prevent harmful interferences, their on-body location should cause difficulties to the human movement. Moreover, the LNA’s armour will act as a metallic scatter on the human body, affecting the measurements results. As a consequence LNAs have been placed close to the oscilloscope. It has been tested that this LNA emplacement does not dramatically affect the signal dynamic since the cables employed present a low attenuation.

**Measurement setup**

One of the main problem in channel measurement with a digital oscilloscope is the low dynamic achieved with respect to acquisitions performed with a Vector Network Analyzer (VNA). In Figure 16 the measured noise floor of the test-bed used for different averaging factor is shown. As expected, increasing the averaging factor will lead to high SNR signals, because the noise level decreases.

![Figure 16: Noise floor for different Averaging factors](image)

The total number of collected signal $N_p$ for every channel is equal to 22500. In order to get an observation time of about 3 seconds, that allows the subject to perform at least an entire walking cycle, the Generator Pulse Repetition Period ($GPRP$) has been set equal to 133 $\mu$s:

$$T_{obs} = N_p \times GPRP = 22500 \cdot 133 \mu s = 3 s.$$  \hspace{1cm} (15)

Preliminary test measurements have shown strong path losses and important fading dips up to -70 dB, in some disadvantageous scenarios. As a consequence the averaging factor ($N_{Avg}$) could not be set to a too small value. The choice done is to set $N_{Avg}=150$, in order to obtain high SNR CIRs, which results into a pulse repetition period

$$PRP = N_{Avg} \times GPRP = 20ms$$  \hspace{1cm} (16)

This value seems reasonable to characterize the time-variant channel, by considering that the speed of a human body in common activities is in the range of 0.5-2 m/s.
3.2 Frequency domain measurement setup for dynamic channel measurements

In the Off-Body and Body-to-Body scenarios some preliminary measurement tests have pointed out the existence of significant path loss (PL) values with fadings which yield to very low link budgets, up to -100dB. This trend is clearly evident in Non Line-of-Sight (NLOS) conditions, when the receiving antenna is completely shadowed from the transmitting one by the human body itself.

For that reason another measurement test-bed has been set up. A Vector Network Analyser (VNA) has been employed in order to have a higher signal dynamic with respect to the Digital Oscilloscope.

The test-bed is mainly composed by a Rohde&Schwarz R&S®ZVA24 4-ports Vector Network Analyzer, some RF cables and the antennas (one at the transmitter side and three at the receiver side), as shown in Figure 17.

![Figure 17: Test bed with R&S®ZVA24 Vector Network Analyzer 4-ports](image)

The main technical characteristics of the VNA used are listed in Table 9:

<table>
<thead>
<tr>
<th>Device</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vector Network Analyser (VNA)</td>
<td>Model: R&amp;S®ZVA24 4-ports</td>
</tr>
<tr>
<td></td>
<td>Frequency range: 10 MHz to 24 GHz</td>
</tr>
<tr>
<td></td>
<td>Measurement bandwidth: 1 Hz to 1 MHz</td>
</tr>
<tr>
<td></td>
<td>Number of measurement points: 1 to 60001</td>
</tr>
<tr>
<td></td>
<td>Dynamic range: &gt;130 dB, typ. 135 dB @2.45GHz</td>
</tr>
<tr>
<td></td>
<td>Power range: -30 dBm to +13 dBm, typ. -40 to +18 dBm</td>
</tr>
<tr>
<td></td>
<td>Noise level @10Hz Measurement Bandwidth: &lt; -115 dBm</td>
</tr>
<tr>
<td></td>
<td>Operational Mode: Continuous Wave (CW)</td>
</tr>
</tbody>
</table>

Table 9: VNA technical characteristics

The VNA has been used in Continuous Wave (CW) operational mode that allows the continuous acquisition of the data for a specified interval of time $T_{obs}$, focusing just on a single frequency carrier $f_0$. The acquisition parameters that have to be properly set according to the specific investigated scenario are the Sampling Rate ($R_s$) that depends on the Number of sampling points ($N_p$), the IF Bandwidth and $T_{obs}$ and the power level used for the transmission.
For the Off-Body scenario the parameters set has been defined as:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier Frequency:</td>
<td>( f_0 = 2.45 \text{GHz} )</td>
</tr>
<tr>
<td>Tx Power Level:</td>
<td>+18\text{dBm}</td>
</tr>
<tr>
<td>Number of Sampling Points:</td>
<td>( N_p = 5001 )</td>
</tr>
<tr>
<td>Observation Interval:</td>
<td>( T_{\text{obs}} = 10\text{sec} )</td>
</tr>
<tr>
<td>IF Bandwidth:</td>
<td>1kHz</td>
</tr>
</tbody>
</table>

Sampling Rate \( R_s = 2\text{ms} \)

while for the Body-to-Body scenario the parameters set has been chosen as:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier Frequency:</td>
<td>( f_0 = 2.45 \text{GHz} )</td>
</tr>
<tr>
<td>Tx Power Level:</td>
<td>+18\text{dBm}</td>
</tr>
<tr>
<td>Number of Sampling Points:</td>
<td>( N_p = 5001 )</td>
</tr>
<tr>
<td>Observation Interval:</td>
<td>( T_{\text{obs}} = 5\text{sec} )</td>
</tr>
<tr>
<td>IF Bandwidth:</td>
<td>1kHz</td>
</tr>
</tbody>
</table>

Sampling Rate \( R_s = 2\text{ms} \)

### 3.3 Frequency-domain measurement setup at CSEM

The initial study of this work is focused on the influence of the body tissues on the antenna performance, followed by an investigation of the influence of the human body movement and the effect of the multipath caused by the surrounding environment on the BAN channel properties. Therefore we propose a measurement procedure in two different environments: an anechoic environment, where the effect of the surrounding environment is negligible, and an indoor office/laboratory environment with office furniture, computers and lab equipment. The measurement system utilizes a Vector Network Analyzer HP8720D (VNA) to generate and measure the test signals. The transmitting antenna was excited using a continuous wave (CW) signal at 2.45 GHz generated by the transmitter system of the VNA. The VNA has been properly configured to permit simultaneous measurements of the absolute power of the signal at both receiving antennas. The control of the measurement procedure and the acquisition of the measurement data are conducted by a computer connected with the VNA. The widely used method for measuring human body influence on antenna characteristics is to use a homogeneous model as it is shown in Figure 18. The on-body antenna measurements are performed by using a physical body phantom. This phantom is constructed using a PVC tube filled with a body tissues simulating solution. It allows modelling EM and geometrical characteristics of a biological body.
The propagation investigation will follow process below:

- Perform simulations (HFSS good anatomically correct model of human body);
- Measurements with some antennas in free space (planar dipoles, top-loaded monopoles);
- Measurements with antennas placed on human body and on the SAM phantom;
- Measurements with different distances between antenna and body to characterize the antenna-body interaction.

The aim will be:

- Investigating the effect of antennas and deriving the best topology for different use cases;
- Investigating the effect of polarization (antennas with tangential vs. normal polarization to the body surface);
- Channel modeling for various distance dependencies and measurements using the SAM phantom.

The measurement setup at CSEM consists of fully equipped anechoic chamber for antenna and RF system measurements. The fully anechoic chamber with remote control offers a controlled propagation environment for antenna radiation pattern and gain measurement, e.g. for WPANs, BANs and UWB systems. The chamber consists of a metallic Faraday cage of 4.72 x 4.05 x 3.05 meters with absorbent materials and a rotating platform on the inside. If required, the chamber can be made semi-anechoic by removing the absorbers on the floor. The useful space inside the chamber is 3.81 x 3.14 x 2.14 meters, and the chamber can be used for measurements above 400 MHz. The upper limit is determined by measurement equipment. The chamber is equipped with reference antennas, a 40 GHz network analyzer and a 26.5 GHz spectrum analyzer. It can be used for 2-D antenna radiation pattern measurements, total radiated power (TRP) measurements and for EMC measurements. A human body phantom and a human hand phantom are also available.
Figure 19: Fully equipped anechoic chamber

Main specifications of the anechoic chamber:
- Faraday box outer dimensions 4726 × 4056 × 3056 mm
- The available dimensions for measurements inside 3812 × 3142 × 2142 mm
- Frequency coverage 420 MHz – 40 GHz
- Facility of radiation pattern measurement: fully 360°
- Facility of gain measurement using reference antennas

Figure 20: Schematic view on the antenna measurements setup

A cylindrical phantom is used to analyze the in-body communication channel. The phantom dimensions are indicated in Figure 21. About half of the phantom volume is filled with muscle simulating liquid MSL2450V2 fabricated by Schmid & Partners Engineering AG (SPEAG).
The target parameters of the body tissue simulating liquid are defined in the IEEE 1528 and IEC 62209 compliance standards. The measured and targeted dielectric properties for the desired frequency range of 2.4 – 2.5 GHz is given in Table 10. As the present study is mainly focused on narrowband antennas, dispersion models have not been applied to these electrical properties, and therefore constant permittivity and loss tangent values have been assumed for the whole operating band.

<table>
<thead>
<tr>
<th>Frequency [MHz]</th>
<th>Measured</th>
<th>Target</th>
<th>Diff. to Target [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2400</td>
<td>51.1</td>
<td>52.8</td>
<td>-3.2</td>
</tr>
<tr>
<td>2425</td>
<td>51.0</td>
<td>52.7</td>
<td>-3.3</td>
</tr>
<tr>
<td>2450</td>
<td>50.9</td>
<td>52.7</td>
<td>-3.4</td>
</tr>
<tr>
<td>2475</td>
<td>50.8</td>
<td>52.7</td>
<td>-3.5</td>
</tr>
<tr>
<td>2500</td>
<td>50.7</td>
<td>52.6</td>
<td>-3.7</td>
</tr>
</tbody>
</table>

Table 10: Dielectric properties of body tissues simulating liquid

Another important aspect is the size of the numerical phantom used in EM simulation in order to validate the measurements and speed up the antennas and communication link design processes. This aspect will have a strong impact on the simulation time and therefore an optima trade-off between the accuracy and simulation time has to be taken into account while using a body phantom for measurements campaigns. It has been derived in [78] that simulation results for different phantom length and width values are converging a minimum dimension around 117 mm. The sizes of our cylindrical phantom are fully satisfying these minimal dimensions required at 2.45 GHz. The shell thickness of a body phantom is an important factor for measuring on-body antennas; however these effects are easily calibrated out during the channel characterization of the in-body communication link. The shell thickness of the used phantom is 5 mm and it is made of a transparent Plexiglas.
4 Antennas on the body

In this section we present the antennas employed for channel measurements and the first results on the antenna-body interaction.

4.1 Identified antennas

Within the WiserBAN project all the antennas belong to the category of electrically small antennas. One of the challenges in small antenna design is to precisely measure an electrically small antenna. In the antennas integrated in small wearable devices the sizes of the radiating top patch and the ground plane are different, which yields an unbalanced radiating behaviour of the antenna as a whole. If one designs an antenna, where the bottom ground plane and the top radiator have comparable sizes and most of their area is overlapping, the antenna then becomes more balanced, with both (top and bottom) elements radiating virtually equal. In general, the size of the ground plane is a very important issue when miniaturizing the antenna. It becomes a significant radiation source in the case of small antennas and has a big influence on the antenna impedance. The measurement equipment uses unbalanced coaxial cables. If we connect one of the balanced or semi-balanced antennas, spurious currents will flow on the outside of the outer conductor of the coaxial line. These common-mode currents degrade the quality of the measurement results. The use of ferrite chokes around the coaxial cable would effectively suppress common-mode current. Unfortunately, this solution works well at low frequencies. It barely helps at frequencies higher than 2GHz depending on the type of ferrite material used. A solution can be to design a purely balanced antenna and to connect it to the coaxial cable through a balun transformer. For instance in UWB applications the majority of non-dispersive antennas have differential feeding. The most popular are Vivaldi, bow-tie, elliptical dipole antennas etc. In [99] impact of common mode currents on performance of an UWB elliptical dipole antenna was investigated. The solution was again the use of an UWB balun, which was placed perpendicular to the antenna plane. This precludes the balun integration in the same PCB board together with the antenna. First the characteristic case of designing a planar balun for a narrowband dipole antenna will be considered. The proposed narrowband balun is co-designed in the same PCB board with the microstrip dipole antenna, using the two metallization layers and one through substrate metal VIA. This antenna will be presented in paragraph 4.1.1. Additionally a wideband planar dipole with integrated balun and a top-loaded monopole fed by stripline, designed at CEA will be presented, in paragraph 4.1.2 and 4.1.3.

4.1.1 Microstrip dipole antenna with integrated FR4-based balun dedicated for antenna-body interaction measurements

In widely used microstrip-based monopole antennas the sizes of the radiating top patch and the ground plane are different, which yields an unbalanced radiating behavior of the antenna as a whole. The ground plane becomes a significant radiation source and has a big influence on the antenna impedance especially in a close vicinity to a human body. Additionally, the measurement equipment uses unbalanced coaxial cables. Connecting balanced or semi-balanced antennas will cause spurious currents
flowing on the outside of the outer conductor of the coaxial line. These common-mode currents degrade the quality of the measurement results. The use of ferrite chokes around the coaxial cable would effectively suppress common-mode current. Unfortunately, this solution works well at low frequencies. It generally does not help at frequencies higher than 1.5 GHz depending on the type of ferrite material used. An enabling solution in our work is to design a purely balanced antenna and to connect it to the coaxial cable through a balun transformer, which is directly integrated to the antenna substrate.

To evaluate antenna performance within the vicinity of a human body a balanced and an unbalanced antenna have been designed. Figure 22 shows a sketch of the proposed microstrip dipole antenna, where the length of a dipole arm is about $\lambda/4$. The two antennas were optimized for working in the ISM band with a centre frequency at 2.45 GHz. The dipoles were realised on FR4 substrate with a thickness of 1.5 mm. The dipole with the differential feed consists of soldering pads for two SMA connectors, transitions from an unbalanced 50Ω CPW line to a balanced 100Ω CPS line and the radiating microstrip dipole. For the measurements a similar dipole but with a single-ended feeding was used. The dipole with an unbalanced microstrip line feeding is shown in Figure 23.

![Figure 22: Top view on the ISM dipole with balanced feed (left). Detail on the principal radiation pattern planes (right). All dimensions are in mm.](image)

**GREEN** – top metallization  
**ORANGE** – bottom metallization  
**BLUE** – through via  
**GREY** – substrate outline
The feeding microstrip line accommodates the end-launch SMA connector at the edge of the board and its remaining part comprises the top metal layer of the integrated balun. This structure was a part of a polarization diversity antenna in [100]. The microstrip via-hole balun acts as a transformer from the single-ended microstrip feeding to the two printed dipole strips. The ground plane of the microstrip line is realized in the bottom metal layer of the PCB together with the dipole strips. An etched slot in the ground plane provides 180° phase difference at the feeding point of the dipole arms, where the through via is placed.

The ready for measurements ISM dipole with an integrated balun is shown in Figure 24.

Figure 25 shows return loss measurements and simulations, which are in a good agreement. The measured radiation pattern presented in Figure 26 is similar to the one of a classical half-wave dipole antenna. The normalized pattern for the half-wave dipole with the balun has a symmetrical toroidal shape, which is not disturbed by the presence of the integrated balun. The proposed integrated balun validates our supposition, that by integrating it close to the antenna in the same substrate, the antenna radiation properties remain unchanged. Such radiation pattern with stable and predictable polarization properties is very suitable for on-body measurements, as its polarization can be intuitively changed relatively to the human body surface.
4.1.2 Wideband planar monopole with integrated balun

The starting point of the antenna design is a classical notch antenna with reduced ground plane. Nevertheless, the reduction of the ground plane yields to a radiating behaviour similar to a short-circuited printed dipole antenna. Thus the ground plane acts as dipole arms at $\lambda/2$.

Since the printed dipole presents a relatively small bandwidth, the notch design has been modified in order to achieve wideband behaviour. This is obtained by means of an elliptical shape of the dipole arms, which results into a larger notch. As a consequence the wideband impedance matching is obtained by combining two different antenna modes: in the first octave the antenna acts as a dipole, with omni-directional characteristics in the azimuth plane; while at highest frequencies the notch acts as an aperture antenna with small directive characteristics.

Additional antenna size reduction is obtained by folding up the dipole arms, which leads to a miniaturization factor of $\lambda/5$ instead of $\lambda/2$. A prototype has been realized on FR4 substrate of 0.8 mm thickness (Figure 27) at CEA.
The antenna reflection coefficient has been measured in “on-air” and “on-body” conditions, as depicted in Figure 28. This antenna was originally designed to work in the 1.5–3.1 GHz band ($|S_{11}| < -7 \text{dB}$). Nevertheless it can be employed up to 5 GHz if a slightly higher mismatch can be accepted ($|S_{11}| < -6 \text{dB}$), since the antenna presents good performance in terms of total efficiency. Figure 28 shows a total efficiency larger than 75 % in the 1.5–5 GHz, with except of a small dip at 60 % in the 3.2–3.7 GHz band.

One of the main issues in small antenna characterization is the influence of the RF cable. This parasitic effect can greatly affect the channel characterization. To avoid these phenomena, this design presents a Balun structure, which allows the use of a SMA connector placed on the plane of the dipole structure. At the same time the SMA connector and RF cable orientation are orthogonal to the antenna radiated field, thanks to the Balun design.

A cable-less test-bed has been set up to characterize the radiation pattern of small antennas. The test bed is based on a fibre optic link. A Transmitter Optical Sub-Assembly converts RF signal to an optical one. Then a Receiver Optical Sub-Assembly converts the optical signal into a RF feed to the Antenna Under Test. The angle-dependent transfer function, $H(f, \theta, \phi)$, of the antenna has been measured by using the optic link and the classical RF cable, in order to highlight the influence of the parasitic effect due to the cable.

Given the large bandwidth of the antenna, the Mean Realized Gain (MRG) computed in the azimuth plane. Figure 29 shows the MRG measured with both methods for two different bandwidths: from 1.5 GHz to 3 GHz and from 1.5 GHz to 5 GHz. The antenna presents good omni-directional characteristics in both bands. Nevertheless the poor impedance matching at higher frequencies yields to a slight gain decrease, as observed in Figure 29b.
The most important outcome is that the differences between the RF cable and optic link measurements are practically irrelevant. This result shows that the antenna is notably a good candidate for on-body channel sounding, avoiding RF cable parasitic effect.

A second Planar (PL) monopole has been designed without folding the dipole arms (Figure 30).

This antenna, realized on FR4 substrate, presents 25x35x0.8 mm³ dimensions and its impedance matching band is 2.22-5.06 GHz, with respect to $S_{11}<-6$dB. The antenna presents a quasi-omnidirectional behaviour as the previous antenna, and 70% total efficiency on the air at 2.4 GHz. This antenna has been employed in the second measurement campaigns at CEA.

4.1.3 Top-loaded monopole

A wide band top loaded monopole has been designed in the scope of the WiserBAN project to investigate on-body channel by considering a polarization normal to the ground plane. The antenna is fed by a stripline on Roger 4003 substrate. This feeding allows the use of coaxial cables normal with respect to the main antenna polarization, and minimizes its influence on channel measurements. The antenna height is 11.5 mm and the ground plane is 50mmx50mm. Antenna design and prototype are shown in Figure 31.
Measurement results show that reflection coefficient is below -7 dB over a very large bandwidth from 2.33 GHz up to 11 GHz, so that both 2.4 GHz and UWB can be investigated by using this antenna.

A human homogenous body phantom ($\varepsilon_r=41, \sigma=0.7$ S/m) has been considered in simulation. Simulation results show that total efficiency is at least 70% from 2.36 to 5 GHz.
Figure 33 shows the simulated gain pattern at 2.4 GHz on the body. The antenna keeps good monopolar behaviour even when it is placed on the body.

In addition a narrow-band band top-loaded monopole has been designed (Figure 34). Given the smaller bandwidth, the antenna dimension are also reduced to 40x40x5 mm$^3$. The antenna impedance band is 2.36-2.5 GHz with respect to $S_{11}<-10$dB, according to the on-body location, as shown in Figure 35.

In Figure 36 we show the radiation patterns measured on the air. The omnidirectional behaviour on the azimuth plane has been verified.

Simulation results showed that antenna efficiency decreases from 98% to 68% when placed on the body.

![Figure 34 Narrowband top loaded monopole](image)

![Figure 35 Measured return loss on different on-body positions](image)
4.2 Antenna-body interaction

Antennas used in WiserBAN project need to be designed to operate properly in the vicinity of the human body. Two different human body models are used to study antennas performance. The first body model comprises a lossy dielectric rectangular placed next to an antenna under design. The dielectric box is intended to provide an appropriate emulation of the body two thirds body muscle equivalent with $\varepsilon_r = 62 + j55$ (equivalent tan $\delta = 0.89$). This model can give a good initial estimation on antenna-body interaction. The second model comprises a layered structure, which is more representative and yet more demanding for computational resources. The layered model is presented in Figure 37. The three body tissue layers can vary individually and their dimensions are strongly dependent on the chosen area on the human body itself. Table 11 gives some average thicknesses for three different individuals. The EM properties of these tissues are given in Table 12 for 2.45 GHz. Bones and other organs are not considered because of their relatively small volumes and their marginal impact on the antenna performance due to the isolation by the prior layers.

