MIMO Models for Smart On- and Off-Body Communications

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Abstract—This work aims at developing strategies for effective on- and off-body communications using MIMO, addressing a realistic dynamic user in an indoor multipath environment. Original models are proposed for the modelling of wearable antennas in the vicinity of the user (via full wave simulations), including the body dynamics (using motion capture tools), and the environment (clusters of scatterers). A Geometrically Based Statistical Channel model adapted to the Body Area Networks environment is defined. Based on proper metrics, optimum antenna placements are suggested for the case study of a $2 \times 2$ virtual MIMO system. The best performance is obtained when the on-body sink is on the front and back of the body, and data sensors are on the head, with a capacity gain of 0.97. This sink configuration also enables a good connectivity with an external base station (the capacity gain reaches 0.83).

I. INTRODUCTION

Body Area Networks (BANs) are at the core of the next generation of wireless systems [1], being part of the so called “smart society”, with its smart cities and the Internet of Things, where everyone and everything will be wirelessly connected. BANs comprise a network of short-range wearable devices exchanging key data with the world in real time. When connected to any external terminal, BANs give the user access to a gateway of services and applications, ranging from healthcare and sports monitoring, to entertainment or business, security and military forces, among others.

A practical arrangement often used for characterising communications in BANs [1], regarding the transmission channel, is to have on- and off-body communications, Fig. 1. On-body communications deal with on-body sensors and wearable systems. Most of the channel is on the surface of the body, with both transmitter (TX) and receiver (RX) antennas located very near the user. Communications from a wearable or on-body device to an external base station are termed off-body. Only one antenna of the communication link is on the body, and most of the channel is off the body and in the surrounding space. In such a channel, the user almost does not interfere with the propagation environment, but its presence leads to changes in antenna performance, hence, having a strong influence in the overall behaviour of the channel.

The particular characteristics of BANs, like the influence of the user’s body on the radio channel, the dynamics of the user, the short distances of propagation, the link geometry variability, as well as the arbitrary orientation of antennas, demand for explicit solutions that enable the reliability of communications, especially for applications demanding low bit error rates (e.g., healthcare and battlefield). Cooperative techniques are a natural option to save power, to increase the connection reliability, and to overcome the effects of deep fading in BANs [2], [3]. Virtual Multiple-Input Multiple-Output (MIMO) is one of the strategies, using clusters of nodes, on the TX or/and RX sides, then combining multiple independent paths to behave like multi-antennas systems, [4]. The use of MIMO in BANs has been studied essentially through measurements, e.g., [5], [6], [7].

This work is motivated by the challenges above mentioned, and aims at developing strategies for effective BAN communications using MIMO. Original models are proposed to:

- analyse the influence of the user on BANs performance, using voxel models and full wave simulations;
- account for the variability of the on-body channel, using real motion capture tools and a Geometrically Base Statistical Channel (GBSC) model adapted to BANs to calculate environmental Multi-Path Components (MPCs);
- "smartly" select the best on- and off-body placements, with an example for a $2 \times 2$ MIMO system.

This work compliments the results of [8], contributing to the evolution of the state of art on channel modelling for BANs, and also on the use of cooperative techniques, proposing a new combination of methods and addressing realistic scenarios.

The paper is composed of four more sections. Section II describes the proposed models for antenna-user interaction, body dynamics, on- and off-body radio channels, as well as approach to select the best antenna placements. Section III describes the case study scenario. The results of capacity gains obtained for both on- and off-body radio channel models
are gathered in Section IV. Section V concludes the paper, highlighting the main results.

II. MODELS

A. Antenna-User Interaction

A statistical approach to the problem of antenna-user interaction is proposed, [9], as the user modifies the antenna performance (e.g., radiation pattern and resonance frequency). Fig. 2 illustrates the idea of the statistical antenna model, based on a practical scenario of a BAN, where the distance to the body can vary in time (e.g., antennas are buttons on a jacket, whose distance is varying while the user is walking).

![Antenna-user interaction model.](image)

The inputs of this model can be any antenna, any body shape, and different distance distributions of the antenna to the user. Using a full wave simulator (e.g., CST, [10]) together with a realistic body model (e.g., voxel model), from the set of radiation patterns obtained at the different distances of the antenna to the user, the outputs of the model are the statistics of the on-body antenna model, like the average and standard deviation of the radiation pattern, [11]. The calculation of the antenna statistics is performed according to the distribution of the distance to the body, which is defined according to the needs of each particular scenario.