![Figure 37: Proposed adjustable phantom model for various body parts.](image)

The antennas used in on-body application must be designed to favourably propagate trapped creeping waves present with non-perfect conductors and especially in a stratified medium. In this way, the body skin-air interface and interlayer interfaces in the human body itself are used to guide the signal rather than rely solely on multipath reflections.

<table>
<thead>
<tr>
<th>Tissue thickness [mm]</th>
<th>“Skinny” model</th>
<th>“Average” model</th>
<th>“Fat” model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skin</td>
<td>0.6</td>
<td>1.3</td>
<td>2</td>
</tr>
<tr>
<td>Fat</td>
<td>0.4</td>
<td>10.5</td>
<td>20.6</td>
</tr>
<tr>
<td>Muscle</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

**Table 11: Dimensions of body layers**

The lateral dimensions of the body tissues were considered $150 \times 150$ mm in the initial simulations using Ansys HFSS ver.13. These finite dimensions affect not only the losses by the body tissues but also introduce some wave reflections at the boundaries and consequently some spurious refraction from the body phantom edges will affect the radiation properties of the antenna. Later simulations showed a good convergence of the simulation results when the lateral dimensions of the body tissues are decreased to $80 \times 95$ mm, which dramatically saves the computational resources required.
### Table 12: EM properties of human body tissues at 2.45 GHz

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Permittivity</th>
<th>Loss tangent</th>
<th>Conductivity ([\text{S/m}])</th>
<th>Penetration depth ([\text{mm}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry skin</td>
<td>38</td>
<td>0.28</td>
<td>1.48</td>
<td>22</td>
</tr>
<tr>
<td>Wet skin</td>
<td>20</td>
<td>0.84</td>
<td>23.98</td>
<td>1</td>
</tr>
<tr>
<td>Fat</td>
<td>5.3</td>
<td>0.14</td>
<td>0.106</td>
<td>114</td>
</tr>
<tr>
<td>Muscle</td>
<td>52.7</td>
<td>0.24</td>
<td>1.77</td>
<td>21</td>
</tr>
</tbody>
</table>

#### 4.2.1 Body effect on return loss

First of all the measurements of the PCB dipole antenna were performed in free space. Figure 38 presents antenna matching measured in free space. As it can be noticed it is perfectly matched to 50 Ohm at 2.4 GHz without the presence of the human body.

![Antenna measured in free space](image)

The PCB dipole antenna has no coating, which would isolate some conducting parts of the antenna. Therefore the impedance mismatch is evident while dipole side of the antenna is put in direct contact with a human body or SAM phantom. Due to conductive properties of human skin the impedance of the dipole decreases compared to the antenna impedance in free space, as shown in Figure 39. The skin conductivity and permittivity varies dramatically from person to person and even for a single person but in different physical state. Conductivity of a dry and wet human skin varies by factor of 16 at 2.45 GHz (Table 12). Even if the dipole microstrips will not come in a direct contact with human body the difference in the penetration depth for the RF signal at 2.45 GHz will cause a dramatic frequency detuning of a BAN antenna.
Figure 39: Measured antenna detuning (right) due to direct contact its dipole side with body tissues.

Figure 40 show measured antenna detuning due to direct contact its microstrip side with body tissues. Although the real part of the impedance does not change much the imaginary part has a pronounced inductive behaviour. A direct contact of the top microstrip to the skin forces the EM fields to be not entirely confined between the microstrip and its ground plane but also to propagate into the human skin tissues.

Figure 40: Measured antenna detuning (right) due to direct contact its microstrip side with body tissues.

Figure 41 summarizes the antenna detuning due to a direct contact of the dipole side with the skin layer. The measurements are performed on the SAM phantom and two humans.
Figure 41: Measured return loss with antenna dipole side placed on body.

Figure 42 summarizes the antenna detuning due to a direct contact of the microstrip side with the skin layer. The measurements are performed on the SAM phantom and three humans. The obvious conclusion is that some spacing between an antenna and the human tissues has to be respected no matter what side of the dipole antenna is looking into the skin layer.

Figure 42: Measured return loss with antenna microstrip side placed on body.

Figure 43 show a simulation setup used for investigation of antenna-body interaction with various antenna separations to the body tissues. The measured antenna matching at 2.4 – 2.5 GHz is presented in Figure 44. It can be seen that, for an antenna separation starting from 5 mm, the antenna mismatch is satisfactory. For the presented PCB dipole the antenna separation of 10 mm (which corresponds to about $\lambda/10$) does not have a significant impact on the antennas input impedance.
Figure 43: Validated human tissues model for EM simulations.

Figure 44: Antenna matching versus the separation distance for frequency sweep 2.4 – 2.5 GHz.

In Figure 45 the simulated in Ansoft HFSS and measured return loss are compared for antenna separation of 5 mm. The measurements and simulation results have a satisfactory agreement except for the measurements using the SAM body phantom. There is a good grouping of the measurements for different people as the dipole did not come in a direct contact to skin. A significant results difference for the SAM phantom has still be investigated. The SAM body phantom is constructed using a PVC tube filled with a kind of Ringer solution. A liter of Ringer solution is composed of:

- Industrial Ethylene Glycol (Ethanediol) OH-CH₂-CH₂-OH 482 mL
- Distilled water H₂O 354 mL
- Natrium Chloride NaCl 18.6 g
Figure 45: Return loss simulation and consolidated measurements for various tissue models for separation distance of 5 mm.

Figure 46: Return loss simulation and consolidated measurements for various tissue models for separation distance of 10 mm.

For the antenna separation of 10 mm the convergence of the measured and simulated return Loss is quite good (Figure 46). The results for different humans and the SAM phantom are converging at all the frequencies of interest, which indicates a fading effect of the body vicinity to the radiating antenna elements.

4.2.2 Body effect on radiation proprieties

Using a specially shaped numerical or physical phantom (Figure 47 and Figure 48) it is possible to distinguish the surface wave effects from other propagation modes, so that on-body antennas can be investigated and optimized.
Figure 47 shows E-field distribution for the PCB dipole in free space at 2.45 GHz. The field distribution is rather homogeneous in all the direction. The presence of the layered human body phantom completely changes the E-field distribution on both near- and far-field of the antenna (Figure 48). One can notice some field confinements in the upper (skin) layer of the human tissues. By a proper selection of the antenna characteristics stronger surface waves can be launched along the body surface. This can facilitate the on-body communication channel where no line of sight is available. On Figure 48 blue colour corresponds to the lowers E-field magnitude and red colour corresponds to the strongest E-field components. Compared to Figure 47 the lateral spread (along X axis) of the E-fiels is significantly more pronounced in Figure 48, when the human body is present.

Figure 48: Simulated E-field distribution for antenna with separation distance of 1 mm.

Compared to 418 MHz and 868 MHz, antenna performance can be relatively better at 2.45 GHz despite much higher losses. Particularly when the antenna body spacing is around λ/8 – λ/10 and more. The negative effects of body proximity increase as antenna-body separation decreases, but the dielectric properties of body tissues vary significantly with the frequency increase. For instance the relative permittivity of dry skin decreases from 46 at 400 MHz to about 38 at 2.45 GHz, the loss tangent changes from 0.66 to 0.28 respectively. These dielectric properties at 2.45 are more advantageous for antenna working at 2.45 GHz rather than at 400 MHz.
5  BAN channel characterization

5.1 Identified scenarios for WiserBAN

One of the use cases in WiserBAN involves an insulin pump wirelessly connected to a handheld glucometer and a remote control. The pump is mounted directly on the body in the upper abdominal region (Figure 49). The pump receives a command from a glucometer on an amount and timing for injecting insulin into the body. All activity of the pump and the glucometer is logged and transmitted to the remote control, which will deliver these data to the remote health provider via conventional communication infrastructure such as Wi-Fi, GSM etc. The remote control is based on a commercially available mobile phone with an installed proprietary micro SD card, which bridges the BAN data to the operation system of the phone. The importance of the dynamic behaviour of the BAN communication channel is primary for this scenario. While local scattering will play a part in communication between sensor nodes or medical devises mounted on the body, significant variation in the channel are also due to changes in the geometry of the body. Even when standing or sitting the body is subjected to small movements. Thus channel characterization needs to account both for variable positioning of the on- or in-body transmitter, and the dramatic changes of the local environment. Additionally, the local geometry changes of the human body may also affect the input impedance or radiation pattern of the antenna.

Figure 49: WiserBAN use-case for operation of an insulin pump wirelessly connected to a handheld glucometer and a remote control.

Over the past decade, large improvements in hearing aid developments have been observed especially due to the introduction of digital hearing aids and the development of sophisticated audio signal processing algorithms, such as beamformers, noise reduction, and signal compression. However, speech understanding in noisy environments still poses problems to hearing aid users. Latest applications such as wireless audio transmission integrated in hearing aids show one direction addressing this problem. This application allows the wireless transmission of audio signals such as telephone or TV signals directly into hearing aids in order to present them at the best available signal-to-noise ratio (SNR). To further enhance speech intelligibility in noisy acoustic environments multiple research works are done with one direction focusing binaural signal processing. Here, a wireless acoustic link between the hearing aids is supposed to be available. Binaural beamformers then offer the possibility to enhance the signals even more than currently possible with monaural
solutions. The use 2.4 GHz wireless link is a promising candidate for satisfying a demand to high data-rate.

![Diagram of WiserBAN use case for hearing aids](image)

Figure 50: WiserBAN use case for the hearing aids.

A WiserBAN user case related to this problem is concerned for both in-the-ear and behind-the-ear hearing aids. The considered cochlear implants can also benefit from use of the binaural audio link. Figure 50 details on such use case scenario. The mounted on- or in-body hearing aids systems have to establish a robust wireless link between each other. Additionally some audio streaming devices can be connected to the hearing aid devices with a RF link. A shown in Figure 50 remote control can be carried on-body, it can also present a classical off-body communication link problem.

5.2 On-body measurement campaigns at CEA

In this section we present the measurement campaigns for on-body channel characterization. Two time-domain measurement campaigns have been performed on real human subjects at CEA, to investigate the effect of movement and antenna on channel characteristics. In addition a frequency domain channel measurement campaign on human phantom has been realized at CSEM.

5.2.1 Preliminary on-body channel measurement campaign

Previous on-body channel measurement campaigns have been carried out at CEA-Leti in time domain. The test-bed was able to collect simultaneously up to four channel impulse responses (CIRs), each one corresponding to a different location on the body. Besides the need to characterize the time variations of the channel, this choice enables to investigate the time-spatial correlations of the channel. CIRs are collected every 20 ms, obtained by averaging over 30 CIRs to enhance the measurement Signal-to-Noise Ratio (SNR). In the scope of WiserBAN project the test-bed has been upgraded in order to increase the repetition period. This acquisition rate is considered enough for our purposes, since it allows measuring Doppler shifts up to 25 Hz, corresponding to a maximum speed of 3.1 m/s at 2.4 GHz. Measurements were performed in anechoic chamber and indoor environments. In anechoic chamber a catwalk of 3 meters, realized by solid RF absorber, was placed to allow human movements. The indoor scenario is a medium-large room used for exhibition. Wood desks, chairs, computers and office furniture are present and a large partition in the middle is used for presentations. Three different human moving conditions have been measured: standing still, walking, running on a spot. In the first one the human subject does not move (with except of involuntary breathing movements) and 3 different right arm angular positions have been tested: 0°, 45° and
90° with respect to the body axis in the front direction. In the walking condition the human subject walks on 3 meters, while in the other scenarios (still and running) he stands on a fixed point. The walking average speed was approximately 0.75 m/s. In a first set of measurements the transmitting antenna is on “Hip” (left side) and we collect the simultaneously received signal on “Chest”, “Right Thigh”, “Right Wrist” and “Right Foot”. In a second set of measurements the transmitting antenna is placed on “Left Ear” and we collect the simultaneously received signal on “Right Ear”, “Hip”, “Right Wrist” and “Right Foot”. In order to reproduce the same antenna emplacement for the different human subjects some reference points were adopted. The “Hip” position is situated 18 cm to the left of the navel, the “Thigh” position is 13 cm above the knee, the “Chest” position is on the sternum, “Foot” position is on toes and “Wrist” position corresponds to a watch-like emplacement. The two on-body schemes are presented in Figure 52.

**Figure 51:** Measured environments: anechoic chamber (left), indoor (right)

**Figure 52:** Measurement setups: TX on the Hip (left), TX on the Left Ear (right)

<table>
<thead>
<tr>
<th>Human Subject</th>
<th>Weight (Kg)</th>
<th>Height (m)</th>
<th>Waist (US)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>72</td>
<td>1.79</td>
<td>31</td>
</tr>
<tr>
<td>B</td>
<td>72</td>
<td>1.80</td>
<td>32</td>
</tr>
<tr>
<td>C</td>
<td>79</td>
<td>1.84</td>
<td>34</td>
</tr>
<tr>
<td>D</td>
<td>73</td>
<td>1.71</td>
<td>36</td>
</tr>
<tr>
<td>E</td>
<td>67</td>
<td>1.87</td>
<td>32</td>
</tr>
<tr>
<td>F</td>
<td>63</td>
<td>1.69</td>
<td>30</td>
</tr>
<tr>
<td>G</td>
<td>58</td>
<td>1.69</td>
<td>30</td>
</tr>
</tbody>
</table>

**Table 13:** Human body characteristics for different subjects

For both anechoic chamber and indoor environment three cycles of 4 seconds (equivalent to 3×200 CIRs) have been recorded in the still and walking scenarios, while one cycle of 20 seconds (equivalent to 1 × 800 CIRs) has been collected in the
running scenario. The human body variability was taken into account by repeating the experiment for 7 different male human subjects, whose characteristics are reported in Table 13. The antenna employed is the wideband planar monopole described in section 4.12.

The great non-homogeneity of the human body, and the variability given by the human subjects, suggests a “scenario based” channel model, depending on antenna emplacement. The analysis presented in the next sessions is carried out for a specific scenario, which identifies:

- a transmitting antenna \( TX \in \{ \text{Hip, Left Ear} \} \)
- a receiving antenna \( RX \in \{ \text{Hip, Chest, Right Wrist, Right Thigh, Right Foot, Right Ear} \} \)
- a movement \( m \in \{ \text{Still, Walking, Running} \} \)
- an environment \( e \in \{ \text{Anechoic, Indoor} \} \)

More generally we indicate a particular scenario in our notation as \( S = \{ TX, RX, m, e \} \). The “scenario-based” approach attempts to model the on-body channel by defining a specific condition instead of giving a unique model for the whole human body.

### 5.2.2 Full on-body channel measurement campaign at CEA

Considering the specific needs of the WiserBAN project, the second measurement campaign performed at CEA-Leti focused on the characterisation of the propagation channel only at the frequency \( f_0 = 2.45 \) GHz in the ISM band.

The main goal of the work performed was to extract a channel model that takes into account different sources of channel variability. These could be listed as follows:

- **Nature of the link**: On-body (intra-BAN perspective), Off-body (off-BAN perspective) and Body-to-Body (inter-BAN perspective);
- **Human variability**: different human subjects used during the measurement process;
- **Environment variability**: the measurement were performed in different locations (anechoic chamber and indoor premises);
- **Antenna type**: two different sets of antennas were used, one normally polarised in respect to the body surface (Top Loaded Monopole – TL Monopole), while the other one is characterised by tangential polarisation (Planar Monopole – PL Monopole);
- **Time-variant channel**: different dynamic movements were reproduced by the subjects.

As already pointed out in the previous paragraph, all these elements of variability suggest the idea to extract a channel model that is “scenario-based”, where each scenario is identified by the movement performed, the environment considered, the type of antenna and the positions of the Transmitter (Tx) and the Receiver (Rx) antenna that define the particular link considered.

The on-body analysis focuses on the characterisation of the propagation channel that is set up between a Transmitter node (Tx) and a Receiver (Rx) both placed on the
subject’s body. The node emplacement considered for the measurement campaign performed is presented in Figure 53.

![Node emplacement for On-body scenario](image)

**Figure 53: Node emplacement for On-body scenario**

The measurement test bed used for this scenario, and that has been fully described in Section 3.1, allows the simultaneous collection of four different channel impulse responses, each one corresponding to one specific Tx-Rx.

As shown in Figure 53, the Rxs are always placed on the same positions, namely:

- Rx1: Right Thigh;
- Rx2: Right Hand;
- Rx3: Left Hand;
- Rx4: Left Ear;

while the transmitter is alternatively positioned on:

- Tx1: Left Hip;
- Tx2: Heart;
- Tx3: Right Ear.

On-body channel for four different human subjects, two males and two females, has been investigated; the most relevant physical characteristics are listed in Table 14.
Subject's physical characteristics

<table>
<thead>
<tr>
<th>Subject</th>
<th>Weight (Kg)</th>
<th>Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject A (male)</td>
<td>63</td>
<td>1.69</td>
</tr>
<tr>
<td>Subject B (female)</td>
<td>45</td>
<td>1.6</td>
</tr>
<tr>
<td>Subject C (male)</td>
<td>74</td>
<td>1.75</td>
</tr>
<tr>
<td>Subject D (female)</td>
<td>61</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Table 14: Subjects' main physical characteristics

In order to reproduce the same antenna emplacement for the different human subjects, some reference points have been adopted. The “Rx1” is situated 32 cm above the knee, “Rx2” and “Rx3” positions correspond to a watch-like emplacement, “Tx1” is placed on the left hip bone while “Tx2” lies 5 cm left to the sternum. For the nodes placed on the ears (“Rx4” and “Tx3”), a hat with two side pockets has been used to host the antennas.

The environmental variability has been taken into account repeating the same measurements in two different locations: an anechoic chamber and an indoor office equipped with tables, chairs and general office furniture. In the anechoic chamber a catwalk of 3 meters, realized by solid RF absorbers, was placed to allow human movements. Anyway, the presence of the floor and some portions of uncovered metallic floor (even if far away from the area where measurements were performed) makes the environment not perfectly anechoic, and so we will refer to it as a quasi-anechoic chamber. A schematic plan of both the environments considered is presented in Figure 54, where the red arrows represent the length of the walk performed by the subjects.

![Figure 54: On-Body measurements locations: indoor office (left) and quasi-anechoic chamber (right)](image)

For every transmitting antenna position, namely “Tx1”, “Tx2”, “Tx3”, each subject has performed 2 walking cycles covering 3.5 m distance in the indoor office and 3m in the quasi-anechoic chamber, considering an approximate human walking speed in the range of 1-1.2 m/s.
Moreover, other two cycles of measurements have been acquired, while the subject simulates the movement of standing up and sitting down from a chair. Every acquisition lasted 3 seconds, that is an interval of time large enough to let the subject performing a complete movement cycle, and is composed of \( N_p = 22500 \) CIRs, considering a GPRP equal to 133\( \mu \)s (for more details see section 3.1). In order to reduce the noise level, getting then high SNR signals, the total number of CIRs has been averaged by \( N_{\text{avg}} = 150 \) in the post-processing treatment. It is equivalent to say that during each acquisition cycle \( N \) low noise CIRs have been recorded, where \( N = N_p / N_{\text{avg}} = 22500 / 150 = 150 \).

Two acquisitions have been performed only in the quasi-anechoic premises, while the subjects stood still with the arms lying along the body, and the only source of channel time-variability is related to involuntary breath movements.

Finally, for every single link the set of data available for the investigations could be summed up as shown in Table 15:

<table>
<thead>
<tr>
<th>Number of available CIRs</th>
<th>Quasi-anechoic chamber</th>
<th>Indoor Office</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walking</td>
<td>2x150</td>
<td>2x150</td>
</tr>
<tr>
<td>Sitting down/</td>
<td>2x150</td>
<td>2x150</td>
</tr>
<tr>
<td>Standing up</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standing Still</td>
<td>2x150</td>
<td>/</td>
</tr>
</tbody>
</table>

Table 15: Number of available CIRs for On-Body scenario

It is also necessary to remark that all the acquisitions described above have been realised with both sets of antennas: PL Monopole and TL Monopole. This kind of measurements could finally give the opportunity to draw some considerations about the different influence that the type of polarisation plays on the on-body propagation channel performances.

Unfortunately, given some mechanical constraints on the antenna SMA connector and cable, the sitting down/standing up scenario was not considered when receiver is on the hip. As a consequence the results on channel modelling won’t be presented in the next sessions.

Always keeping in mind the “scenario-based” approach used to model the on-body channel, all the analysis presented in the next sections will refer to a particular scenario \( S \) which is identified by:
- a Tx antenna position \( \in \{ \text{Left Hip, Heart, Right Ear} \} \)
- a Rx antenna position \( \in \{ \text{Right Thigh, Right Hand, Left Hand, Left Ear} \} \)
- a Movement \( m \in \{ \text{Walking, Sitting down/Standing up, Standing still} \} \)
- an Environment \( e \in \{ \text{Quasi-Anechoic Chamber, Indoor Office} \} \)
- an Antenna set \( a \in \{ \text{Top Loaded Monopole, Planar Monopole} \} \)

More generally, a particular scenario will be further indicated with the notation \( S_{\text{On-Body}} = \{ \text{TX,RX,m,e,a} \} \).
5.3 Off-Body measurement campaign

The off-body analysis focuses on the characterisation of the propagation channel that is set up between a Receiving (Rx) node placed on the subject’s body and an external gateway that plays the role of the Transmitter (Tx). The node emplacement considered for the measurement campaign performed is presented in Figure 55.

![Diagram of Off-Body measurement campaign](image)

**Figure 55: Node emplacement and measurement test bed for Off-Body scenario at CEA**

The measurement test bed used for this scenario, and that has been fully described in section 3.2, allows the simultaneous collection of three different channel transfer functions through the acquisition of the $S_{11}$ parameters, each one corresponding to the $i$-th receiving antenna. As shown in Figure 55, the Rxs are always placed on the same on-body positions, namely:

- Rx1: Left Hip;
- Rx2: Heart;
- Rx3: Right Ear;

while the transmitter (Tx) is placed on the top of a support 1.2 m high, acting as an external gateway.

“Rx1” is placed on the left hip bone, “Rx2” lies 5 cm left to the sternum, while “Rx3” is hosted by the right pocket on the very same hat also used for the On-body measurements.

The human subject considered is 1.8 m tall and weighs 73 kg.

The environmental variability has been taken into account by repeating the same measurements in two different locations: the quasi-anechoic chamber (as explained above) and a large indoor laboratory equipped with tables, chairs and some devices. In the quasi-anechoic chamber a catwalk of 3 meters, realized by solid RF absorber, was placed to allow human movements. A schematic plan of both the environment
considered is presented in Figure 56, where the red arrows represent the length of the walk performed by the subject.

![Figure 56: Off-Body measurements locations: indoor laboratory (left) and quasi-anechoic chamber (right)](image)

In order to get a complete characterisation of the off-body channel, four different movement conditions have been reproduced and the related data have been recorded. The first set of measurements has been performed while the subject stood still at a fixed distance from the transmitter antenna for the entire duration of the acquisition, which is 5 seconds (see Paragraph 3.2). Starting from 1 meter far from the Tx, the measurements have been repeated every Δd=2λ (25 cm at 2.45 GHz), up to a distance of 4 meters from the external gateway. The subject stood alternatively in LOS (0°) and NLOS (180°) conditions, facing or giving his back side to the transmitting antenna.

A schematic representation of the measurement process is given in Figure 57.

![Figure 57: Distance discrete off-body measurements setup](image)

This set of distance-discrete measurements will be useful in order to extract the distance-dependent component from the global expression of the link channel gain (G(d)_{ofB}). More details on the channel model extracted for the off-body scenario will be given in the following chapter.

In the second group of measurements the subject has performed 10 dynamic walking cycles of 5 seconds each, covering a distance of 3 meters (from 1m to 4m far from the transmitter).
The first 5 acquisitions reproduce LOS conditions, with the user walking towards the transmitter, whereas in the other 5 he moves away from it (NLOS case).

The third set of acquisitions aimed to model the expression of the channel gain as a function of the relative angle \( \alpha \) created by the front side of the user with respect to the external gateway. For that purpose several measurements have been performed while the subject stood still 2m far from the transmitter and rotates by an angular step \( \Delta \alpha = 45° \), making a complete clockwise rotation from \( \alpha = 0° \) to \( \alpha = 360° \).

In this way the shadow effect of the body could be completely described; from LOS (\( \alpha = 0° \)) to the maximum shadowing condition (\( \alpha = 180° \)) before returning back to LOS (\( \alpha = 360° \)). Figure 58 shows a schematic representation of the measurement performed.

![Figure 58: Angle-dependent off-Body measurement setup](image)

In the last set of measurements the user has performed a continuous rotation from 0° to 360° with respect to the Tx, considering an averaged angular velocity of 70°/s (360°/5s). The measurements have been repeated 3 times at different distances from the gateway (2m, 3m and 4m).

Considering that every acquisition is composed of 2501 samples, acquired in an interval of 5 seconds with a sampling rate of 2 ms, the total amount of data available for the post processing treatments could be summarised as in Table 16:

<table>
<thead>
<tr>
<th>Number of available sampled Data</th>
<th>Quasi-anechoic chamber</th>
<th>Indoor Laboratory</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stationary Walk LOS</strong> (( \Delta d = 2 \lambda ))</td>
<td>1x2501 (for every step)</td>
<td>1x2501 (for every step)</td>
</tr>
<tr>
<td><strong>Stationary Walk NLOS</strong> (( \Delta d = 2 \lambda ))</td>
<td>1x2501 (for every step)</td>
<td>1x2501 (for every step)</td>
</tr>
<tr>
<td><strong>Dynamic Walk</strong></td>
<td>5x2501</td>
<td>3x2501</td>
</tr>
<tr>
<td><strong>Stationary Rotation</strong> (( \Delta \alpha = 45° ))</td>
<td>1x2501 (for every step)</td>
<td>1x2501 (for every step)</td>
</tr>
<tr>
<td><strong>Dynamic Rotation</strong></td>
<td>3x2501</td>
<td>3x2501</td>
</tr>
</tbody>
</table>

**Table 16: Number of available sampled data for Off-Body scenario**

It is also necessary to remark that all the acquisitions described above have been realised with both sets of antennas: PL Monopole and TL Monopole.
Always keeping in mind the “scenario-based” approach used to model the off-body channel, all the analysis presented in the next sections will refer to a particular scenario $S$ which is identified by:

- the Tx antenna used as external gateway
- a Rx antenna position $\in \{\text{Left Hip, Heart, Right Ear}\}$
- a Movement $m \in \{\text{Stationary Walk, Dynamic Walk, Stationary Rotation, Dynamic Rotation}\}$
- an Environment $e \in \{\text{Quasi-Anechoic Chamber, Indoor Laboratory}\}$
- an Antenna set $a \in \{\text{Top Loaded Monopole, Planar Monopole}\}$

More generally, a particular scenario will be further indicated with the notation $S_{\text{Off-Body}} = \{\text{TX, RX, m, e, a}\}$.

### 5.4 Body-to-Body measurement campaign

The body-to-body analysis aims at characterising the propagation channel set up between two subjects, namely A and B, each one representing a single Body Area Network. For the specific analysis realised, subject A always wears the transmitter (Tx), while B hosts the receiving antennas (Rx).

The node emplacement considered for the measurement campaign performed is presented in Figure 59.

![Figure 59: Node emplacement and measurement test bed for Body-to-Body scenario](image)

The measurement test bed used for this scenario, described in Paragraph 3.2, allows the simultaneous collection of three different channel transfer functions through the acquisition of the $S_{ii}$ parameters, each one coming from one of the $i$-th receiving antenna.

As shown in Figure 59, the Rxs are always placed on the same positions on subject B, namely:

- Rx1: Left Ear;
• Rx2: Heart;
• Rx3: Right Hip;
while subject A always wears the transmitter, which is alternatively positioned on:
• Tx1: Left Thigh;
• Tx2: Right Hip;
• Tx3: Right Hand.

“Rx1” is hosted by the left pocket on the very same hat also used for the On-body measurements. “Rx2” lies 5cm left to the sternum, while “Rx3” is placed on the right hip bone.
“Tx1” is located 32cm above the knee, “Tx2” stands on the right hip bone, and “Tx3” position corresponds to a watch-like emplacement.

Four different human subjects, sorted by couple, have been used during the measurements. Their main physical characteristics are listed in Table 17, as well as their role in the couple.

<table>
<thead>
<tr>
<th>Subject's physical characteristics</th>
<th>Weight (Kg)</th>
<th>Height (m)</th>
<th>Couple/Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject A</td>
<td>63</td>
<td>1.69</td>
<td>Couple 1 B</td>
</tr>
<tr>
<td>Subject B</td>
<td>45</td>
<td>1.6</td>
<td>Couple 2 A</td>
</tr>
<tr>
<td>Subject C</td>
<td>74</td>
<td>1.75</td>
<td>Couple 2 B</td>
</tr>
<tr>
<td>Subject D</td>
<td>61</td>
<td>1.7</td>
<td>Couple 1 A</td>
</tr>
</tbody>
</table>

Table 17: Subjects' main physical characteristics and role in the couple

The measurements have been performed only in indoor premises: a laboratory equipped with tables, chairs and some technical equipment. A schematic plan of this environment is presented in Figure 60 where the red arrow represents the length of the walk performed by the subject.

In order to characterise the Body-to-Body channel different movement conditions have been reproduced and the related data have been recorded.

The first set of measurements has been performed in the case where subject A stood still at one end of the room while subject B performed 4 walking cycles, alternatively forwards (LOS) and backwards (NLOS) A. In the first case, starting from the same position where subject A stands, B realises a continuous walk covering a distance of 8 meters in 10 seconds, with an average speed of 0.8m/s. The same distance and
acquisition time characterise the two backwards walking cycles. A schematic representation of the measurement process is given in Figure 61.

![Figure 61: First set of Body-to-Body measurements](image)

The second group of acquisitions is similar to the previous one, but in this case subject B performs a complete rotation, from α=0° to α=360°, in front of user A, at different distances from him (1m, 3m, 5m and 7m). Every trial has been repeated four times, twice clock-wise and twice anti clock-wise, and assuming an approximate angular speed of 36° (360°/10s). The Tx was placed only in the Heart position.

This kind of measurements is well suited to point out the shadow effect that the human body exerts on the propagation channel.

Considering that every acquisition is composed of 5001 samples, acquired in an interval of 10 seconds with a sampling rate of 2ms (see Paragraph 3.2), the total amount of data available for the post processing treatments could be summarised as in Table 18.

<table>
<thead>
<tr>
<th>Number of available sampled Data</th>
<th>Indoor Laboratory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic Walk LOS case</td>
<td>2x5001</td>
</tr>
<tr>
<td>Dynamic Walk NLOS case</td>
<td>2x5001</td>
</tr>
<tr>
<td>Dynamic Rotation</td>
<td>4x5001 (at every distance step)</td>
</tr>
</tbody>
</table>

Table 18: Number of available sampled data for Body-to-Body scenario

All measurements described above have been realised with both sets of antennas: PL Monopole and TL Monopole.
Always keeping in mind the “scenario-based” approach used to model the body-to-body channel, all the analysis presented in the next sections will refer to a particular scenario \( S \) which is identified by:

- a Tx antenna position \( \in \{ \text{Right Hand, Right Hip, Left Thigh} \} \)
- a Rx antenna position \( \in \{ \text{Left Ear, Heart, Right Hip} \} \)
- a Movement \( m \in \{ \text{Dynamic Walk LOS, Dynamic Walk NLOS, Dynamic Rotation} \} \)
- an Environment \( e \in \{ \text{Indoor Laboratory} \} \)
- an Antenna set \( a \in \{ \text{Top Loaded Monopole, Planar Monopole} \} \)

More generally, a particular scenario will be further indicated with the notation \( S_{\text{Body-to-Body}} \equiv \{ \text{TX,RX,m,e,a} \} \).

For the sake of completeness, it is worth to say that other two sets of acquisition have been performed for the body-to-body scenario, but the data acquired have not been post-processed. The first one concerns the two subjects performing a parallel march, walking side by side covering the same distance of 8 m (Figure 62b). On the contrary, the second group of measurements has been done when users A and B walk one towards the other passing from LOS to NLOS conditions when they cross each other approximately at the middle of the 8m-path (Figure 62a). These data are available for WP4 investigations on protocol aspects and interferences.

**Figure 62: Additional Body-to-Body measurements: a) opposite walk, b) parallel walk**

### 5.5 Frequency domain measurement campaign on human phantom

The frequency domain measurements using SAM phantom will indicate the main link budget parameters for the WiserBAN project use scenarios. For all the measurements the planar monopole antennas with integrated balun are used. As the SAM phantom is representing the human upper body and the head the following measurement campaigns are considered. In a numerical analysis a generic body model can be realized by introducing the body tissues as a homogeneous media of two-thirds muscle equivalent tissues, which has according to IEEE standard permittivity of 52.7, conductivity of 1.95 S/m and loss tangent of 0.24. This standardized SAM phantom produced by MCL Technology Ltd (the UK) can be used for all the on-body propagation measurements.

Firstly we will investigate the radio propagation channel between the upper abdominal and the ears. This scenario will emulate propagation channel between the hearing aid devices and the insulin pump. In Figure 63 the placement points for the hearing aids are marked with green circles “1” and “2” and the insulin pump is fixed.
in the blue point “P”. The receiving antenna is placed on the upper abdominal and its polarization is parallel to the floor and also tangential to the human body. Further on the dipole antenna positioned in a way that its polarization is parallel to the floor will be referred as horizontally polarized (HP). Likewise the dipole antenna with main polarization perpendicular to the floor will be referred as vertically polarized (VP). In both HP and VP cases the antenna polarization plane is always tangential to the surface of the human body. Figure 63 gives details on the aforementioned measurement cases.

As it was already mentioned, to derive essential BAN channel characteristics the dynamics of the channel during arbitrary body motions should be taken into account. The arm movement is a dominant factor that influences the on-body propagation channel [98]. An additional study in WiserBAN considers the effect of the arm movement of a mobile user on the performance of on-body channels in both an anechoic chamber and an indoor environment. These measurements have been performed on a moving human subject in an anechoic chamber.

For the ear-to-ear channel characterization we propose scenario specific approach, where in both measurements and simulations the interaction between the antennas and the human body are taken into account. For the given dipoles it has been empirically derived that with antenna-body separation above 10 mm (which corresponds to about $\lambda/10$) the convergence of the measured and simulated return loss and input impedances is good. Therefore all further antenna placements will be done with spacing to the body of 10 mm.
The measurements scenarios for ear-to-ear channel characterization are detailed in Figure 64. The total over the head distance from left to right ear is 36 cm, which corresponds to about $3\lambda_0$ at 2.45 GHz. Every step in antenna placement is 3 cm ($\sim \lambda_0/4$) and they are indicated by points U1 through U11 in Figure 64. During the first measurement one dipole is fixed on the left ear (Rx) and another (Tx) is moving to it over the head.

During the second measurement a simultaneous movement of antennas to the top of the head is performed. During these measurements, the antennas are in mutual cross-polarization, when one antenna has a polarization parallel to the floor (HP) and the other has a perpendicular one (VP). Otherwise, they are in mutual co-polarization when both antennas are having their polarization parallel to the floor (HP). All the measurements with the planar dipoles have the polarization tangential to the human surface.

Similarly the distance dependencies are measured for the around the head paths (in front of the face and behind the human occiput). One antenna is fixed on the left ear and another is moving to it around the face of the SAM phantom (Figure 65). Simultaneous antenna movement around the head is shown in details in Figure 67. The hearing aids in the WiserBAN project will exploit the ear-to-ear communication.
As it was proposed in [97] the monopole antenna cables were mounted with sleeve baluns, in order to reduce the radiation from the cables. As an example Figure 66 shows the setup where the propagation paths are blocked around-the-front and around-the-back, but not over-the-top. Such setup allows analysing constructive and destructive interferences are for propagation around the head and to suggest the most favourable antenna characteristics and placement in this regard.

![Figure 66: Measurements setup with SAM head phantom which permits the ear-to-ear radio propagation only abote the head [95].](image)

![Figure 67: Schematic view on the distance dependencies with both antennas moving: : in front of the face (left), behind the head (right)](image)

For the implanted behind the ear cochlear implant the antenna should be within an absorbing material representing the signal attenuating tissues of the human head. The channel gain loss for the implanted antennas should be initially estimated using a measurement setup proposed in the Figure 68. This setup will be utilized for the channel measurements of a cardiac implant as well. The first scenario has one antenna outside the human phantom ant the other is inside phantom. The distance D4 remains constant and equal 45 cm. The transmit antenna immersed in the liquid phantom is moving inwards the center of the phantom (D1). The second measurements campaign has two antennas immersed in the liquid together. The receive antenna Rx2 remains in a permanent position at a fixed distance D3 from the outer shell of the body phantom. The transmit antenna Tx is moving
away from the Rx2 antenna towards the symmetry axis of the cylindrical body phantom. In other words while distance to the outer shell D3 remains constant the distance D2 changes.

Figure 68: Measurements scenarios using liquid body phantom
6 On-body Channel modelling for BANs

A common assumption is to define the radio channel as a composite of the linear wave interactions, which occur between a transmitting and a receiving antenna, and can be represented by means of a time-varying linear filter characterized by its impulse response $h(t; \tau)$, also known as input-delay spread function according to the classical Bello’s definition. A snapshot of $h(t; \tau)$ at observation time $t_n$ can be expressed as:

$$h(t_n; \tau) = \sum_{k=1}^{K(t_n)} a_k(t_n) e^{j \theta_k(t_n)} \delta(\tau - \tau_k(t_n))$$

(17)

where $a_k(t_n)$, $\theta_k(t_n)$ and $\tau_k(t_n)$ represent respectively the amplitude, phase and delay of the k-th path, while $K(t_n)$ is the total number of multi path components.

Imposing a limited rectangular bandwidth $B$, the discrete delays are combined into $L$ delays bins. When the delay separation between a number of paths $(\tau_i(t_n) - \tau_j(t_n))$ for $i, j = 1, 2, ..., N(t_n)$ is less than the bin separation $T = 1/B$, they cannot be resolved as distinct. As a consequence the resolved path is:

$$A_i(t_n) = \sum_{k=1}^{N(t_n)} d_k(t_n) e^{j \theta_k(t_n)}$$

(18)

The channel impulse response can be written as:

$$h(t_n; \tau) = \sum_{l=1}^{L(t_n)} A_l(t_n) \sin\{B(\tau - \tau_l(t_n))\}$$

(19)

where $\tau_l(t_n)$ are the discrete time bin. The time variant transfer function can be expressed as:

$$H(t; f) = \int_{-\infty}^{\infty} h(t; \tau) e^{-j 2\pi f \tau} d\tau$$

(20)

By integrating over the frequency we obtain the time dependent power transfer function averaged over the band of interest:

$$P(t) = \frac{1}{B} \int_{-B}^{B} |H(t; f)|^2 df$$

(21)

where $B$ is the bandwidth of interest. This quantity is often approximated by the RSSI signal at the receiver.

6.1 Results from the preliminary campaign

6.1.1 Channel gain model

For a given channel transfer function the total power, or channel gain, is given by:

$$G_0 = \frac{1}{T_{obs} B} \int_{-\infty}^{\infty} \int_{-B}^{B} |H(t; f)|^2 df dt$$

(22)

where $T_{obs}$ is the averaging observation period. The channel gain is a key parameter, which determines the signal-to-noise ratio, averaged over small-scale and large-scale
fading, which can be achieved by the wireless system. The averaging operation over the bandwidth supposes that all the dielectric constant of materials and all propagation phenomena related with, do not depend on the frequency. This assumption corresponds in a certain way to a WSS assumption in Bello’s definitions. In classical indoor and outdoor channels the $G_0$ is often expressed as a function of antenna separation. A number of studies in the literature investigated the channel gain, or equivalently the mean path loss, as a function of the antenna separation, by defining a path loss coefficient.

Here we use a “scenario-based” approach as explained above. We computed the channel gain by means of (22) for each scenario and we found a significant variation between different human subjects. These results can be easily explained by the fact that even if the antenna position is carefully reproduced on each human subject, the differences on body shape and dielectric proprieties yield to different path losses. From measurement results we found that the most appropriate way to describe $G_0$ is a log-normal distribution. As a consequence the channel gain in dB can be represented by a Gaussian random variable (r.v.):

$$G_{|dB} \sim N(\mu_0, \sigma_0)$$

(23)

where the mean value and standard deviation depend on the scenario S, as described above. The statistical analysis is here performed on the mean channel gain of different subjects, so that normal distribution accounts for the dissimilarities between human bodies. Some local micro-variations of the antenna emplacement due to dissimilar body shapes, produce also differences in mean channel gain, and their effect is taken into account by (23). In Table 19 and Table 20 we list the results for the investigated scenarios.