It is important to state that, although results are dependent on the chosen inputs, the concept is generally usable.

B. Body Dynamics Model

Concerning on-body communications, the first step of the model starts with an animation tool (e.g., Poser, [12]), with the selection of a body geometric model, considering an accurate body shape. The location of the antennas on the body model is identified by "guides", located at a given distance to the surface of the phantom. These guides are then "linked" to the body skeleton, and will move according to the movement of the phantom. The animation tool allows the user to apply realistic human motion movements to the phantom (e.g., walk, run), based on motion capture. Each point of time in the human motion is then framed, corresponding to specific postures, Fig. 3.

![Dynamic user reproduced in Poser.](image)

For each time frame, two CAD format files are then exported from the animation tool: one containing the location of the antennas, and the other containing the 3D body model. The next stage is to import the motion frames into the full wave simulator (e.g., CST, which applies the Finite Integration Technique). For each frame, the file containing the rectangles location is imported into the simulator, and the antenna is manually attached to each one of the "guides". This is the most sensitive part of the procedure, as it is important to keep the same antenna orientation for all the time frames. Then, the file containing the body model is imported and filled with tissue properties. The movement is studied in the full wave simulator in a discrete way, running the transient solver for each time frame. The procedure described above is flexible enough to be extended to other phantoms, antennas, motion actions, or BAN configurations. However, the proposed solution is a time consuming and delicate process, especially due to the manual antenna addition in the full wave simulator.

Alternatively, the model for body movement can be directly extracted from motion capture analysis. Such data consists of a static component (i.e., skeleton hierarchy information, which is composed of several nodes, linked to each other by a translation vector), and a dynamic one (i.e., motion data), which is a list of rotations of the nodes for each time frame of the body movement. This modelling approach can describe any movement in a frame-by-frame manner. For each time frame, the position of the antenna and its normal to the body surface is determined, [13]. Then, in the radio channel model, the MPCs are calculated according to the positions and orientation of the on-body antenna (taking into account the shift of the radiation pattern), position of external antenna, and the distribution of scatterers. This method simplifies the setup of the simulations, moreover, since the model is geometry based, calculations are very fast compared to full wave methods. However, this modelling approach still does not reproduce all the phenomena that are caused by the presence of the moving body. For instance, when the whole body moves, and the movement of the antenna is analysed (e.g., located on the chest), some radiation directions can be additionally obstructed by the presence of other body segments (e.g., hands).

C. Radio Channel Model

Radio channels can be characterised by the impulse response approach, assuming that the channel is a linear filter with impulse response $h$, [14]:

$$h(\tau) = \sum_{k=1}^{N_m} h_k \delta(\tau - \tau_k)$$  \hspace{1cm} (1)

where:

- $h_k$: amplitude of the $k^{th}$ MPC,
- $\tau_k$: delay of the $k^{th}$ MPC,
- $\tau$: delay,
The multipath characteristics of the radio channel are assumed to be the result of signal bounce over numerous environment scatterers, as proposed by the GBSC model [15]. This model can be used to characterise both on- and off-body communications, by addressing a statistical description of the wearable antenna patterns (by means of the average on-body antenna gain) at different locations on the body. Moreover, a geometrical description of on-body antenna positions with the body dynamics is also addressed. This modification of the GBSC model to BANs is named GBSC_B. Accordingly, the amplitude of the $k^{th}$ MPC is calculated from:

$$|h_k| = \frac{|\Gamma_k| \lambda}{d_k} \sqrt{\frac{P_T G_{T_k} G_{R_k}}{4\pi}} \quad (2)$$

where:

- $|\Gamma_k|$: reflection loss of the $k^{th}$ MPC,
- $d_k$: total length of the $k^{th}$ MPC,
- $\lambda$: wavelength,
- $P_T$: transmitted power,
- $G_{T_k}$ and $G_{R_k}$: TX and RX antenna gains for the $k^{th}$ MPC, respectively. Note that, for the case of wearable antennas, these gains are the average on-body antenna ones.