<table>
<thead>
<tr>
<th>RX</th>
<th>Anechoic chamber</th>
<th>Indoor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\mu_0$ [dB]</td>
<td>$\sigma_0$ [dB]</td>
</tr>
<tr>
<td>Chest</td>
<td>-60.8792</td>
<td>4.15</td>
</tr>
<tr>
<td>Thigh</td>
<td>-64.3146</td>
<td>1.5457</td>
</tr>
<tr>
<td>Right Wrist</td>
<td>-63.2105</td>
<td>2.6178</td>
</tr>
<tr>
<td>Right Foot</td>
<td>-67.1255</td>
<td>5.1838</td>
</tr>
<tr>
<td>Chest</td>
<td>-53.3737</td>
<td>7.8693</td>
</tr>
<tr>
<td>Thigh</td>
<td>-61.9708</td>
<td>6.4907</td>
</tr>
<tr>
<td>Right Wrist</td>
<td>-62.1787</td>
<td>5.9615</td>
</tr>
<tr>
<td>Right Foot</td>
<td>-68.6067</td>
<td>7.411</td>
</tr>
<tr>
<td>Chest</td>
<td>-52.7866</td>
<td>3.3482</td>
</tr>
<tr>
<td>Thigh</td>
<td>-59.121</td>
<td>4.4368</td>
</tr>
<tr>
<td>Right Wrist</td>
<td>-65.8698</td>
<td>4.3149</td>
</tr>
<tr>
<td>Right Foot</td>
<td>-71.2233</td>
<td>8.4303</td>
</tr>
</tbody>
</table>

Table 19: Channel gain parameters TX on Hip
As shown in Table 19 and Table 20 the dispersion on channel gain can be considerable especially in anechoic chamber (large $\sigma_{\mu S}$), where the propagation occurs mainly by creeping waves on-body, line-of-sight and by a small reflection on the ground. Moreover the path loss is stronger in the anechoic chamber, while in indoor the propagation occurs by multiple bounces (e.g; reflections, diffractions...) in the environment, which results into an additional energy contribution. This phenomenon is particularly clear when the receiving antenna is significantly masked by the human body. For instance in the Hip-Foot and Ear-Foot links we measured a channel gain up to 10 dB and 15 dB stronger in the indoor environment. We can remark a more important dispersion in the Hip-Chest and Ear-Hip links, showing a significant variability of the human body. When the antennas are placed on torso the propagation is mainly due to creeping waves and no “on-air” propagation occurs. Thus in these kinds of scenarios the body shape and composition plays a more important role, which yields to a large $\sigma_{\mu S}$.

### 6.1.2 Shadowing and fading model

It is well-known that one can distinguish a slow fading component $S(t_n)$ and a fast one $F(t_n)$ in the time-dependent power transfer function:

$$P(t_n) = G_0 \cdot S(t_n) \cdot F(t_n)$$

We extracted from our measurements the slow fading component by applying a low pass filter, practically realized by averaging the time-dependent power transfer function on a sliding temporal window.

The slow component is basically due to the shadowing by human body. As shown in Figure 69, the shadowing strictly depends on the movement condition. When the human subject does not move the slow component is quite moderated, since the shadowing condition basically remains identical. The shadowing also depends on the

<table>
<thead>
<tr>
<th>RX</th>
<th>Anechoic chamber</th>
<th>Indoor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\mu_{\mu S}$ [dB]</td>
<td>$\sigma_{\mu S}$ [dB]</td>
</tr>
<tr>
<td>Right Ear</td>
<td>-63.2533</td>
<td>6.3566</td>
</tr>
<tr>
<td>Hip</td>
<td>-60.1378</td>
<td>8.941</td>
</tr>
<tr>
<td>Right Wrist</td>
<td>-72.9014</td>
<td>2.6375</td>
</tr>
<tr>
<td>Right Foot</td>
<td>-70.3591</td>
<td>4.5385</td>
</tr>
<tr>
<td>Right Ear</td>
<td>-61.0003</td>
<td>2.7018</td>
</tr>
<tr>
<td>Hip</td>
<td>-57.9352</td>
<td>7.1715</td>
</tr>
<tr>
<td>Right Wrist</td>
<td>-71.855</td>
<td>2.9189</td>
</tr>
<tr>
<td>Right Foot</td>
<td>-72.9939</td>
<td>4.6507</td>
</tr>
<tr>
<td>Right Ear</td>
<td>-61.3644</td>
<td>3.649</td>
</tr>
<tr>
<td>Hip</td>
<td>-63.8337</td>
<td>7.545</td>
</tr>
<tr>
<td>Right Wrist</td>
<td>-71.9968</td>
<td>2.2282</td>
</tr>
<tr>
<td>Right Foot</td>
<td>-77.7146</td>
<td>3.4217</td>
</tr>
</tbody>
</table>

Table 20: Channel gain parameters TX on Ear
way of moving of each human subject. Figure 70 shows for instance that the amplitude of the slow component is larger in subject B than D, since one oscillates his arms more the other one, when walking. 

The statistical analysis on the slow component has been carried out on the time dependent samples $S(t_n)_{dB}$ of the whole population of the human subjects. It has been found that the shadowing in dB follows a normal distribution:

$$S(t_n)_{dB} \sim N(0, \sigma_{s5})$$  \hspace{1cm} (25)$$

where the standard deviation $\sigma_{s5}$ accounts for the slow variations of the power transfer function given by shadowing from human body, in a specific scenario.

![Figure 69: Time-variant power transfer function and slow fading in indoor: TX on Hip, 2.45 GHz band, still (left) and walking subject (right)](image)

![Figure 70: Shadowing for human subject B and D: Walking Hip-to-Wrist link](image)

In Table 21 and Table 22 we list the values of $\sigma_{s5}$ when TX is on Hip. As expected we have a larger standard deviation in moving scenario. It is interesting to notice that the larger variations around the mean value have been found in the walking case. The standard deviation of the running subject is smaller than the walking one, since people tend to keep arms close to the body, limiting their oscillating movement. Similarly, the legs’ movement is faster than in the walking scenario but, since the subject keeps standing on the same spot, the feet do not move backwards and forwards in a circular
arc with respect to the body axis. As a consequence the shadowing condition is less time-varying than in the walking scenario, which results into a smaller $\sigma_S$. Moreover the slow fading effect is smaller in indoor since the propagation occurs also by reflection on the surrounding environment, which somewhat mitigate the shadowing by human body. The two random variables describing the channel gain and shadowing are obtained by statistical analysis on human body variability and human body movement, so that it is reasonable to consider that they are uncorrelated. As a consequence the channel gain (in dB) presents a slow variation around the mean value $\mu_0$, which is described by a total variance $\sigma_{0S}^2 + \sigma_S^2$.

<table>
<thead>
<tr>
<th>Anechoic</th>
<th>TX on Hip</th>
<th>R ear</th>
<th>Hip</th>
<th>R Wrist</th>
<th>R Foot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Still</td>
<td>0.6329</td>
<td>0.4269</td>
<td>1.0185</td>
<td>0.4564</td>
</tr>
<tr>
<td></td>
<td>Walking</td>
<td>2.2892</td>
<td>5.4279</td>
<td>4.4565</td>
<td>5.2028</td>
</tr>
<tr>
<td></td>
<td>Running</td>
<td>2.3997</td>
<td>2.5117</td>
<td>3.6504</td>
<td>2.8322</td>
</tr>
<tr>
<td>Indoor</td>
<td>Still</td>
<td>0.638</td>
<td>0.2578</td>
<td>0.2706</td>
<td>0.2593</td>
</tr>
<tr>
<td></td>
<td>Walking</td>
<td>1.6049</td>
<td>3.486</td>
<td>2.7915</td>
<td>2.734</td>
</tr>
<tr>
<td></td>
<td>Running</td>
<td>2.0977</td>
<td>2.0965</td>
<td>2.5062</td>
<td>1.8854</td>
</tr>
</tbody>
</table>

Table 21: Shadowing parameters TX on Hip

<table>
<thead>
<tr>
<th>Anechoic</th>
<th>TX on Left Ear</th>
<th>R Wrist</th>
<th>R Foot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R ear</td>
<td>Hip</td>
<td>R Wrist</td>
</tr>
<tr>
<td></td>
<td>Still</td>
<td>0.7205</td>
<td>1.1237</td>
</tr>
<tr>
<td></td>
<td>Walking</td>
<td>0.7293</td>
<td>2.1193</td>
</tr>
<tr>
<td></td>
<td>Running</td>
<td>0.5409</td>
<td>2.9261</td>
</tr>
<tr>
<td>Indoor</td>
<td>Still</td>
<td>0.5768</td>
<td>1.5246</td>
</tr>
<tr>
<td></td>
<td>Walking</td>
<td>0.9393</td>
<td>2.2444</td>
</tr>
<tr>
<td></td>
<td>Running</td>
<td>0.7259</td>
<td>2.282</td>
</tr>
</tbody>
</table>

Table 22: Shadowing parameters TX on Ear

The shadowing effect discussed above, represents a large scale variation of the power transfer function which is mainly due to the masking effect by human body. Nevertheless a fast fading component is also present, as depicted in Figure 69. Obviously by integrating over a large bandwidth in (22) the fast fading is sensibly reduced. As a consequence here we focus on the power transfer function at single frequency at 2.45 GHz. The bandwidth is implicitly the one employed in measurements, i.e. 10 MHz. The slow fading is extracted by applying a sliding temporal window.

<table>
<thead>
<tr>
<th>Fast Fading</th>
<th>Slow Fading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chest</td>
<td>4.39</td>
</tr>
<tr>
<td>Thigh</td>
<td>6.93</td>
</tr>
<tr>
<td>R Wrist</td>
<td>6.54</td>
</tr>
<tr>
<td>R Foot</td>
<td>7.98</td>
</tr>
</tbody>
</table>

Table 23: Fading characteristics at 2.45 GHz (B =10 MHz): TX on Hip, Indoor, walking scenarios.
In Table 23 we report the slow and fast fading characteristics when the human subject walks in an indoor environment. The fading duration is computed as the average time below the mean value. Measurement results show that the fade duration can affect directly the single symbol transmission, while the shadowing can affect the packet one (Table 24).

Measurement results show that fast fading follows a Rice distribution:

$$pdf_f = \frac{\chi}{\sigma^2} \exp\left(-\frac{\chi^2 + v^2}{2\sigma^2}\right) I_0\left(\frac{\chi v}{\sigma^2}\right)$$

(26)

Where $I_0(\cdot)$ represents the modified Bessel function of the first kind with order zero, and $v_f$ and $\sigma_f$ are the parameters of the distribution. Figure 71 shows the good agreement of data and the Rice model, in the walking and running scenarios.

![Figure 71: Fast fading distribution in indoor: TX on Hip, walking (left) and running (right).](image)

In Table 24 we list the parameters of the Rice distribution of $|\chi(t)|$ obtained by Akaike method from measurement results. Results show a high $k$-factor ($K = v_f^2 / 2\sigma_f^2$) when the human subject does not move, which means that there is a main path with a strong energy contribution. As a consequence the channel experiment a little fast fading, which is mainly due to involuntary breathing movements. In walking scenarios, the $K$-factor is low, which results in a more important fast fading. For instance in the Hip-Foot link the nodes are often masked by the body and propagation occurs by reflection on surrounding environments. As a consequence $K$-factor is close to 0 and we can approximate the fading statistic with a Rayleigh distribution.

<table>
<thead>
<tr>
<th></th>
<th>Still</th>
<th></th>
<th></th>
<th>Walking</th>
<th></th>
<th></th>
<th>Running</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\nu_f$</td>
<td>$\sigma_f$</td>
<td>$K$</td>
<td>$\nu_f$</td>
<td>$\sigma_f$</td>
<td>$K$</td>
<td>$\nu_f$</td>
<td>$\sigma_f$</td>
<td>$K$</td>
</tr>
<tr>
<td>Chest</td>
<td>0.998</td>
<td>0.220</td>
<td>10.266</td>
<td>0.991</td>
<td>0.351</td>
<td>3.983</td>
<td>0.981</td>
<td>0.413</td>
<td>2.821</td>
</tr>
<tr>
<td>Thigh</td>
<td>0.999</td>
<td>0.210</td>
<td>11.328</td>
<td>0.923</td>
<td>0.566</td>
<td>1.331</td>
<td>0.944</td>
<td>0.533</td>
<td>1.568</td>
</tr>
<tr>
<td>R Wrist</td>
<td>0.998</td>
<td>0.114</td>
<td>38.424</td>
<td>0.962</td>
<td>0.519</td>
<td>1.720</td>
<td>0.901</td>
<td>0.943</td>
<td>0.900</td>
</tr>
<tr>
<td>R Foot</td>
<td>1.000</td>
<td>0.109</td>
<td>42.030</td>
<td>0.582</td>
<td>0.825</td>
<td>0.249</td>
<td>0.740</td>
<td>0.754</td>
<td>0.482</td>
</tr>
</tbody>
</table>

Table 24: Fading statistics at 2.45 GHz (B =10 MHz): TX on Hip, Indoor.
energy contribution the mean channel gain increases, as shown in the previous section. On the other hand, increasing the number of multi-path gives out an enhancement of fast fading. This effect is directly transposed on the statistic of $|\chi(t_n)|$. In Figure 72 we compare the K factor of the fast fading distribution in indoor and anechoic chamber. We can notice that the K factor in indoor is quite lower than in anechoic chamber, which describes a more important contribution of the non-line of sight components and consequently a larger fading.

![Figure 72 K factor in Walking scenarios: TX on hip (left) and on the left ear (right)](image)

### 6.1.3 Space-time slow fading correlation

In cooperative networks if the quality of communication is too low on a radio link, one can hop to a second link which presents a higher SNR with respect to the first one. This idea can also be used in BANs, when different sensors are placed on-body. Obviously one has to estimate the correlation between two different links, which undergo to different shadowing effects. To this aim, for a given scenario $S$ the correlation coefficient has been computed as follows:

$$
\rho_{i,j} = \frac{E[S_{TX,j} - E[S_{TX,j}]][S_{TX,j} - E[S_{TX,j}]]}{\sqrt{E[S_{TX,j}^2 - E[S_{TX,j}]^2][E[S_{TX,j}^2 - E[S_{TX,j}]]^2]}}
$$

(27)

where $S_{TX,j}$ represents the slow fading component in dB in the radio link associated to the TX transmitting antenna position and $i$-th receiving antenna position. The statistical mean operator $E$ has been applied on the samples $S(t_n)|_{dB}$, relative to the considered link, of the whole population of human subjects. So that the correlation coefficient defined above is obtained by a statistical analysis on the time-variant slow fading.

In Figure 73 we present the correlation coefficients at 2.45 GHz in indoor environments when transmitting antenna is on the Hip. Measurement results in anechoic chamber are not reported for sake of briefness, but they show that the correlation is only slightly higher than in indoor. This can be explained by the fact that only propagation around the body and reflection on the ground are present in anechoic chamber, but body movement is mainly responsible of slow fading. Shadowing correlation is relatively high when the human body does not move.
Nevertheless the small value of $\sigma_s$ reduces the correlation significance in Still scenarios. The scenarios which present high shadowing (generally when one antenna is on a limb) present the highest correlation. For instance in walking scenarios the Hip-Wrist, Hip-high and Hip-Foot are strongly correlated. It is very interesting to see that correlation is inverted for Wrist/Thigh and Wrist/Foot. This is due to the fact that the receiving antennas are all on right limbs while the transmitting antenna is on the left side. During a walk, humans tend to alternate the movement of legs and arms. As a consequence shadowing on right wrist is the opposite of shadowing on right thigh and right foot, while shadowing on foot and thigh follow the same temporal behaviour (as depicted in Figure 73. This macro effect is verified in both anechoic and indoor environments. Finally in running scenarios the shadowing on limbs are more correlated than shadowing on chest, but generally less correlated than in walking scenarios. This is due to the fact that the human subjects have less control on the synchronism of movements, which results into a higher asynchronism of shadowing thus a lower correlation.

![Figure 73: Correlation coefficients: TX on Hip](image)

### 6.1.4 Doppler spectrum modelling

In classical time-variant channel models, the mobility is often taken into account by a movement of the receiving antenna at speed $v$ with respect to the transmitting one. By considering that a small movement, corresponding to a time separation $\Delta t$, the amplitude and phase of the $k$-th MPC can be considered constant, while the phase variation is $\left(\frac{2\pi}{\lambda}\right) \cdot v \cdot \Delta t \cdot \cos \phi_k$. In the case of isotropic scattering, the received signals come from all directions with equal probabilities. The isotropic scattering model, also known as the Clarke's model, corresponds to the uniform distribution for the angle of arrival $\phi_k \in [-\pi, \pi]$. This assumption and hypothesis of uncorrelated scatters (US) yields to the classical Jake’s bath-tube like Doppler spectrum [101]. Previous works on indoor channel with fixed antennas and moving scenarios have highlighted Doppler behaviour different from the Jakes/Clarke model [102],[103]. In these scenarios the time variance of the channel is given by the people movement in the environment where the fixed antennas are placed. The Doppler spectrum in this case is centred around a mean value at 0 Hz and can be modelled by a Laplacian distribution [104].

In BANs the antennas are placed on-body, and the human subject is set free to move. The scatters are given by the surrounding environment and the human body itself. In
practical situations the antennas reciprocal positions do not vary significantly, while the scatters position, with respect to the TX-RX link, can change with the human movement. Thus the on-body channel can be assumed, in a first approximation, as a fixed TX-RX situation with moving scatters, producing the time variance of the channel. This assumption is quite correct when both transmitting and receiving antennas are placed on the torso or on the same limb, or, more generally, when there is a slight movement of the receiver antenna with respect to transmitter (e.g. Hip-Foot link, and arm swinging). In these cases the Doppler function is centred at $\nu = 0$ Hz. In anechoic chamber no scatters are present except the body itself. In Figure 74 we show the normalized Doppler Spectra at 2.4 GHz, when the human subject walks in anechoic chamber. When one antenna is on the torso and the other on a moving limb, the distance between TX and RX can change slightly. However the velocity of the receiving antenna with respect to the transmitting one is very low, and the time-variance is mainly given by the varying position of the scatters. As a consequence the Doppler function is still centred at $\nu = 0$, but it presents a smoother behaviour, as shown in Figure 74.

The difference between the levels of the floor when the receiving node is on the chest, with respect to the nodes on the limbs, can be explained by the increased degree of mobility in the latter case. Given this behaviour of the Doppler spectra it is useful to identify the bandwidths with respect to a threshold, e.g. -20 dB below the peak value at 0 Hz, instead of the maximum Doppler Shift. In Table 25 we list the results obtained from our measurements in anechoic chamber.

A rigorous mathematical formulation of Doppler spectrum from moving scatterers has been recently given in [105]. By assuming uniform scattering pattern and independence of scatterers, the Doppler spectrum can be decomposed by Bessel and Legendre functions. Instead of Laplacian distribution a simplified expression of the normalized Doppler spectrum can be the following:

$$D_{\text{on-body}}(\nu) = \frac{1}{\gamma + \nu^2}$$  \hspace{1cm} (28)
In Figure 74 we show the good approximation of this model with the measurement results, by using the values of listed in Table 25. A small value of $\gamma$ represents a modest degree of mobility, as in the Hip-Chest, Ear-Ear and Ear-Hip links.

<table>
<thead>
<tr>
<th>Radio link</th>
<th>$BW_{-20dB}$[Hz]</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip-Chest</td>
<td>1.5</td>
<td>0.004</td>
</tr>
<tr>
<td>Hip-Thigh</td>
<td>6.4</td>
<td>0.067</td>
</tr>
<tr>
<td>Hip-Wrist</td>
<td>7.3</td>
<td>0.094</td>
</tr>
<tr>
<td>Hip-Foot</td>
<td>10</td>
<td>0.231</td>
</tr>
<tr>
<td>L. Ear-R. Ear</td>
<td>0.3</td>
<td>0.013</td>
</tr>
<tr>
<td>L. Ear-Hip</td>
<td>1.3</td>
<td>0.007</td>
</tr>
<tr>
<td>L. Ear-Wrist</td>
<td>8</td>
<td>0.574</td>
</tr>
<tr>
<td>L. Ear-Foot</td>
<td>12.6</td>
<td>0.862</td>
</tr>
</tbody>
</table>

Table 25: Doppler Bandwidth at -20 dB and model parameter of on-body Doppler

Some important differences can be noticed when moving from the anechoic scenario to a realistic one. In Figure 75 we show the normalized average power of effective scattering distribution, for the Hip to Wrist channel in walking scenarios. When the human subject is in anechoic chamber, since no off-body scatterers are present, most of energy is concentrated around 3ns, which is close to time-of-flight between the node locations. The effective scattering distribution presents a high peak at the frequency Doppler $\nu = 0$. When human subjects are in indoor environment we can clearly identify some off-body scatterers, far away from the on-body ones. It is interesting to notice that the presence of these scatterers yields to no-symmetric scattering distribution. This is mainly due to the fact that the antennas are placed on the front side of the body. As a consequence the scatterers in a half space behind the body are strongly masked by the shadowing of the body itself.
Figure 75: Average power of effective scattering distribution in dB: Hip-Wrist link walking in anechoic chamber (up) and in office environment (down)

As depicted in Figure 76 the effect on the Doppler spectrum is a component at around 10 Hz when the Tx is on the Hip. This frequency is related to mobility of the human subject, who walks at about \( v = 0.7 \text{m/s} \). Since both transmitting and receiving antennas are moving at the same time the equivalent Doppler shift is twice the maximum shift at the frequency of interest. When the transmitter is on the Left Ear the shadowing effect from the body is different and the angular distribution of the off-body scatterers is not concentrated in half space like in the previous scenarios. As a consequence a Doppler component at positive frequencies is not present, and the main effect of on-body scatterers is to enlarge the -20 dB Doppler band around 0 Hz.
When a well-identified Doppler component is present, like in the on Hip scenario, is it possible to separate the off-body scatterer Doppler contribution from the purely on-body one. In these cases one can express the total Doppler Spectrum as the combination of two independents factors:

\[
D_{\text{TOT}}(v) = D_{\text{ON-BODY}}(v) \cdot D_{\text{OFF-BODY}}(v)
\]  

(29)

where \(D_{\text{ON-BODY}}\) is the component related to the on-Body scatterers, as in (28), and \(D_{\text{OFF-BODY}}(v)\) to the off-body ones. Obviously the factorization of these two components is a strong approximation, but it yields to a simple model. In the scenarios with TX on the Hip, it was found that the off-body presents a Gaussian shape in dB:

\[
D_{\text{OFF-BODY}}(v)_{\text{dB}} = D_0 \cdot \exp \left[ \frac{(v - v_m)^2}{2\sigma_v^2} \right]
\]  

(30)
In Figure 77 we show the good agreement between measurements and the model expressed in (29). Table 26 lists the parameters of Doppler Spectrum for some scenarios in indoor on-body channels. It is interesting to notice that the off-body component presents in all scenarios a mean value around 10 Hz, showing some reproducibility of the effect of the off-body scatterers.

![Normalized Doppler Spectra: human walking in Indoor, Hip- Wrist Channel](image)

**Figure 77: Normalized Doppler Spectra: human walking in Indoor, Hip- Wrist Channel**

<table>
<thead>
<tr>
<th>Radio link</th>
<th>$\gamma$</th>
<th>$D_0$</th>
<th>$\nu_m$ [Hz]</th>
<th>$\sigma_{\nu}$ [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip-Chest</td>
<td>0.0017</td>
<td>8.178</td>
<td>9</td>
<td>2</td>
</tr>
<tr>
<td>Hip-Thigh</td>
<td>0.358</td>
<td>4.920</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>Hip-Wrist</td>
<td>0.74</td>
<td>4.924</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>Hip-Foot</td>
<td>1.091</td>
<td>2.952</td>
<td>12</td>
<td>5</td>
</tr>
</tbody>
</table>

**Table 26: Doppler parameters in indoor**

The knowledge of Doppler Spectrum allows the quantification of how much broadening is imposed on the spectrum of signal, according to the rate of change in the channel state. In multi-path scenarios the Doppler shift of each path can be different from that of another path, which results into a Doppler spreading. The Doppler spread can be used to evaluate the time-variance of the channel and estimate the coherence time at 0.5 correlation threshold and shown in Figure 78, [106].

![Choerence time: TX on Hip (left), on Ear (right)](image)

**Figure 78: Choerence time: TX on Hip (left), on Ear (right)**
6.2 Full measurement campaign results

Starting from the same assumptions presented in the previous section, the studies performed on the acquired data aim at extracting a complete on-body channel model through the description of the three different components constituting the time-dependent channel power transfer function \( P(t) \). Considering the “scenario-based” approach, all the results presented will refer to a specific scenario \( S_{\text{On-Body}} \) that will be clarified every time when needed.

6.2.1 Channel gain model

The mean channel gain \( G_0 \) is here computed by means of (22), by considering \( T_{\text{obs}} \) is the duration of the acquisition set to 3 seconds, and \( B \) is the bandwidth considered equal to 10 MHz and centred on the carrier frequency 2.45 GHz.

In order to consider the variation on channel gain related to the characteristics of the body, it is more appropriate to describe the channel gain in dB giving its mean value (\( \mu_{0S} \)) and standard deviation (\( \sigma_{0S} \)) for every investigated scenario \( S_{\text{On-Body}} \).

Table 27, Table 28 and Table 29 list the values obtained, sorted by scenario. It’s worth to remember that channel model for the sitting/standing scenario and Tx on hip is not available, since measurements were not performed.

<table>
<thead>
<tr>
<th>Rxs</th>
<th>( \mu_{0S}[\text{dB}] )</th>
<th>( \sigma_{0S}[\text{dB}] )</th>
<th>( \mu_{0S}[\text{dB}] )</th>
<th>( \sigma_{0S}[\text{dB}] )</th>
<th>( \mu_{0S}[\text{dB}] )</th>
<th>( \sigma_{0S}[\text{dB}] )</th>
<th>( \mu_{0S}[\text{dB}] )</th>
<th>( \sigma_{0S}[\text{dB}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Walking</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right Thigh</td>
<td>-38,45</td>
<td>1,06</td>
<td>-38,65</td>
<td>1,15</td>
<td>-66,77</td>
<td>3,35</td>
<td>-62,72</td>
<td>2,41</td>
</tr>
<tr>
<td>Right Hand</td>
<td>-47,07</td>
<td>2,16</td>
<td>-49,47</td>
<td>1,2</td>
<td>-63,87</td>
<td>6</td>
<td>-60,15</td>
<td>5,79</td>
</tr>
<tr>
<td>Left Hand</td>
<td>-43,86</td>
<td>2,46</td>
<td>-42,97</td>
<td>3,19</td>
<td>-60,42</td>
<td>4,35</td>
<td>-58,35</td>
<td>1,5</td>
</tr>
<tr>
<td>Left Ear</td>
<td>-48,62</td>
<td>3,62</td>
<td>-46,82</td>
<td>4,57</td>
<td>-61,06</td>
<td>5,18</td>
<td>-60,48</td>
<td>3,5</td>
</tr>
<tr>
<td><strong>Sitting/Standing</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right Thigh</td>
<td>-39,45</td>
<td>1,59</td>
<td>-41,04</td>
<td>1,44</td>
<td>-63,96</td>
<td>5,36</td>
<td>-58,02</td>
<td>3,61</td>
</tr>
<tr>
<td>Right Hand</td>
<td>-46,54</td>
<td>2,46</td>
<td>-47,73</td>
<td>4,6</td>
<td>-58,41</td>
<td>2</td>
<td>-56,06</td>
<td>4,89</td>
</tr>
<tr>
<td>Left Hand</td>
<td>-43,52</td>
<td>2,35</td>
<td>-43,02</td>
<td>2,76</td>
<td>-54,62</td>
<td>3,07</td>
<td>-56,21</td>
<td>3,53</td>
</tr>
<tr>
<td>Left Ear</td>
<td>-48,34</td>
<td>2,43</td>
<td>-43,47</td>
<td>1,98</td>
<td>-63,07</td>
<td>2,72</td>
<td>-59,13</td>
<td>4,47</td>
</tr>
<tr>
<td><strong>Standing Still</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right Thigh</td>
<td>-38,75</td>
<td>0,92</td>
<td>/</td>
<td>/</td>
<td>-68,34</td>
<td>4,92</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Right Hand</td>
<td>-46,58</td>
<td>1,69</td>
<td>/</td>
<td>/</td>
<td>-66,25</td>
<td>6,17</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Left Hand</td>
<td>-42,12</td>
<td>1,87</td>
<td>/</td>
<td>/</td>
<td>-62,43</td>
<td>2,36</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Left Ear</td>
<td>-45,01</td>
<td>1,36</td>
<td>/</td>
<td>/</td>
<td>-60,96</td>
<td>2,27</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>

Table 27: Channel Gain values for scenarios where Tx is placed on Heart
The analysis has been performed gathering the mean channel gain of the four different subjects, so that the standard deviation $\sigma_{0S}$ accounts for the heterogeneity brought by the human bodies in terms of body shape and dielectric properties. Moreover, even if the nodes emplacement is carefully reproduced, some local micro-variations of their
position could produce differences in the mean channel gain values, which are also considered in $\sigma_{0S}$.

The numerical results presented in Table 27, Table 28 and Table 29 are useful in order to make some comparative considerations between the two different sets of antennas (for more details see Paragraph 4.1.2 and Paragraph 4.1.3) and the influence of the environments where the measurements have taken place.

First of all, it is possible to remark how the path loss is generally stronger when Planar Monopole antennas (PL Monopole) have been used, comparing to the case with Top Loaded Monopole (TL Monopole), as shown in Figure 79. As expected, the antenna with normal polarisation with respect to the body surface (TL Monopole) is more suited for On-Body applications, supporting the creeping-waves propagation over the body. This leads to higher values in terms of channel gain up to 22-25dB with respect to the ones found for tangentially polarised antennas (PL Monopole). This effect is particularly evident for those channels with a strong on-body propagation component and where no “on-air” propagation occurs, such as Heart-Thigh, Hip-Thigh and Ear-Ear links.

![Figure 79: $G_0$ comparison for different antenna sets](image)

For PL Monopoles it could also be pointed out that the dispersion on the channel gain is relevant especially in quasi-anechoic environment, where the $\sigma_{0S}$ values are larger than those found for the indoor scenario. Same considerations could not be drawn for the TL Monopole case, where the standard deviations are generally smaller than in the former case and the difference between indoor and anechoic environment is not so stressed. This is due to the fact that the presence of a ground plane makes the antenna less influenced but the human body.

The different behavior of the two sets of antennas in respect with the environment considered could be explained assuming that in anechoic chamber the propagation occurs mainly by creeping waves on-body and small reflection on the ground, and
these phenomena affects more the performances of tangentially polarized antennas, like the PL Monopole, than those of antennas with normal polarization.

It could also be noticed that, for the PL antenna, the mean path loss is stronger in the anechoic chamber than in indoor, because in the latter environment the multi-paths contribution due to reflections and diffractions from the environment is very significant, leading to an additional energy contribution. This trend is more evident when one of the nodes composing the link is considerably masked by the human body. For instance, channel gain stronger up to 10 dB in indoor than anechoic chamber have been measured for the Right Ear-Left Hand channel, where the whole body shadows the communication.

For the same reasons explained above, this is not at all valid for the TL Monopoles, where all the scenarios present almost the same values for the channel gain.

A graphical example is given in Figure 80:

![Figure 80: G0 values in different environment for PL Monopole (up) and TL Monopole (down)](image_url)
6.2.2 Shadowing and fast fading model

As pointed out in (24) the time-dependent power transfer function is also defined by a slow fading or shadowing $S(t)$ and a fast fading $F(t)$ components. In order to extract $S(t)$ from the data acquired, a low pass filter has been applied to $P(t)$, practically realised by averaging it on a sliding temporal window, letting the slow variations of this function to be followed.

![Figure 81: Time-variant power transfer function and slow fading component: standing still (up) and walking (down) conditions](image)

In wireless communications, the slow fading component accounts for the shadowing effect of some obstacles that obstruct the direct link between nodes. For the specific case of BANs this term is strictly connected to the shadowing produced by the human body itself, and heavily depends on the movement conditions. This effect is graphically represented in Figure 81 where it is possible to notice that when the subject stands still (up) in the same position, the shadowing component is almost
constant, and the only slight variations of $P(t)$ are due to the involuntary breathing movements. On the other side, the shadowing effect of the human body is stronger when the subject walks (down), in particular for those links where one node is placed on a limb. For example, focusing on the Hip-Right Hand link, it is possible to reconstruct the walking movement following the shadowing trend and considering that the subject swings his arms cyclically.

It is interesting to notice how Thigh and Hand links show negative correlation, as shown by red (Right Tight) and blue (Right Hand) lines in Figure 81. Their trends follow opposite pattern since, during a normal walk, hands swing opposite to the legs movements.

It is also worth noticing that every subject walks or, in general, moves in a different way, and this obviously affects the shadowing trend. This dispersion is more evident for those links where at least one of the nodes is placed on a limb (i.e. hand or thigh) and Figure 82 gives an example of how differently two subjects could move in walking (up) and sitting down/standing up (down) conditions.

![Graph showing shadowing trend](image1)

![Graph showing shadowing trend](image2)

**Figure 82:** Different subjects’ movement in walking (up) and sitting down/standing up (down) conditions. Heart-Hand link.

In order to completely describe the slow fading component $S(t)$, a statistical analysis has been performed gathering the acquired data of all the subject sorted by scenario
As in the previous section, it has been found that the shadowing in dB follows a normal distribution $S(t_n)_{dB} \sim N(0, \sigma_S^S)$, where the standard deviation $\sigma_S^S$ accounts for the slow variations of the power transfer function given by the shadowing from human body, in a specific scenario. As an example of the statistic given, Figure 83 presents the normal fitting obtained for the shadowing values in dB for the scenario with PL Monopole in anechoic chamber when the Tx is placed on the Hip.

The statistical description of the shadowing has been given through its standard deviation $\sigma_S^S$, as well as other characteristic parameters like the mean duration of the fade in ms, its mean depth in dB and the rate of appearance in $s^{-1}$. The characterisation has been performed for every combination of antenna, environment and moving condition, as reported in Table 30, Table 31, Table 32, Table 33, Table 34 and Table 35.
### Shadowing statistics - Top Loaded Monopole - Tx Heart

<table>
<thead>
<tr>
<th>Rxs</th>
<th>Walking</th>
<th></th>
<th></th>
<th>Sitting Down / Standing Up</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>σₜ</td>
<td>Duration [ms]</td>
<td>Depth [dB]</td>
<td>Rate [s⁻¹]</td>
<td>σₜ</td>
<td>Duration [ms]</td>
</tr>
<tr>
<td><strong>Anechoic Chamber</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right Thigh</td>
<td>1,07</td>
<td>554</td>
<td>-1,12</td>
<td>0,88</td>
<td>2,01</td>
<td>535</td>
</tr>
<tr>
<td>Right Hand</td>
<td>3,46</td>
<td>664</td>
<td>-5,53</td>
<td>0,58</td>
<td>2,15</td>
<td>713</td>
</tr>
<tr>
<td>Left Hand</td>
<td>3,67</td>
<td>540</td>
<td>-4,93</td>
<td>0,72</td>
<td>2,57</td>
<td>588</td>
</tr>
<tr>
<td>Left Ear</td>
<td>1,06</td>
<td>616</td>
<td>-0,97</td>
<td>0,72</td>
<td>1,12</td>
<td>706</td>
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<tr>
<td><strong>Indoor</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Right Thigh</td>
<td>1,4</td>
<td>488</td>
<td>-2,31</td>
<td>0,79</td>
<td>3,22</td>
<td>764</td>
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<tr>
<td>Right Hand</td>
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<td>517</td>
<td>-3,39</td>
<td>0,79</td>
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<tr>
<td>Left Hand</td>
<td>1,97</td>
<td>546</td>
<td>-3,28</td>
<td>0,75</td>
<td>2,83</td>
<td>590</td>
</tr>
<tr>
<td>Left ear</td>
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<td>404</td>
<td>-1,87</td>
<td>1</td>
<td>0,9</td>
<td>507</td>
</tr>
</tbody>
</table>

Table 30: Shadowing statistics for TL antenna Tx on Heart

### Shadowing statistics - Planar Monopole - Tx Heart

<table>
<thead>
<tr>
<th>Rxs</th>
<th>Walking</th>
<th></th>
<th></th>
<th>Sitting Down / Standing Up</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>σₜ</td>
<td>Duration [ms]</td>
<td>Depth [dB]</td>
<td>Rate [s⁻¹]</td>
<td>σₜ</td>
<td>Duration [ms]</td>
</tr>
<tr>
<td><strong>Anechoic Chamber</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right Thigh</td>
<td>3,2</td>
<td>536</td>
<td>-4,1</td>
<td>0,81</td>
<td>4,09</td>
<td>631</td>
</tr>
<tr>
<td>Right Hand</td>
<td>4,34</td>
<td>556</td>
<td>-6,1</td>
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<td>3,13</td>
<td>698</td>
</tr>
<tr>
<td>Left Hand</td>
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<td>660</td>
<td>-4,89</td>
<td>0,71</td>
<td>5,25</td>
<td>871</td>
</tr>
<tr>
<td>Left Ear</td>
<td>0,97</td>
<td>663</td>
<td>-0,93</td>
<td>0,67</td>
<td>1,15</td>
<td>702</td>
</tr>
<tr>
<td><strong>Indoor</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Right Thigh</td>
<td>1,82</td>
<td>322</td>
<td>-1,57</td>
<td>1,38</td>
<td>3,14</td>
<td>678</td>
</tr>
<tr>
<td>Right Hand</td>
<td>2,99</td>
<td>338</td>
<td>-1,98</td>
<td>1,42</td>
<td>4,42</td>
<td>688</td>
</tr>
<tr>
<td>Left Hand</td>
<td>4,21</td>
<td>612</td>
<td>-5,55</td>
<td>0,75</td>
<td>4,93</td>
<td>681</td>
</tr>
<tr>
<td>Left ear</td>
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<td>321</td>
<td>-1,88</td>
<td>1,25</td>
<td>2,39</td>
<td>542</td>
</tr>
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</table>

Table 31: Shadowing statistics for PL antenna Tx on Heart

### Shadowing statistics - Top Loaded Monopole - Tx Left Hip

<table>
<thead>
<tr>
<th>Rxs</th>
<th>Walking</th>
<th></th>
<th></th>
<th>Sitting Down / Standing Up</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>σₜ</td>
<td>Duration [ms]</td>
<td>Depth [dB]</td>
<td>Rate [s⁻¹]</td>
<td>σₜ</td>
<td>Duration [ms]</td>
</tr>
<tr>
<td><strong>Anechoic Chamber</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right Thigh</td>
<td>1,43</td>
<td>551</td>
<td>-1,77</td>
<td>0,75</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Right Hand</td>
<td>4,05</td>
<td>380</td>
<td>-4,58</td>
<td>1</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Left Hand</td>
<td>3,73</td>
<td>564</td>
<td>-5,27</td>
<td>0,67</td>
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<td>/</td>
</tr>
<tr>
<td>Left Ear</td>
<td>1,35</td>
<td>478</td>
<td>-1,87</td>
<td>0,84</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td><strong>Indoor</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right Thigh</td>
<td>1,01</td>
<td>345</td>
<td>-1,2</td>
<td>1,13</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
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<td>3,98</td>
<td>484</td>
<td>-5,04</td>
<td>0,84</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Left Hand</td>
<td>3,45</td>
<td>514</td>
<td>-4,33</td>
<td>0,84</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Left ear</td>
<td>2,79</td>
<td>397</td>
<td>-2,75</td>
<td>1</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>

Table 32: Shadowing statistics for TL antenna Tx on Left Hip
### Shadowing statistics - Planar Monopole - Tx Left Hip

<table>
<thead>
<tr>
<th>Rxs</th>
<th>Walking</th>
<th>Sitting Down / Standing Up</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma_s$</td>
<td>Duration [ms]</td>
</tr>
<tr>
<td><strong>Anechoic Chamber</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right Thigh</td>
<td>3.49</td>
<td>360</td>
</tr>
<tr>
<td>Right Hand</td>
<td>6.07</td>
<td>529</td>
</tr>
<tr>
<td>Left Hand</td>
<td>7.17</td>
<td>520</td>
</tr>
<tr>
<td>Left Ear</td>
<td>3.4</td>
<td>600</td>
</tr>
<tr>
<td><strong>Indoor</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right Thigh</td>
<td>3.05</td>
<td>560</td>
</tr>
<tr>
<td>Right Hand</td>
<td>3.76</td>
<td>730</td>
</tr>
<tr>
<td>Left Hand</td>
<td>7.22</td>
<td>506</td>
</tr>
<tr>
<td>Left ear</td>
<td>2.38</td>
<td>328</td>
</tr>
</tbody>
</table>

Table 33: Shadowing statistics for PL antenna Tx on Left Hip

### Shadowing statistics - Top Loaded Monopole - Tx Right Ear

<table>
<thead>
<tr>
<th>Rxs</th>
<th>Walking</th>
<th>Sitting Down / Standing Up</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma_s$</td>
<td>Duration [ms]</td>
</tr>
<tr>
<td><strong>Anechoic Chamber</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right Thigh</td>
<td>4.06</td>
<td>570</td>
</tr>
<tr>
<td>Right Hand</td>
<td>2.25</td>
<td>588</td>
</tr>
<tr>
<td>Left Hand</td>
<td>2.53</td>
<td>383</td>
</tr>
<tr>
<td>Left Ear</td>
<td>0.12</td>
<td>634</td>
</tr>
<tr>
<td><strong>Indoor</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right Thigh</td>
<td>3.17</td>
<td>379</td>
</tr>
<tr>
<td>Right Hand</td>
<td>2.89</td>
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<tr>
<td>Left Hand</td>
<td>1.72</td>
<td>306</td>
</tr>
<tr>
<td>Left ear</td>
<td>0.67</td>
<td>388</td>
</tr>
</tbody>
</table>

Table 34: Shadowing statistics for TL antenna Tx on Right Ear

### Shadowing statistics - Planar Monopole - Tx Right Ear

<table>
<thead>
<tr>
<th>Rxs</th>
<th>Walking</th>
<th>Sitting Down / Standing Up</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma_s$</td>
<td>Duration [ms]</td>
</tr>
<tr>
<td><strong>Anechoic Chamber</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right Thigh</td>
<td>2.91</td>
<td>345</td>
</tr>
<tr>
<td>Right Hand</td>
<td>2.42</td>
<td>545</td>
</tr>
<tr>
<td>Left Hand</td>
<td>6.4</td>
<td>613</td>
</tr>
<tr>
<td>Left Ear</td>
<td>0.67</td>
<td>855</td>
</tr>
<tr>
<td><strong>Indoor</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right Thigh</td>
<td>2.23</td>
<td>336</td>
</tr>
<tr>
<td>Right Hand</td>
<td>2.58</td>
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<tr>
<td>Left Hand</td>
<td>2.37</td>
<td>411</td>
</tr>
<tr>
<td>Left ear</td>
<td>2.15</td>
<td>501</td>
</tr>
</tbody>
</table>

Table 35: Shadowing statistics for PL antenna Tx on Right Ear
The data presented could draw to some interesting conclusions: in general the shadowing effect results smaller in indoor premises than in anechoic chamber, leading to smaller values of $\zeta$. This is reasonable considering that in indoor the propagation occurs also by reflections on the environment, which somehow mitigate the shadowing due to human body movement. This is true for all the links except for those where the receiver is placed on the left ear, probably due to the particular position of the node.