Concerning on-body communications, both TX and RX are wearable antennas, located very near the user. The proposed model is based on the concept that the received on-body signals result from the contribution of an on-body component, and of the several environment MPCs (obtained from the GBSC_B model, where the TX and RX antennas are both on the body). Accordingly, (1) is expressed as:

$$h(\tau) = h_{body} \delta(\tau - \tau_1) + \sum_{k=2}^{N_m} h_k \delta(\tau - \tau_k) \quad (3)$$

where:

- $h_{body}$: amplitude of the on-body component, obtained from full wave simulations, combined with animation software.

Regarding off-body communications, the body is on one side of the radio link, and the other is an external terminal. In this case, the modelling has been separated into wearable antennas in the vicinity of the body, including body dynamics, and indoor environment (i.e., GBSC_B model). In a first stage, for the static body, the radiation pattern of the antenna is calculated using CST. In a second stage, the antenna radiation patterns on the moving body are calculated [13].

### D. Smart MIMO Antenna Placements

The MIMO capacity, $C$, is obtained from the channel matrix $H$ [16], and, as a consequence of the correlation between channels being between zero and one, it is possible to derive the upper and lower bounds for capacity.

In order to have a statistical viewpoint on the propagation conditions in a particular type of environment, a number of simulations, $N_s$, is performed for randomly generated scatterers. For each randomised environment, the body is always moving along the same path with the desired behaviour (i.e., walking). Therefore, for a given time frame $t_s$ (which always occurs for the same body posture and position in the cell), the variations in output parameters come from the differences in the propagation environment. The average capacity at each time frame $C_{m,n}(t_s)$, for a $2 \times 2$ MIMO system, including the $m^{th}$ and $n^{th}$ on-body antennas, and its standard deviation $\sigma_{C_{m,n}}(t_s)$, are calculated by:

$$C_{m,n}(t_s) = \frac{1}{N_s} \sum_{s=1}^{N_s} C_{m,n}(t_s, s) \quad (4)$$

$$\sigma_{C_{m,n}}(t_s) = \sqrt{\frac{1}{N_s} \sum_{s=1}^{N_s} \left[ C_{m,n}(t_s, s) - C_{m,n}(t_s) \right]^2} \quad (5)$$

These statistics can also be averaged in the required time range, giving the average MIMO capacity and the standard deviation of the average capacity.

For convenience, the metric BAN MIMO capacity gain is defined, to evaluate the performance of a given $2 \times 2$ combination of TX/RX within a specific BAN system:

$$C_{G,BAN} = (C - C_{lower})/(C_{upper} - C_{lower}) \quad (6)$$

The selection of the optimum placements is based on the values of the BAN MIMO capacity gain, the best placements corresponding to the systems with the highest values of $C_{G,BAN}$.

### III. Case Study Scenario

#### A. Body Environment

An adult female is taken as case study (no large changes are expected between genders), and two phantom models are considered: homogeneous (from the Poser library [12]) and heterogeneous (Virtual Family [17]). A typical dynamic scenario is considered, namely a walking user. Due to the periodic nature of the body dynamics, the motion capture description contains $N_f = 30$ time frames, with a duration of 1/30 s each, corresponding to one walking period.

The 2.45 GHz Industrial, Scientific, and Medical (ISM) band, used in BAN standards [18], is addressed. The narrowband case is considered, with 1 MHz of RX bandwidth (1 $\mu$s time resolution). Small patch wearable antennas are used [19], easily integrated into clothes or equipment due to their flat configuration. The power transmitted from the wearable antennas is 1 mW, and the noise floor -100 dBm. Fig. 4 shows the wearable antenna placements, namely, TO_F and TO_B (front and back side of the chest), WA_F (front side of the waist), HE_F, HE_B, HE_L and HE_R (front, back, left and right side of the head), and AB_L and AB_R (left and right side of the arm).
The nodes in the BAN can cooperate in many different ways, according to the application. The case study of a $2 \times 2$ virtual MIMO scheme is considered, with the sink nodes (RXs) on front/back of the body (RXs: TO$_F$ & TO$_B$). The aspects of synchronisation between the wearable nodes are beyond the scope of this work. One assumes the optimistic scenario of perfect synchronism among the on-body sensors and the sink.