Figure 84 helps in better understanding the effect explained above. The particular examples refer to the PL Monopole used in walking scenario for the Tx placed on the Heart, it is possible to notice that the indoor shadowing, i.e. continuous lines, (Figure 84 up) is in general less varying) than in anechoic (down). This yields to (smaller value of the shadowing standard deviation. Figure 84 shows also that for Planar Monopole the path loss is stronger in anechoic chamber that in indoor environment, as stated at the end of Paragraph 6.2.1. On the other hand when moving from an anechoic chamber to an indoor scenario fast fading is obviously increased.

![Shadowing effect: indoor (up) and anechoic chamber (down)](image)
As far as the comparison between the two different set of antenna is concerned, it is possible to notice, from the values presented in the Tables above, that Planar Monopole antenna are generally characterised by a larger value of the standard deviation, meaning that they result more sensitive to the shadowing effect of the human body and to its movement, than TL antenna. This is also due to the fact that the TL monopole has a normal polarization with respect to the body-surface, which advantages the creeping waves. As a consequence the main path due to diffraction around the body is enhanced when using the TL antenna, and becomes predominant with respect to the other paths, which results in a smaller fading.

The last component that completes the channel model for the on-body scenario is the fast fading $F(t)$. It represents the remaining term in $P(t)$ once subtracting the slow varying component, represented by the term $G_0*S(t)$, and it accounts for all the contributions deriving from reflections or diffractions from the human body or the surrounding environment, as presented in Figure 80 or Figure 84.

From the comparison of the results in anechoic and indoor environments, both in moving or still conditions, it is evident how the latter location affects the time-varying power transfer function producing a more significant multipath effect represented by $F(t)$, as it was expected.

Considering that the fast fading could be expressed as $F(t) = |\chi(t)|^2$, measurements results show that $|\chi|$ follows a Nakagami distribution, which is defined through a shape and a spread parameters, respectively $\mu_F$ and $w_F$. A graphical example of the goodness of fit obtained is presented in Figure 85 for TL Monopole in walking conditions:

![Figure 85: Cumulative Distribution Function for Fast Fading component in Indoor for TL Antenna](image)

Table 36, Table 37, Table 38, Table 39, Table 40 and Table 41 list the values obtained for the statistical characterization of the fast fading as well as the mean duration of the fade in ms, its mean depth in dB and the rate of appearance in $s^{-1}$, for all possible scenarios:
### Fast fading statistics - Top Loaded Monopole - Tx Heart

|                    | Walking | |                    | Sitting Down / Standing Up | |
|--------------------|---------|----------------|---------------------------|-----------------------------|
| **Rx**             | **μF**  | **WF** | **Duration [ms]** | **Depth [dB]** | **Rate [s⁻¹]** | **μF** | **WF** | **Duration [ms]** | **Depth [dB]** | **Rate [s⁻¹]** |
| **Anechoic Chamber** |         |        |                  |                  |                |        |        |                  |                  |                |
| Right Thigh        | 67,6    | 1,01  | 118              | -0,6             | 3,88            | 26     | 1,01  | 112              | -0,74            | 0,49            |
| Right Hand         | 70,84   | 1,01  | 146              | -0,49            | 3,05            | 67,13  | 1,01  | 156              | -0,64            | 3,1             |
| Left Hand          | 61,34   | 1,01  | 190              | -0,64            | 2,05            | 88,93  | 1,01  | 144              | -0,57            | 3,63            |
| Left Ear           | 91,14   | 1      | 98               | -0,52            | 4,49            | 87,17  | 1,01  | 84               | -0,36            | 5,35            |
| **Indoor**         |         |        |                  |                  |                |        |        |                  |                  |                |
| Right Thigh        | 35,83   | 1,02  | 79               | -0,8             | 5,56            | 17,1   | 1,03  | 111              | -1,35            | 4,09            |
| Right Hand         | 11,14   | 1,05  | 69               | -1,53            | 6,31            | 19,75  | 1,04  | 86               | -1,27            | 5,14            |
| Left Hand          | 23,49   | 1,02  | 76               | -0,92            | 5,81            | 22,92  | 1,03  | 103              | -1,13            | 4,6             |
| Left Ear           | 8,99    | 1,06  | 63               | -1,81            | 7,02            | 39,64  | 1,02  | 77               | -0,87            | 6,06            |

Table 36: Fast Fading statistics for TL antenna Tx on Heart

### Fast fading statistics - Planar Monopole - Tx Heart

|                    | Walking | |                    | Sitting Down / Standing Up | |
|--------------------|---------|----------------|---------------------------|-----------------------------|
| **Rx**             | **μF**  | **WF** | **Duration [ms]** | **Depth [dB]** | **Rate [s⁻¹]** | **μF** | **WF** | **Duration [ms]** | **Depth [dB]** | **Rate [s⁻¹]** |
| **Anechoic Chamber** |         |        |                  |                  |                |        |        |                  |                  |                |
| Right Thigh        | 12,13   | 1,06  | 88               | -1,7             | 5,39            | 8,53   | 1,04  | 116              | -2,17            | 4,18            |
| Right Hand         | 57,29   | 1,01  | 71               | -0,73            | 6,22            | 99,18  | 1,01  | 90               | -0,41            | 5,06            |
| Left Hand          | 35,61   | 1,02  | 96               | -0,84            | 4,55            | 62,8   | 1,02  | 96               | -0,67            | 4,34            |
| Left Ear           | 101,62  | 1,01  | 51               | -0,43            | 8,74            | 124,38 | 1,01  | 49               | -0,37            | 9,15            |
| **Indoor**         |         |        |                  |                  |                |        |        |                  |                  |                |
| Right Thigh        | 2,13    | 1,27  | 52               | -4,56            | 9,06            | 5,41   | 1,1   | 88               | -2,8             | 5,6             |
| Right Hand         | 2,26    | 1,27  | 52               | -4,45            | 8,81            | 8,71   | 1,08  | 86               | -1,94            | 5,3             |
| Left Hand          | 3,3     | 1,16  | 56               | -3,54            | 8,06            | 8,37   | 1,06  | 85               | -1,69            | 5,47            |
| Left Ear           | 3,49    | 1,16  | 66               | -3,34            | 6,98            | 5,88   | 1,08  | 84               | -2,49            | 5,93            |

Table 37: Fast Fading statistics for PL antenna Tx on Heart

### Fast fading statistics - Top Loaded Monopole - Tx Left Hip

|                    | Walking | |                    | Sitting Down / Standing Up | |
|--------------------|---------|----------------|---------------------------|-----------------------------|
| **Rx**             | **μF**  | **WF** | **Duration [ms]** | **Depth [dB]** | **Rate [s⁻¹]** | **μF** | **WF** | **Duration [ms]** | **Depth [dB]** | **Rate [s⁻¹]** |
| **Anechoic Chamber** |         |        |                  |                  |                |        |        |                  |                  |                |
| Right Thigh        | 23,36   | 1,02  | 139              | -1,05            | 3,55            | /      | /      | /                  | /                  | /               |
| Right Hand         | 8,74    | 1,07  | 213              | -1,98            | 2,38            | /      | /      | /                  | /                  | /               |
| Left Hand          | 7,68    | 1,07  | 200              | -1,97            | 2,51            | /      | /      | /                  | /                  | /               |
| Left Ear           | 58,92   | 1,01  | 142              | -0,55            | 3,3             | /      | /      | /                  | /                  | /               |
| **Indoor**         |         |        |                  |                  |                |        |        |                  |                  |                |
| Right Thigh        | 16,28   | 1,03  | 110              | -1,36            | 4,09            | /      | /      | /                  | /                  | /               |
| Right Hand         | 4,52    | 1,07  | 78               | -3,06            | 6,14            | /      | /      | /                  | /                  | /               |
| Left Hand          | 15,51   | 1,03  | 116              | -2,18            | 4,59            | /      | /      | /                  | /                  | /               |
| Left Ear           | 7,7     | 1,07  | 72               | -2,17            | 6,52            | /      | /      | /                  | /                  | /               |

Table 38: Fast Fading statistics for TL antenna Tx on Left Hip
### Fast fading statistics - Planar Monopole - Tx Left Hip

<table>
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<th>Walking</th>
<th>Sitting Down / Standing Up</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>μF</td>
<td>wF</td>
</tr>
<tr>
<td>Anechoic Chamber</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right Thigh</td>
<td>2.8</td>
<td>1.18</td>
</tr>
<tr>
<td>Right Hand</td>
<td>4.42</td>
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<td>Left Ear</td>
<td>12.75</td>
<td>1.06</td>
</tr>
<tr>
<td>Indoor</td>
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<td></td>
</tr>
<tr>
<td>Right Thigh</td>
<td>3.19</td>
<td>1.16</td>
</tr>
<tr>
<td>Right Hand</td>
<td>3.41</td>
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<td>1.07</td>
</tr>
<tr>
<td>Left ear</td>
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<td>1.2</td>
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</table>

Table 39: Fast Fading statistics for PL antenna Tx on Left Hip

### Fast fading statistics - Top Loaded Monopole – Tx Right Ear

<table>
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<th>Rxs</th>
<th>Walking</th>
<th>Sitting Down / Standing Up</th>
</tr>
</thead>
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<td>μF</td>
<td>wF</td>
</tr>
<tr>
<td>Anechoic Chamber</td>
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<td></td>
</tr>
<tr>
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<td>Indoor</td>
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<td>1.26</td>
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<tr>
<td>Right Hand</td>
<td>4.46</td>
<td>1.12</td>
</tr>
<tr>
<td>Left Hand</td>
<td>1.84</td>
<td>1.33</td>
</tr>
<tr>
<td>Left ear</td>
<td>26.77</td>
<td>1.01</td>
</tr>
</tbody>
</table>

Table 40: Fast Fading statistics for TL antenna Tx on Right Ear

### Fast fading statistics - Planar Monopole - Tx Right Ear

<table>
<thead>
<tr>
<th>Rxs</th>
<th>Walking</th>
<th>Sitting Down / Standing Up</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>μF</td>
<td>wF</td>
</tr>
<tr>
<td>Anechoic Chamber</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right Thigh</td>
<td>3.91</td>
<td>1.13</td>
</tr>
<tr>
<td>Right Hand</td>
<td>59.9</td>
<td>1.04</td>
</tr>
<tr>
<td>Left Hand</td>
<td>4.62</td>
<td>1.12</td>
</tr>
<tr>
<td>Left Ear</td>
<td>137.9</td>
<td>1.01</td>
</tr>
<tr>
<td>Indoor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right Thigh</td>
<td>1.76</td>
<td>1.33</td>
</tr>
<tr>
<td>Right Hand</td>
<td>2.32</td>
<td>1.24</td>
</tr>
<tr>
<td>Left Hand</td>
<td>1.86</td>
<td>1.33</td>
</tr>
<tr>
<td>Left ear</td>
<td>3.57</td>
<td>1.15</td>
</tr>
</tbody>
</table>

Table 41: Fast Fading statistics for PL antenna Tx on Right Ear
It is interesting to notice how the values of the spread parameter characterising the Nakagami distribution are sensibly higher in the Top Loaded Monopole case. This means that there is a main path with stronger energy contribution and, as a consequence, the channel experiments less fast fading in comparison to the case when Planar Monopole are used.

Finally, comparing the values of the duration of the fading and shadowing dips, it is clear that the latter one is a long-term phenomenon that happens fewer times during the channel evolution (slow fading), while the former is short in time and its rate of appearance is higher due to the fact that it takes into account the fast variations of the time-varying channel, as already pointed out in previous paragraphs.

6.3 Frequency domain results on human phantom
The scenario of the radio propagation channel between the upper abdominal and the ears has been described in Section 5.5. In Figure 63 (a) the fixation points of the hearing aid antennas are marked as “1” and “2” and the insulin pump is fixed in point “P”. The receiving antenna is placed on the upper abdominal with constant HP and also tangential to the human body. Figure 63 (a) and (b) give detailed explanation on the antenna fixation points. The measurement results are shown in Figure 86. Black solid lines on the curves represent a moving average (with averaging factor of 20) to the raw measurement data. This allows us to mitigate some noise effects of the measurement equipment. As it can be seen in Figure 86 the mutual cross polarization and positions of Rx and Tx antennas give a spread in path gain of about 9 dB.

Figure 86: Measured path gain for the ear-to-upper abdominal channel

Figure 87 shows measured paths gains for different positions of the ear-chest channel. For the placed on-body antennas a practical scenario will be a mobile phone or mp3 player hanging on a lanyard which wirelessly communicates with a wireless headset worn at/in the ears. The minimum link budget requirement using dipole antennas is around 55 dB and maximum is reaching 70 dB.
The measured path gain results for a SAM phantom (Figure 88) and results simulated in HFSS (v.13) fall within the range from -45 to -50 dB. Some slight disagreement can be attributed to the impact of the measuring cable on the measurements and deviation in dielectric properties of the body simulating liquid used in measurements and simulations. A fair correspondence of simulation and measurement results suggests that such numerical model is capable facilitate a further design process of on-body communication antenna systems. The path loss is stronger in the anechoic chamber, while the measurement in conventional indoor conditions occurs to be quite oscillating over the frequency range. This is caused by multiple reflections in the environment, which results into an additional energy contribution to the path gain of the ear-to-ear link. Generally a channel gain up to 5-7 dB stronger in the indoor environment.
Figure 89 shows an anatomic numerical model used in HFSS in order to reproduce measurement results for ear-to-ear channel model. The topology of this numerical model is homogeneous and replicates the dimensions and the EM properties of the utilized SAM phantom. There is a good agreement between measurement and simulation at 2.45 GHz, which proves the validity of the developed numerical mode for HFSS simulations.

The aforementioned use cases are also characterized with the narrowband top-loaded monopoles described in Section 4.1.3. Generally the path gain is 3 to 10 dB better using the top-loaded monopoles rather than the planar dipoles. Additionally the top-loaded monopoles are less sensitive to the mutual positioning, as they by default having a normal to the human body polarization in all the application cases. Figure 91 illustrates measurement cases for the ear-to-ear links in different environments indoor and in an anechoic chamber. For the planar dipoles described in Section 2.4.1 it has been empirically derived that with antenna-body separation above 10 mm (which corresponds to about λ/10) the convergence of the measured and simulated return loss and input impedances are good. The top-loaded monopole described in Section 4.1.3 has been placed directly on the phantom surface.
During the first measurement one dipole is fixed on the left ear (Rx) and another (Tx) is moving to it over the head. The measured path gain is shown in Figure 92 for both co- and cross- polarization cases.

During the second measurement a simultaneous movement of antennas to the top of the head is performed. Their measured path gains are presented in Figure 93. In both measurements, the antennas are in mutual cross-polarization, when one antenna has a polarization parallel to the floor and the other has a perpendicular one. Otherwise, they are in mutual co-polarization when both antennas are having their polarization parallel to the floor.
One should keep in mind that all the measurements with the planar dipoles have the polarization tangential to the human surface. The cross-polarization decreases the measured path gain to about 10dB. A solution to mitigate such significant signal drop due to polarization mismatch is to use antennas with polarization normal to the human body surface. Therefore a third set of measurement was done using top-loaded monopoles, which radiate with polarization perpendicular to the human surface. The details on the design of this monopole are given in Section 4.1.3. The measured ear-to-ear path gain is generally higher 2-5 dB compared to the results obtained with planar dipoles. It is also worth to mention that the top-loaded monopoles were placed directly on the body, whereas the planar monopoles had an antenna-body separation of 10 mm. The measured top-loaded monopoles path gain can be seen in Figure 94.

![Figure 94: Measured path gain for the above-the-head distance dependencies for top-loaded monopoles](image)

In Figure 95 measures distance dependancy is shown when only one antenna is moving. This set of measurements has been performed with top-loaded monopoles and it is detailed in Figure 65 of Section 5.5. A positive interference is clearly seen in Figure 95. When antennas are at 9 cm from each other the path gain is about -45 dB,
while when they are at 30 cm, the path gain is approaching -20 dB. This 25 dB difference is caused by a destructive interference, when the distance between the antennas above the head and in front of the head are both about a multiple of $\lambda_0/2$. Hence we can draw a conclusion that the ear-to-ear propagation strongly depends on the relative dimensions of the head, as the received signal is a sum of waves that propagate above and around the head. Therefore is important to use an anatomically correct head model and not a geometrical sphere or an infinitely extended cylinder models.

Measurement done with one top-loaded monopole moving behind the head in Figure 96 reveals a similar fading in the propagation channel. A simultaneous movement of the top-loaded monopoles is presented in Figure 97 for in-front-of-the-head scenario, while in Figure 97 and Figure 98 the results for behind-the-head displacement are presented. The worse case scenario for the link budget using the top-loaded monopoles assumes about 45 dB channel losses. For the palnar monopoles however the losses reach 50 dB for the worst propagation condition.

![Figure 96: Measured by top-loaded monopoles path gain when only one antenna is moving behind the head](image1)

![Figure 97: Simultaneous movement of two top-loaded monopoles in front-of-the-head](image2)
Figure 98: Simultaneous movement of two top-loaded monopoles along behind-the-head path

Generally the measured path gain of the ear-to-ear channel is between -40 and -50 dB depending on mutual antennas placement and their type. The measurements on distance dependence revealed some instability with increase of distance, which is stipulated by constructive and destructive interference around the head. This interference effects are more pronounced for the “in front of the head” distance dependencies. These interference effects were also observed in literature. Finally, numerical model of the SAM phantom head was developed. The simulation results correspond well with the measurement.

Nevertheless the great variability of the human body is not taken into account by this model. So that the statistical model of sections 6.1 and 6.2 and the results on human phantom are both useful to get a complementary characterization of the on the on-body channel.
7 Off-Body Channel modelling for BANs

In this section we present a space-time varying channel model for Off-Body scenarios, where one end of the communication is stationary and placed outside the human body, while the other one is located on it in a specific position and moves according to the wearer movements.

The main idea that stands behind the analysis performed is to model the channel gain \( G(\text{dB}) \) extracting a main component dependent on the distance \( G_{d,\text{dB}} \) and/or on the angle between the body and the external gateway, plus a random variable \( F_{\text{dB}} \) that accounts for the movement of the subject and the environment considered, defining in that way a sort of fading contribution.

The model could be represented through the following:

\[
G(d)_{\text{dB}} = G_{d,\text{dB}} + F_{\mu B} = G(d_0)_{\text{dB}} + 10n \log_{10}(d/d_0) + F_{\mu B}
\]

where \( d_0 \) is the reference distance and is set equal to 1 m.

7.1 Distance-dependent model: LOS and NLOS conditions

In order to extract the distance dependent component of the channel gain \( G_{d,\text{dB}} \) some distance-discrete measurements have been performed, as fully described in Section 5.3, for both sets of antenna in LOS and NLOS conditions.

The LOS condition represents the scenarios where the subject stands in front of the external gateway acting as the transmitter, and the angle \( \alpha \) set between the body and the Tx antenna is considered equal to 0°.

On the contrary, in NLOS condition the subject stands with his backside facing the external transmitter, so that the body completely shadows the transmission, and \( \alpha \) is set to 180°.

The characterisation of \( G_{d,\text{dB}} \) is achieved extracting from the data acquired the values of \( G(d_0)_{\text{dB}} \) and \( n \), this last one considered as the path loss exponent. Figure 99 shows a graphical example of the analysis performed.

The vertical sets of crosses represent the data acquired during the measurements at each distance (from 1 to 4 meters far from the tx with a resolution of 0.25 m), while the continuous line is the log-distance fit that allows the evaluation of \( G(d_0) \) and \( n \) for each link.

Just looking at the graphs it is possible to drawn some general considerations: in the LOS case the dispersion of the acquired samples at a fixed distance is very limited, meaning that there is a main direct path that leads the propagation. On the opposite, NLOS scenarios are characterised by a significant dispersion of the data, up to 10-12 dB in indoor, due to the fact that the propagation occurs mainly by reflections or diffractions on the body (if in anechoic chamber) and/or on the surrounding environment (if in indoor).
Figure 99: $G_{0\text{db}}$ trends for TL Monopole LOS conditions (up) and PL Monopole NLOS conditions (down)

Table 42 and Table 43 give an overview on the results obtained respectively for the Planar Monopole and the Top Loaded Monopole cases and for all possible scenarios.

<table>
<thead>
<tr>
<th>Planar Monopole</th>
<th>Quasi-Anechoic Chamber</th>
<th>Indoor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LOS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$n$</td>
<td>$G(d_0)$</td>
</tr>
<tr>
<td>Rx Right Ear</td>
<td>-2,2</td>
<td>-63,48</td>
</tr>
<tr>
<td>Rx Heart</td>
<td>-1,99</td>
<td>-41,75</td>
</tr>
<tr>
<td>Rx Left Hip</td>
<td>-1,61</td>
<td>-50,11</td>
</tr>
</tbody>
</table>

Table 42: $G_0$ characterisation: $G(d_0)$ and $n$ values for Planar Monopole antennas
Top Loaded Monopole

<table>
<thead>
<tr>
<th>Quasi-Anechoic Chamber</th>
<th>Indoor</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOS</td>
<td>NLOS</td>
</tr>
<tr>
<td>( n )</td>
<td>( G(d_0) )</td>
</tr>
<tr>
<td>Rx Right Ear</td>
<td>-2.18</td>
</tr>
<tr>
<td>Rx Heart</td>
<td>-2.44</td>
</tr>
<tr>
<td>Rx Left Hip</td>
<td>-1.83</td>
</tr>
</tbody>
</table>

Table 43: \( G_0 \) characterisation: \( G(d_0) \) and \( n \) values for Top Loaded Monopole antennas

The values presented in tables could suggest some general considerations: the LOS case in anechoic premises presents a value of the path loss exponent \( n \) around -2, depending on the specific position of the receiver. This is in line to what has been expected, considering that for this scenario the propagation is mainly due to a Line of Sight component in the free space whose \( n \) value is commonly assumed to be equal to -2. The slight differences found could be referred to the body effect, the antenna used and the on-body position.

In indoor it is necessary to take into account the influence of the specific environment, and this could explain the higher variability of path loss exponent around the free space reference value.

In NLOS conditions, \( n \) generally assumes smaller values than in the LOS case; this is reasonable considering that when the body completely shadows the transmitting antenna from the receivers, the communication occurs mainly by multipath and there is no more main dominant LOS path. Naturally, this trend is more evident in indoor condition where the influence of the environment leads to a more significant multipath component. In this case \( n \) presents values around 0, meaning that the randomness of different contributions to the propagation globally remove the distance dependence.

As far as the \( G(d_0) \) value is concerned, when the user passes from LOS to NLOS condition the path loss could increase significantly, with a difference up to 31 dB in anechoic chamber. In indoor premises this phenomenon is still present even if slightly less intense with a channel gain decrease up to 23 dB.

In general Top Loaded antennas present lower values for the channel gain (up to 8dB less in anechoic and 7dB in indoor), but the trend is not confirmed by the link with the Rx on Heart. This phenomenon supports the idea that the specific node location and the antenna type play an important part in the definition of the channel characteristics. In particular when the TL monopole is on the heart or on the hip, the LOS path is in radiation pattern null, which gives higher losses.

When the antenna is on the Ear the TL monopole presents a non-null radiation pattern in both LOS and NLOS case. This evidently affects the propagation in a different way, and explain why \( G(d_0) \) has very close values in both LOS and NLOS.

In order to complete the characterisation of the Off-Body channel, the fading component \( F(t) \) has to be extracted and then statistically described.

Firstly, the distance dependent component previously described has been verified through the comparison with the data acquired in dynamic walking conditions (LOS and NLOS) both in anechoic and in indoor. Figure 100 shows the good agreement between the dynamic acquisitions and the fit for \( G_{0dB} \) extracted from the distance discrete measurements:
Then, the fading component has been computed subtracting the $G_{0|dB}$ component from the continuous measurements; considering that $F(t)$ could be expressed as $F(t) = |\chi(t)|^2$.

Measurements results show that $|\chi|$ follows a Nakagami distribution, which is defined through a shape and a spread parameters, respectively $\mu$ and $w$. A graphical example of the data fit to the proposed distribution is shown in Figure 101 for two different scenarios.

Figure 100: Comparison between the fit to distance-dependent component and dynamic acquisitions
Figure 101: Cumulative distribution function of the fading data $F(t)$: NLOS (up) and LOS (down) for TL Monopole

The study has been performed for all the possible scenarios combining the two antennas types, the different environments and the propagation conditions (LOS and NLOS). Table 44 and Table 45 present the whole sets of results obtained for the statistical characterisation of the fading, as well as the mean duration of the fade in ms, its mean depth in dB and the rate of appearance in s$^{-1}$. 
This project is funded by the European Commission under the 7th Research Framework Programme.

### Fading statistics - Planar Monopole

<table>
<thead>
<tr>
<th>Rxs</th>
<th>LOS Conditions</th>
<th>NLOS Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>μ</td>
<td>w</td>
</tr>
<tr>
<td>Anechoic Chamber</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rx Right Ear</td>
<td>1.04</td>
<td>0.66</td>
</tr>
<tr>
<td>Rx Heart</td>
<td>12.02</td>
<td>1.52</td>
</tr>
<tr>
<td>Rx Left Hip</td>
<td>11.43</td>
<td>1.04</td>
</tr>
<tr>
<td>Indoor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rx Right Ear</td>
<td>2.11</td>
<td>0.98</td>
</tr>
<tr>
<td>Rx Heart</td>
<td>5.48</td>
<td>0.73</td>
</tr>
<tr>
<td>Rx Left Hip</td>
<td>2.61</td>
<td>2.06</td>
</tr>
</tbody>
</table>

Table 44: Fading statistics for Planar Monopole Antenna

### Fading statistics – Top Loaded Monopole

<table>
<thead>
<tr>
<th>Rxs</th>
<th>LOS Conditions</th>
<th>NLOS Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>μ</td>
<td>w</td>
</tr>
<tr>
<td>Anechoic Chamber</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rx Right Ear</td>
<td>5.83</td>
<td>1.34</td>
</tr>
<tr>
<td>Rx Heart</td>
<td>2.74</td>
<td>1.08</td>
</tr>
<tr>
<td>Rx Left Hip</td>
<td>4.68</td>
<td>0.81</td>
</tr>
<tr>
<td>Indoor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rx Right Ear</td>
<td>2.15</td>
<td>0.76</td>
</tr>
<tr>
<td>Rx Heart</td>
<td>1.28</td>
<td>1.45</td>
</tr>
<tr>
<td>Rx Left Hip</td>
<td>1.46</td>
<td>1.49</td>
</tr>
</tbody>
</table>

Table 45: Fading statistics for Top Loaded Monopole Antenna
When moving from anechoic to indoor scenario, the values of the shape factor characterising the fading decrease. This is due to the fact that the increasing of the multipath component, related to the influence of the environment, enhances the fading, and this is directly transposed on its statistic, with a lower value of $\mu$ meaning a weaker main path propagation component.

The same consideration can be drawn for the comparison between LOS and NLOS conditions, where in the latter case the multipath is stronger than in the former due to the shadowing effect of the body and, as already explained, the propagation occurs mainly by reflected or diffracted waves.

To confirm this trend, the frequency of appearance of the fading, given by the rate values listed in tables, is sensibly higher when in indoor than in anechoic or when in NLOS than LOS case. In accordance to that, a higher fading rate is always followed by deeper fading phenomena (see depth [dB] values in tables).

As for the channel gain, the link involving the antenna on the Ear results to be peculiar. This is due to the particular shadowing condition and reciprocal antenna positions.

7.2 Angle dependent model: circular movement

In the previous paragraph it has been presented a model for the Off-Body channel where only the dependence on the distance $d$ from the external gateway has been taken into account.

This section is focused on the effect of body rotation, i.e. the angle set up between the subject and the transmitter antenna, which affects the propagation channel. An evaluation of the mean shadow effect due to the human body while it performs a complete 360° rotation (starting from LOS, $\alpha=0^\circ$) is performed.

For this kind of analysis circular, both static and dynamic, measurements have been used. A detailed description of the measurement set-up is given Paragraph 5.3. The circular static measurements performed allow the evaluation of the channel gain for every angular position with a step of 45°. For instance in Figure 102 we show the angular dependent path loss, when receiver is on the Ear (blue line), Heart (green line) and Hip (red line), for both antennas.
The vertical sets of crosses represent the acquired data at every angular step, from 0° to 360°, while the dashed line links the mean values of each group of acquisitions, representing a sort of mean shadowing effect of the body. As it could be expected, it appears clearly that the two sets of antennas are characterised by different shadowing trends, and this is due to the fact that their radiation pattern end polarization characteristics are significantly dissimilar. For details on the antenna sets see Chapter 4. The same considerations could be done also for the measurements performed in indoor, whose graph are not here presented only for the sake of briefness.

The analysis has been performed for every possible scenario, Table 46 and Table 47 list all the values obtained:
### Table 46: Shadowing effect for TL Monopole and PL Monopole in Indoor Environment

<table>
<thead>
<tr>
<th></th>
<th>Rx Right Ear</th>
<th>Rx Heart</th>
<th>Rx Left Hip</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>max / mean / std</td>
<td>max / mean / std</td>
<td>max / mean / std</td>
</tr>
<tr>
<td>0°</td>
<td>/ / /</td>
<td>0.22 / 1.21 / 0.2</td>
<td>/ / /</td>
</tr>
<tr>
<td>45°</td>
<td>-7.12 / -0.91 / -1.37</td>
<td>1.7 / 0.36</td>
<td>-2.4 / 10.15 / -7.77</td>
</tr>
<tr>
<td>90°</td>
<td>-3.26 / -6.75 / -0.58</td>
<td>1.22 / 1.53</td>
<td>-9.41 / 8.34</td>
</tr>
<tr>
<td>135°</td>
<td>-2.97 / -9.31 / -2.8</td>
<td>0.18 / 0.93</td>
<td>-25.68 / -1.03</td>
</tr>
<tr>
<td>180°</td>
<td>-2.5 / -3.47 / -3.68</td>
<td>0.86 / 1.68</td>
<td>-23.33 / -0.66</td>
</tr>
<tr>
<td>225°</td>
<td>2.6 / -9.04 / 1.12</td>
<td>1.43 / 0.8</td>
<td>-15.84 / 0.77</td>
</tr>
<tr>
<td>270°</td>
<td>9.63 / -4.45 / 9.53</td>
<td>0.61 / 0.35</td>
<td>-20.81 / 8.03</td>
</tr>
<tr>
<td>315°</td>
<td>9.07 / -10.33 / 9.14</td>
<td>0.27 / 3.39</td>
<td>-11.57 / 9.2</td>
</tr>
<tr>
<td>360°</td>
<td>3.81 / -3.02 / 4.09</td>
<td>0.12 / 0.64</td>
<td>-1.94 / -0.4</td>
</tr>
</tbody>
</table>

### Table 47: Shadowing effect for TL Monopole and PL Monopole in Quasi-Anechoic chamber

<table>
<thead>
<tr>
<th></th>
<th>Rx Right Ear</th>
<th>Rx Heart</th>
<th>Rx Left Hip</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>max / mean / std</td>
<td>max / mean / std</td>
<td>max / mean / std</td>
</tr>
<tr>
<td>0°</td>
<td>/ / /</td>
<td>0.43 / 0.1</td>
<td>/ / /</td>
</tr>
<tr>
<td>45°</td>
<td>2.37 / -4.6 / -4.65</td>
<td>0.24 / 0.09</td>
<td>-13.48 / 9.06</td>
</tr>
<tr>
<td>90°</td>
<td>-1.96 / -7.74 / -7.95</td>
<td>0.24 / 0.12</td>
<td>-17.3 / 6.53</td>
</tr>
<tr>
<td>135°</td>
<td>6.18 / -9.02 / -9.32</td>
<td>0.07 / 0.23</td>
<td>-26.41 / -5.06</td>
</tr>
<tr>
<td>180°</td>
<td>10.8 / -2.12 / 11.87</td>
<td>0.05 / 0.2</td>
<td>-24.55 / -10.99</td>
</tr>
<tr>
<td>225°</td>
<td>2.42 / -3.56 / 2.68</td>
<td>0.43 / 1.24</td>
<td>-23 / -7.89</td>
</tr>
<tr>
<td>270°</td>
<td>19.84 / -3.37 / 20.66</td>
<td>0.14 / 0.88</td>
<td>-7.06 / 2.33</td>
</tr>
<tr>
<td>315°</td>
<td>20.06 / -5.71 / 20.94</td>
<td>0.17 / 0.96</td>
<td>0.7 / 4.52</td>
</tr>
<tr>
<td>360°</td>
<td>7.38 / -0.41 / 8.06</td>
<td>0.24 / 0.09</td>
<td>1.86 / -0.49</td>
</tr>
</tbody>
</table>

This project is funded by the European Commission under the 7th Research Framework Programme.
Every row represents an angular position, while the columns present the maximum value of the channel gain, its mean and standard deviation normalized to the results obtained for $\alpha=0^\circ$ (first row). The aim is to define an additional loss contribution that could be added to the distance dependent component of the global channel gain ($G_0\,\text{dB}$); this additional term takes into account the angular shift of the body with respect to the position of the external transmitter.

As to confirm the fact that the two sets of antenna behave in a different way while the subject moves circularly, the values in the Max and Mean columns of PL and TL present completely different trends. In order to verify the reliability of the data acquired in the static circular measurements, a comparison with the dynamic circular acquisitions has been performed. Figure 103 shows the good agreement between the two sets of measurements. The dashed line links the mean value of the discrete samples, whereas the dotted curve represents the continuous acquisition while the subject moves circularly. To better compare the curves, a mean shadowing effect component has been extracted from the dynamic data averaging them on a sliding temporal window of a proper size (continuous line). The trends of the dashed and the continuous line result to be very similar, despite the loss of synchronism while performing the dynamic circular walk. This confirms the reliability of the results obtained for the characterization of the body effect in function of the angle.

*Figure 103: Comparison between body shadowing effect computed from static and dynamic measurements*

This project is funded by the European Commission under the 7th Research Framework Programme.
Additionally, dynamic circular walks have been realised at different distances (2m, 3m and 4m far from the external transmitter). Figure 104 shows that the trend of the body shadowing remains always the same no matter which is the distance it is referred to. The variation of the channel gain values as a function of the distance results to be in good accordance with the results previously presented and listed in Table 42 and Table 43 for $\alpha = 0^\circ$ and $\alpha = 180^\circ$.

![Figure 104: Comparison of the body shadowing effect at different distances for the PL Monopole case](image-url)
8 Body-to-Body Channel modelling for BANs

In this section we present a space-time varying channel model for body-to-body scenarios, where each end of the communication channel is “worn” by a different human subject and located in a specific on-body position.

The main idea that stands behind the analysis performed is to model the channel gain \( G_{|dB} \) extracting a main component dependent on the distance \( G_{0|dB} \) plus a random variable \( F_{|dB} \) that accounts for the movement of the subject and the environment considered, defining in that way a sort of fading contribution. The model could be represented through the following:

\[
G(d)_{|dB} = G_{0|dB} + F_{|dB} = G(d_0)_{|dB} + 10n\log_{10}(d/d_0) + F_{|dB}
\]  

where \( d_0 \) is the reference distance and is set equal to 1 m.

8.1 Channel gain and fading model

As fully described in Section 5.4, in order to extract the distance dependent component of the channel gain \( G_{0|dB} \) different sets of measurement have been realised while one subject walks towards (LOS) or backwards (NLOS) the other one who stands still in the meantime, for both sets of antenna but just in indoor premises. Figure 105 gives two examples of the acquisitions obtained: the one on the top represents LOS conditions while the other one NLOS. It is clear that the latter case suffers more from a fading effect with respect to the former one. When one subject walks backward the other one (NLOS), the entire body stands in between the transmitters and the receivers and the propagation occurs mainly by reflections and diffraction on the body and/or on the environment; this leads to a more significant multipath effect, strictly related to the fading component.
In order to characterise the distance dependent component of the channel gain it is necessary to evaluate $G(d_0)$ and $n$, respectively the channel gain at the reference distance $d_0$ and the path loss exponent. Those values have been extracted using a polynomial fitting of the data acquired. The results are listed in Table 48 and Table 49 for all the possible body-to-body scenarios and a graphical example is given in Figure 105, where the black line represents the log-distance fit.

<table>
<thead>
<tr>
<th>Planar Monopole - Indoor</th>
<th>Tx Right Hip</th>
<th>Tx Left Thigh</th>
<th>Tx Right Hand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$n$</td>
<td>$G(d_0)$</td>
<td>$n$</td>
</tr>
<tr>
<td><strong>LOS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rx Left Ear</td>
<td>-1,14</td>
<td>-56,8</td>
<td>-0,75</td>
</tr>
<tr>
<td>Rx Right Hip</td>
<td>-3,33</td>
<td>-37,88</td>
<td>-1,68</td>
</tr>
<tr>
<td>Rx Heart</td>
<td>-1,14</td>
<td>-54,02</td>
<td>-1</td>
</tr>
<tr>
<td><strong>NLOS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rx Left Ear</td>
<td>-0,8</td>
<td>-70,59</td>
<td>-0,82</td>
</tr>
<tr>
<td>Rx Right Hip</td>
<td>-1,15</td>
<td>-66,33</td>
<td>-0,67</td>
</tr>
<tr>
<td>Rx Heart</td>
<td>-0,67</td>
<td>-70,77</td>
<td>-0,46</td>
</tr>
</tbody>
</table>

Table 48: $G_0$ characterisation: $G(d_0)$ and $n$ values for Planar Monopole antennas

Figure 105: Examples of acquired data while one subject performs a walk towards (up) and backwards (down) the other one
Table 49: $G(d_0)$ characterisation: $G(d_0)$ and $n$ values for Top Loaded Monopole antennas

<table>
<thead>
<tr>
<th></th>
<th>$n$</th>
<th>$G(d_0)$</th>
<th>$n$</th>
<th>$G(d_0)$</th>
<th>$n$</th>
<th>$G(d_0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LOS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rx Left Ear</td>
<td>-0.95</td>
<td>-52.97</td>
<td>-1.33</td>
<td>-52.9</td>
<td>-1.2</td>
<td>-48.34</td>
</tr>
<tr>
<td>Rx Right Hip</td>
<td>-1.7</td>
<td>-46.89</td>
<td>-1.99</td>
<td>-47.1</td>
<td>-1.86</td>
<td>-45.2</td>
</tr>
<tr>
<td>Rx Heart</td>
<td>-2.19</td>
<td>-44.85</td>
<td>-2.57</td>
<td>-41.67</td>
<td>-2.46</td>
<td>-43.7</td>
</tr>
<tr>
<td><strong>NLOS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rx Left Ear</td>
<td>-0.77</td>
<td>-60.3</td>
<td>-0.92</td>
<td>-59.76</td>
<td>-0.7</td>
<td>-58.06</td>
</tr>
<tr>
<td>Rx Right Hip</td>
<td>-1.47</td>
<td>-55.47</td>
<td>-1.28</td>
<td>-56.77</td>
<td>-1.01</td>
<td>-56.53</td>
</tr>
<tr>
<td>Rx Heart</td>
<td>-1.64</td>
<td>-56.1</td>
<td>-1.99</td>
<td>-53.86</td>
<td>-1.91</td>
<td>-52.46</td>
</tr>
</tbody>
</table>

From the data presented above some general considerations could be drawn: first of all the path loss exponent significantly decreases when switching from LOS to NLOS scenario, meaning that the multipath phenomenon that greatly affect the propagation in the latter case reduces the distance dependence of the mean channel gain. This behavior is true for both the sets of antenna used, even if it is more stressed for the Planar Monopoles, and not always valid for the link which involves the ear. As already stated, this channel is kind of particular, considering that LOS and NLOS conditions are not referred to a complete masking effect of the body, but are equivalent just to an inversion of the antenna position, from right side of the head to the left side.

Another observation that could be done is that the values of $n$ strongly depends on the specific position of the receiver more than that of the transmitter, this could be explained by the fact that the three Txs are placed approximately on the same horizontal line, i.e. barely at the same height from the floor, so the different position of the Rxs play a more important role in the channel performances. To confirm this assumption, if looking to a single row (both in LOS or NLOS), the $n$ values are very similar for the three transmitters, with a maximum dispersion of 0.35 in the worst case. To generalize this conclusion, it is possible to say that the path loss exponent strongly depends on the specific relative position of the ends of the communication links.

As far as the $G(d_0)$ value is concerned, when the user passes from LOS to NLOS condition the path loss could increase significantly, with a difference up to 29 dB for PL monopole, and 12 dB for TL Monopoles.

In general, Top Loaded antennas present higher values for the channel gain (up to 14dB more), but this is not true for a couple of links (i.e. Hip-Hand and Hip-Hip) confirming that the specific node location and the antenna type play an important part in the definition of the channel characteristics.

In order to complete the characterisation of the body-to-body channel, the fading $F(t)$ has to be extracted and then statistically described.

It has been calculated subtracting the distance dependent component $G_0|dB$, defined through the values listed in Table 48 and Table 49, from the data acquired through the dynamic measurements.

The analysis results show that fast fading follows a Nakagami distribution, which is defined through a shape and a spread parameters, respectively $\mu$ and $w$. Figure 106
shows a graphical examples of distribution fit obtained in for two different scenarios, respectively LOS and NLOS for Top Loaded Monopole.