As capacity for off-body communications depends on the mutual location of the antennas (i.e., Front (F), Back (B), Left (L) and Right (R)), the following classes are considered:

- Co-Directed (CD): both antennas are located on the same side (i.e., F, B, L and R).
- Cross-Directed (XD): one antenna is located on the B or F sides, whereas the other is placed on the L or R sides (i.e., FL, FR, BL and BR).
- Opposite-Directed (OD): one antenna is located on the B side and the other on the F one, or one antenna is located on the L side and the other on the R one (i.e., FB and LR).

### B. Indoor Environment

An indoor room scenario is considered, Fig. 5, including a set of 6 clusters, of 3 scatterers each, with a Uniform Distribution in the room, [15]. An isotropic base station antenna is located in the middle of the left wall, at a 2.5 m height, being used as the RX for off-body communications. The user is walking on a straight line, in the middle of the room (i.e., $y=2.5$ m), in $x \in [1.8, 3.2]$ m.

### IV. Case Study Results

#### A. On-Body

The capacity gain was calculated for the selected on-body example, which can represent a probable scenario for a $2 \times 2$ MIMO BAN. Fig. 6 shows the statistics of the on-body capacity gains, namely their average ($C_{GBAN}$) and standard deviation ($\sigma_{C_{GBAN}}$).

Results show that the sink nodes location on the front and back of the body enables balanced and uncorrelated signals, meaning that capacity gains are high. The worst performance ($C_{GBAN}=0.77$) is obtained when the sensors are on HE$_L$ & HE$_R$, where the symmetry is high, and branches are correlated.

The combination enabling the best performance corresponds to the sensors on the head (TXs: HE$_F$ & HE$_B$), and the sink nodes on front and back of the body (RXs: TO$_F$ & TO$_B$). For this combination, $C_{GBAN}$ is very high (0.97), meaning that capacity approaches the upper bound. The low values of the standard deviation metrics obtained for this configuration also show that it is stable, not fluctuating with the environment, neither with the body dynamics.

#### B. Off-Body

The capacity gain has been calculated for all possible combinations of antenna pairs. In Fig. 7, the statistics (i.e., the average and the standard deviation) and the allocation to the class are presented.
In the case of strong power imbalances between the branches, as for OD antennas, when one antenna is on the left and the other one on the right (i.e., LR case), the system cannot benefit from the capacity gains. Therefore, the average gain is the lowest, 0.4. For all other cases, results show that the usage of virtual MIMO in BANs can benefit from the capacity gain above 0.6. Results indicate that the HE_L & AB_L pair (L class) outperforms the others, with a gain of 0.84.

Taking the case studied for on-body communications, i.e., the pair TO_F & TO_B (FB class), which can be used to connect the on-body environment with the base station, the average gain is also very high (0.83). Fig. 7 illustrates the optimum configuration for the selected case study.

![Optimum configuration for the selected case study.](image)

**Fig. 8.** Optimum configuration for the selected case study.

V. CONCLUSION

The use of virtual MIMO in Body Area Networks (BANs) can benefit from the capacity gain and enhancement of the overall performance of on- and off-body links. In order to minimise the outage of the system, multiple on-body antennas can be distributed on various locations on the body. In this paper, the $2 \times 2$ MIMO capacity of various configurations of multiple antennas located on the body is analysed for both on- and off-body communications.

The proposed model includes the coupling between the antenna and the user (obtained via full wave simulations), the body dynamics (taken from motion capture), and a realistic propagation environment (clusters of scatterers). A Geometrically Based Statistical Channel model adapted to BANs (GBSC_B) calculates bounces of the transmitted signal over randomly distributed scatterers to obtain the Multi-Path Components and the channel impulse responses. Concerning on-body communications, the proposed approach considers that the received signals result from the contribution of one on-body component (obtained from the full wave simulator) and of the several MPCs present in the environment (obtained from the GBSC_B model).

A BAN with patch antennas operating at 2.45 GHz and 9 possible locations on a female body has been analysed. An indoor scenario is considered, and the user is walking. Based on proper metrics, optimum $2 \times 2$ antenna placements are suggested.

Concerning on-body communications, the MIMO capacity was estimated for selected configurations and shows that the best performance is obtained when the sink nodes (RXs) are on front and back of the body, and the data sensors (TXs) are on the head, with a capacity gain of 0.97, almost reaching the upper MIMO capacity bound. Taking this sink configuration (TO_F & TO_B) from the on-body study, to connect with an external base station, the average gain is also high (0.83), being a suitable option.

REFERENCES