Figure 106: Cumulative distribution function of the fading data $F(t)$: LOS (up) and NLOS (down) for TL Monopole

The study has been performed for all the possible scenarios combining the two antenna types and the propagation conditions (LOS and NLOS). Table 50 and Table 51 present the whole sets of results obtained for the statistical characterisation of the fading, as well as the mean duration of the fade in ms, its mean depth in dB and the rate of appearance in $s^{-1}$.
### Table 50: Fading statistics for Planar Monopole Antenna

<table>
<thead>
<tr>
<th>Rxs</th>
<th>LOS Conditions</th>
<th>NLOS Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rate $[s^{-1}]$</td>
<td>Duration $[ms]$</td>
</tr>
<tr>
<td>Tx Right Hip</td>
<td>1,05</td>
<td>2,06</td>
</tr>
<tr>
<td>Rx Right Hip</td>
<td>0,62</td>
<td>1</td>
</tr>
<tr>
<td>Rx Left Ear</td>
<td>0,59</td>
<td>1,77</td>
</tr>
<tr>
<td>Rx Heart</td>
<td>1,15</td>
<td>2,31</td>
</tr>
<tr>
<td>Rx Left Ear</td>
<td>0,76</td>
<td>2,37</td>
</tr>
<tr>
<td>Rx Heart</td>
<td>0,75</td>
<td>1,83</td>
</tr>
<tr>
<td>Rx Left Ear</td>
<td>0,9</td>
<td>2,74</td>
</tr>
</tbody>
</table>

### Table 51: Fading statistics for Top Loaded Monopole Antenna

<table>
<thead>
<tr>
<th>Rxs</th>
<th>LOS Conditions</th>
<th>NLOS Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rate $[s^{-1}]$</td>
<td>Duration $[ms]$</td>
</tr>
<tr>
<td>Tx Right Hip</td>
<td>0,95</td>
<td>3,57</td>
</tr>
<tr>
<td>Rx Right Hip</td>
<td>0,93</td>
<td>2,94</td>
</tr>
<tr>
<td>Rx Left Ear</td>
<td>0,92</td>
<td>3,29</td>
</tr>
<tr>
<td>Rx Heart</td>
<td>1,1</td>
<td>4,63</td>
</tr>
<tr>
<td>Rx Left Ear</td>
<td>0,98</td>
<td>4,31</td>
</tr>
<tr>
<td>Rx Heart</td>
<td>1,31</td>
<td>3,66</td>
</tr>
<tr>
<td>Rx Left Ear</td>
<td>1,93</td>
<td>4,67</td>
</tr>
<tr>
<td>Rx Heart</td>
<td>0,94</td>
<td>3,43</td>
</tr>
<tr>
<td>Rx Left Ear</td>
<td>0,89</td>
<td>4,8</td>
</tr>
</tbody>
</table>

It is interesting to notice that moving from LOS to NLOS scenario, the shape parameter slightly decrease, but, differently from the Off-Body case previously considered.
Nevertheless, to confirm the more significant fading contribution when the subject is in NLOS conditions, fades result to be more frequent than in LOS (up to 7,5 times per seconds), as well as deepest, with a mean value up to -11 dB in the worst case.

A second set of measurements has been performed in order to quantify the average body shadowing effect on the channel performances. The data has been acquired while one subject stands still and the other one performs a complete rotation, starting from LOS ($\alpha=0^\circ$), passing to NLOS conditions ($\alpha=180^\circ$) and finishing in the starting position ($\alpha=360^\circ$). The moving subject wears the Tx only in the Heart position and the circular walks have been repeated at difference distance from the still user (1m, 3m, 5m, 7m), for more details see Paragraph 5.4.

The mean body masking effect has been calculated averaging the samples recorded over a temporal sliding window of a proper size, following the slow variations of the curves. An example of the results obtained is presented in Figure 107.

![Shadowing Effect - Planar Monopole - Indoor - Tx Heart - Rx Heart](image1)

![Shadowing Effect - Top Loaded Monopole - Indoor - Tx Heart - Rx Heart](image2)

**Figure 107:** Mean shadowing effect of the body for PL Monopole (up) and TL Monopole (down) in function of the distance with the Rx placed on the Heart
The dashed lines represent the acquired data while the subject performs the dynamic circular movement, each one related to a particular distance, whereas the continuous curves refers to the averaged contribution, representing the shadowing effect of the body.

It is possible to notice that the two sets of curves, related to the different antenna types, present quite similar trends, even if the ones obtained for PL Monopole show a deepest dip, meaning that they suffer from a stronger shadowing when moving from LOS to NLOS conditions.

This phenomenon is also confirmed in Table 52, where the values for the mean body shadowing effect are listed. They have been computed as the mean difference between the maximum and minimum values of the slow varying curves shown in Figure 107.

Except for the case where the Rx is placed on the Ear, Planar Monopole generally present a higher value of the mean shadowing in respect to what has been found for Top Loaded antennas.

| Mean Shadowing Effect [dB] - Dynamic Circular - Tx Heart - Indoor |
|------------------------|--------|--------|--------|--------|
|                        | 1 meter| 3 meter| 5 meter| 7 meter|
| Planar Monopole        |        |        |        |        |
| Rx Right Ear           | 18,69  | 16,5   | 15,23  | 13,7   |
| Rx Heart               | 23,5   | 17,23  | 19,71  | 21     |
| Rx Left Hip            | 23,39  | 16,84  | 19,18  | 17,36  |
| Top Loaded Monopole    |        |        |        |        |
| Rx Right Ear           | 19,6   | 14,32  | 15,2   | 13,57  |
| Rx Heart               | 14,24  | 13,97  | 14,12  | 15,5   |
| Rx Left Hip            | 17,44  | 15,4   | 11,42  | 14,83  |

Table 52: Mean shadowing body effect for the two sets of antenna as a function of the distance

Finally, another consideration that could be drawn from Figure 107 is that the trend of the channel gain as a function of the angle is not strictly dependent on the distance at which the movement has been performed. For both the antenna sets, the curves present in fact approximately the same trends. However, the depth of the fade could vary in function of the distance considered, as shown in Table 52.

Considering that the transmitter is not located in the same position as for the previously illustrated measurements, it is not so easy to make a direct comparison between the values in Table 52 and those in Table 42 and Table 43. Anyway, considering the reference distance of 1 meter, it is possible to notice a good agreement between the data that reveals a very similar shadowing effect, with a relatively small dispersion mainly due to the different node emplacement.
9 In-body channel model

In this section the simulation models for the in-body propagation is presented and compared with the measurements using the planar dipole. All the simulation results are obtained by using a simplified dipole antenna in order to be able to use available computational resources. The dipole is tuned to have a resonance frequency at 2.45 GHz. It is a classical wire dipole with wire radius of about 1 mm and a total length of the two arms of 5.51 cm. The dipole has a protective radome in order to isolate it from a direct contact with the. The numerical human phantom is a solid cylinder filled with body simulating liquid which represents a homogeneous body tissue. The body simulating liquid is modeled with tabulated dielectric properties at 2.45 GHz, which are: permittivity = 52.7, conductivity = 1.95 Siemens/m and loss tangent = 0.24.

The first simulation scenario is somewhat idealistic, as it assumes the body tissues evenly surrounding one immersed dipole and the other one remains in free space at a constant separation distance of 58 cm. The topology of the simulation setup is depicted in Figure 108. The simulated path loss for this scenario is given in Figure 109.

![Simulation model for the dipole evenly surrounded by body tissues](image1)

Figure 108: Simulation model for the dipole evenly surrounded by body tissues

![Simulated path loss for the dipole evenly surrounded by body tissues](image2)

Figure 109: Simulated path loss for the dipole evenly surrounded by body tissues
The next two simulation scenarios have already been described in Section 5.5. For both of the ideal wire dipoles are utilized with an air radome, which is an air shell of 1 mm entirely surrounding the antenna. The simulation model is detailed in Figure 110 (left) and its simulated path gain results are given in Figure 110 (right).

![Figure 110: Simulation of the S21 parameter for one antenna placed in free space and the other one inside the phantom: simulation setup (left) path gain results (right)](image)

The simulation campain when both antennas are inside the body phantom is depicted in Figure 111 (left). The simulation results for the path gain are given in Figure 111 (right). The receive antenna was placed with distance of 1 cm from the outer shell of the phantom, while the transmit antenna was moved with 1cm steps away from the receive antenna inside towards the phantom symmetry axis.

![Figure 111: Simulation of the S21 parameter for both antennas placed inside the phantom: simulation setup (left) path gain results (right)](image)

Generally, the expression for the maximum gain $G(dB)$ at a given distance $X$ can be describe by the following expression:

$$G(dB) = G_{\text{antenna\_air}}(dB) - \text{Setup\_Const} - LF \cdot (X - 1)$$

(33)
where $G_{\text{antenna \_air}}$ is antenna gain in dB measured in free space. The variable $\text{Setup\_Const}$ is defined by the topology and initial distances of the existing measurement or simulation setup. For instance the distance of the antenna placed outside of the body phantom has a the free space loss which shows a square law dependence on both frequency and distance. Finally, $LF$ is a loss factor stipulated by the propagation losses in the muscle simulating liquid at a given frequency.

From the simulation results shown in Figure 108 and in Figure 111 an averaged expression for the maximum gain at 2.45 GHz can be derived using:

$$G(\text{dB}) = G_{\text{antenna \_air}}(\text{dB}) - 14.1 - 2.5*(X-1)$$

The measurements campaigns for evaluating the in-body propagation channel were performed with the planar dipoles. These dipoles have to be prevented from a direct contact with the body simulating liquid. As it was derived earlier the radome of 1 cm all around the antenna will keep the dipoles impedances and radiation properties with similar values to those of free space. Figure 112 shows the dipole antenna enclosed with a Styrofoam material with thickness of 1 cm. The dielectric constant of styrofoam at RF/microwave frequencies is about 1.02. That is, it is virtually identical to air/free space. All the measurements are performed in an anechoic chamber, which is free of multipath and interference effects.

![Figure 112: Planar dipole antennas enclosed in Styrofoam used for in body channel characterization: side view (left) and top view (right)](image)

The first measurements campaign has been described in Section 5.5 and it is similar to the simulation done for the setup depicted in Figure 110 (left). The outer antenna is placed at a constant distance to the body phantom which equals 45cm. The antenna inside the phantom is gradually moving from the outer of the phantom to its middle. Figure 113 shows a photo of such measurements setup. Despite of having an integrated baluns on the antenna substrates high frequency ferrites were used in order to suppress spurious common modes induced on cables at the air-liquid interface. The raw measurement results for a frequency sweep are depicted in Figure 114 for all the antenna separation distanced. It can be seen that below the level of -70 dB for the measured S21 the noise effects of the measurement equipment are quite pronounced. Therefore an averaging factor for 20 subsequent measurements was applied. The raw measurements results with the averaging applied is presented in Figure 117.
The integrated curve for the path gain at 2.45 GHz of the first setup (Figure 113) is shown in Figure 115. To derive the maximum path gain at 2.45 the following expression can be used:

$$ G(dB) = G_{\text{antenna,air}}(dB) - 39.14 - 4.62 \times (X - 1) $$ (35)

This equation is derived from the fitted linear regression, which is shown as a black dashed line in Figure 115.
The measurements campaign when both antennas are inside the body phantom is depicted in Figure 116. The measured raw results in frequency domain for frequency range of 2.35 – 2.55 GHz are given in Figure 117. The receive antenna was placed with distance of 5 cm from the outer shell of the phantom, while the transmit antenna was moved with 1 cm steps away from the receive antenna inside towards the phantom symmetry axis.
Figure 117: Measured path gain for the frequency sweep with different distances between two antennas in the body phantom

The integrated curve for the path gain at 2.45 GHz of the second setup (Figure 116) is shown in Figure 118. To derive the maximum path gain at 2.45 the following expression can be used:

$$G(dB) = G_{\text{antenna-air}}(dB) - 12.15 - 4.57*(X-1)$$ \hspace{1cm} (36)

This equation is derived from the fitted linear regression. The fitted regression line is shown as a black dashed line in Figure 118.

Figure 118: Measured at 2.45 GHz path gain between two antennas immersed in the body phantom
10 Conclusions

In this deliverable we have presented a state-of-the art of body-centric channels and the preliminary results in T3.1 of the WiserBAN project. In Section 2 it has been shown that there is a large dispersion of results presented in literature, due to the fact that BAN channel is characterised by a large variability as regards to population (human subjects), postures and movements (including involuntary micro-movements, breathing, internal fluxes, etc.), used antennas (including distance from the body and polarization), positioning on the body and surrounding environment.

The numerous sources of variability lead to the conclusion that a scenario-based approach is far more appropriate and promising.

Contributions on in-body propagation are mainly focused on 400 MHz. A common approach is to consider the in-body to on-the-body (or external device) as a mix of on-body propagation and free-space, taking into account the antenna gain in situ, i.e. in the body, which includes the in-body propagation itself. The same approach can be used in the WiserBAN project at 2.4 GHz.

Concerning body-to-body and off-body channels there is a small contribution in literature at 2.45 GHz which do not include the human mobility which is fundamental for a correct and realistic channel modelling or the scenarios are not suited for WiserBAN.

In addition a state of the art of the antenna for body-centric application has been presented. Generally it has been shown that antennas based on patch topologies provide the best results as they operate against a ground plane that shields them from the body at the expense of having mainly off-body radiation. At the same time the antenna topologies such as planar monopoles or dipoles place tangentially to the human body can only operate correctly if some isolation technique is applied. For each application a trade-off between compactness, efficiency and desired radiation pattern has to be found.

In Section 3 we presented the test-beds that have been employed to characterize the body-centric channels. CEA has been focus on time-domain measurements: two different test-beds have been employed for on-body and the off-body (or body-to-body) channel characterization. This choice is due to the difference constraints on signal dynamic and acquisition rate for the different channels.

CSEM has been focusing on frequency domain characterization. For this a narrow band dipole antenna has been developed. It has an integrated balun on the same substrate and allows clearly define polarization planes. With this antenna numerous modelling and experimentation campaigns were performed. The antenna has to have a separation finite applied when placed on the human body.

In Section 4 we presented the antennas employed for channel characterization. CSEM use a narrowband dipole with integrated balun plus a narrowband top loaded monopole from CEA. CEA employed wideband planar monopole and a top-loaded monopole fed by stripline, in order to investigate two different polarizations on the body. The results on antenna-body interaction showed an antenna detuning when placed on the body;

Section 5 presented the measurement campaigns that have been carried out in the scope of T3.1. In particular CEA has been focusing on dynamic aspect of body-centric channels, while CSEM on the antenna-body interaction and the static channel, by employing a human phantom.

The WiserBAN on-body channel model has been presented in Section 6.
It has been pointed out that the time-dependent power transfer function could be divided into three main components: the mean channel gain, shadowing and fast fading. These components have been statistically modelled in several scenarios. Moreover new results on Doppler modelling in on-body channels have been presented, showing that we can separately model the contribution of the on-body scatterers and off-body scatterers. Doppler spectrum modelling allows indirectly the characterization of the coherence time, which can be assumed as the fading rate. Further measurements carried out by employing a top-loaded monopole and planar monopole showed the differences due to the polarization orientations. It has been proven that normal polarization with respect to the body surface is generally more suited to propagate creeping waves around the body. This effect implies a higher channel gain and smaller fading effect with respect to the parallel orientation. Thus antenna designs with vertical orientation are recommended for WP4.

Sections 7 and 8 presents the channel modelling for off-body and body-to-body scenarios, based on an extensive measurement campaign carried out at CEA. A distance dependent model has been extracted according to the antenna emplacement, the environment and the antennas employed. It’s been shown how the joint-effect of the antenna design (polarization and radiation pattern) and emplacement can strongly affect the channel characteristics. In particular the distinction between the LOS and NLOS condition is not the same when considering the antenna and ear or on the torso. As a consequence a complete channel model including losses, fading, and shadowing, due to the angular dependent masking effect of the body, has been given according to the specific scenario considered, on both LOS and NLOS conditions.

Section 9 is dedicated to the in-body channel characterization. A homogeneous fluid phantom was utilized for these purposes. A number of expressions were derived for estimation of the in-body channel for when both antennas are in the body simulating liquid and when one antenna is placed outside of the body phantom. The amount of isolation around the antenna is important for its correct functioning. Finally numerical models of body tissues were developed for antenna design purposes.

This deliverable presented the results of T3.1 for channel modelling. These results have been or will be employed in WP3 for antenna design and WP4 for protocol performance evaluation. Besides the models provided in this document, some additional measurements have been performed for WP4 purposes and reported in appendix.
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Glossary

BAN: Body Area Networks
PHY: Physical
MAC: Medium Access Control
UWB: Ultra Wide Band
MICS: Medical Implant Communication Service
PL: Path Loss
MPC: Multi Path Component
LOS: Line Of Sight
NLOS: Non Line Of Sight
TL Monopole: Top Loaded Monopole
PL Monopole: Planar Monopole
CIR: Channel Impulse Response
HP: Horizontal Polarization
VP: Vertical Polarization
SAM: Specific Anthropomorphic Mannequin
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[74] Dino Miniutti, Leif Hanlen, David Smith, Andrew Zhang, Daniel Lewis, David Rodda, Ben Gilbert, “Narrowband on body to off body channel characterization for ban,” IEEE 802.15-08-0559-00-0006, August 2008.
[80] ACE: Antenna Centre of Excellence, FP6-IST (http://www.antennasvce.org/)
[81] ACE2: Antenna Centre of Excellence 2 (http://www.antennasvce.org/)
Appendix: Additional measurement campaigns for protocol performance evaluation

Additional measurements campaigns have been performed aiming at studying the possibilities for nodes cooperation in the context of the Body Area Networks. Some results obtained from this analysis have been included in the WiserBAN D4.1 Deliverable. For the sake of completeness, the test-bed and measurements set up used for collecting the data used for this specific study will be presented hereafter.

In order to be able to perform an analysis on cooperation, a full mesh network topology, where all the devices could communicate with any other one in the network, has to be set up. This has been realised through the use of the test-bed presented in Figure 119:

![Test-bed used for acquisitions for cooperative studies](image)

As it could be seen, the test-bench is very similar to the one presented in Section 3.1, but it differs for the addition, at the transmitter side, of an electro-mechanical switch with six possible outputs connected to six different antennas. In this way, it will be possible to multiply the number of the transmitters; co-locating them in the same on-body positions as the receivers will then allow some cooperative investigations to be performed.

The other devices composing the test-bed are the same as the one presented in Section 3.1, except for the Digital Oscilloscope that is an older model with more constraints in term of memory, and with a maximum possible number of recordable frames equal to 4500.

The reference measurements scenario considered for these experiments is presented in Figure 120 with the indication of the position of the antennas on the body:
To collect a significant amount of data to have a solid base on which performing the post-processing, each measurement has been repeated three times and for three different subjects.

The most interesting movement to be realised is the walking one; it is obviously important that the subject repeats, for each acquisition period, more or less the same movement from a specific starting point.

Three different walking sequences have been performed and they could be described as:

1. Vertical walk from one side of the room to the opposite side; in Figure 1 are shown the walk direction and the corresponding transmitter:

   ![Figure 121: First set of measurements](image)

2. Vertical walk from one side of the room to the opposite side; in Figure 122 are shown the walk direction and the corresponding transmitter:

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>TX1</td>
<td>right wrist</td>
</tr>
<tr>
<td>RX1</td>
<td>right wrist</td>
</tr>
<tr>
<td>TX2</td>
<td>right thigh (18cm up from knee)</td>
</tr>
<tr>
<td>RX2</td>
<td>right thigh (18cm up from knee)</td>
</tr>
<tr>
<td>TX3</td>
<td>left hip</td>
</tr>
<tr>
<td>RX3</td>
<td>left hip</td>
</tr>
<tr>
<td>TX4</td>
<td>back (kidney level)</td>
</tr>
<tr>
<td>RX4</td>
<td>back (kidney level)</td>
</tr>
<tr>
<td>TX5</td>
<td>left arm (lateral side)</td>
</tr>
<tr>
<td>TX6</td>
<td>right ear</td>
</tr>
</tbody>
</table>
3. Diagonal walk from the lower right corner of the room to the upper left corner; in Figure 123 are shown the walk direction and the corresponding transmitter.

For the sake of completeness, it is worth to say that another measurements campaign has been performed for the Off-Body scenarios using the test bed presented in Section 3.1, which employs the Digital Oscilloscope even if its low dynamic is not well suited for these kind of measurements, as already explained in Section 3.2.

Briefly, the measurements scenario could be summed up as in Figure 124.

Four different external gateways as been used at the same time, while the user worn the transmitter every time in a different position.
The measurements have been repeated both in indoor and in anechoic and for the two sets of antenna. Four different subjects have been used during the acquisitions. Red crosses in Figure 125 show the position of the receiving antennas while in indoor. The movement performed were: 2 front walk (from side to side of the room), 2 back walks (from side to side of the room) and 2 circular walks (in the middle of the room).

Figure 125: Plan of the office and position of the external gateways

The data recorded could be useful in order to perform some analysis on the communication possibilities with external devices and on localisation issues.