A Mobility Model for Wearable Antennas on Dynamic Users

KENAN TURBIC1, (Student Member, IEEE), LUIS M. CORREIA1, (Senior Member, IEEE), AND MARKO BEKO1,2,3

1INEC-ID / Instituto Superior Técnico (IST), University of Lisbon, Portugal (e-mail: {kenan.turbic, luis.m.correia}@tecnico.ulisboa.pt)
2COPELABS, Universidade Lusófona de Humanidades e Tecnologias, 1749-024 Lisboa, Portugal (e-mail: beko.marko@ulusofona.pt)
3CTS/UNINOVA, FCT/UNL, 2829-516 Caparica, Portugal (e-mail: mbeko@uninova.pt)

Corresponding author: Kenan Turbic (e-mail: kenan.turbic@tecnico.ulisboa.pt).

ABSTRACT This paper presents a mobility model for the variations in position and orientation of wearable antennas on dynamic users, considering walking and running motions. Motion is represented as a composition of a linear forward movement plus a periodic component, modelled by a Fourier series with up to two harmonics. The model is simple, yet realistic, as Motion Capture (MoCap) data are used to calculate its parameters. It is suitable for use with a variety of propagation channel models, including deterministic ray-tracing and stochastic geometry-based ones, but can also allow for analytical inference in simplified scenarios. Considering an off-body communication scenario, simulations show that the proposed mobility model provides similar received power as the skeleton-based model with MoCap data, the maximum difference in the considered scenario being below 1 dB. A significant influence of user’s motion on the channel is observed for both free-space and multipath propagation, yielding received power variations up to 28 dB in the considered scenarios.

INDEX TERMS Antenna mobility model, body area networks, dynamic users, off-body channels, wireless communications

I. INTRODUCTION

BODY Area Networks (BANs) have gained a considerable attention in recent years, with potential applications being recognised in various fields [1]. While BANs promise to significantly improve healthcare, they are also expected to improve training for professional sports people, provide on-field logistics support for military, or serve as advanced Human-Computer Interface (HCI) [2], [3], among other applications.

The performance of BANs highly relies on the ability to exchange information among nodes, hence, a proper knowledge of the communication channel is of great importance for a system designer. The convenience of radio makes it a natural choice for BAN communications. However, the radio channel is characterised by severe signal degradations, where the motion of wearable antennas on a dynamic user plays an important role [4]. While changing antenna position yields signal variations associated with multipath fading and body shadowing [5], its rotation imposes variations in the gain and polarisation mismatch associated with Multipath Components (MPCs) arriving at the receiver (Rx). For the Line-of-Sight (LoS) component, the latter is primarily due to physical misalignment between the antennas on the two communication ends [6], [7].

Most of the studies related to dynamic BAN channels are based on measurements [8]- [11], where the proposed empirical models consider the influence of motion only through parameters of the statistical distributions for path loss. In a more theoretical approach [12], [13], the authors use an autoregressive model to represent the temporal and cross-correlation properties of the on-body channels for a dynamic user. While in this case the Rx signal characteristics for the dynamic user are represented directly within a statistical channel model, a more detailed mobility model is required for use with ray-tracing or Geometry-Based Stochastic Channel (GBSC) models [14]. Hence, several proposals, discussed in what follows, have been presented by researchers.

Adopting the existing approach used for mobile communications networks [15], the mobility models proposed in [16] and [17] are based on a general Reference Point Group Mobility (RPGM) framework. The motion of an antenna is modelled as a composition of the motion of a reference point associated with a group of antennas within the same BAN, and the individual motion of the antenna relative to
this reference. In both of these models, the former is represented by a set of straight path segments with randomly chosen direction and velocities, and the latter by a random displacement vector. While [16] assumes horizontal motion, the model in [17] is 3D and additionally considers different user activities. However, it should be pointed out that these models only consider the antennas’ positions, and generally fail to capture the true characteristics of human motion.

Following the proposal in [18], [19], some authors have used animation software to obtain realistic human body motion for on-body channel simulations [20]–[23]; this software is used to generate a sequence of postures for virtual body phantom models in numerical Electromagnetic (EM) simulators. In [24] and [25], the authors use animation software to obtain wearable antenna positions for the body-to-body channel and inter-BAN interference simulations based on ray-tracing. A similar approach is used in [26] to extract on-body antenna motion, in order to analyse its influence on the radiation pattern during movement. The authors further use this approach in [27], for body-to-body channel simulations based on a GBSC model.

In order to eliminate the need for animation software, in [28] the authors use a skeleton-based motion model with MoCap data to obtain postures of a simplified cylinder-based body phantom for EM simulations. A similar approach is used in [29], [30], to obtain the time-varying distances between wearable antennas, in order to improve the on-body channel simulations based on statistical models [31]. Together with a cylinder-based body model, the motion model is further exploited to account for body shadowing loss by performing a simple LoS obstruction test. A similar skeleton-based model is used to obtain the antennas positions and orientations for their individual mobility within the RPGM model adopted in [32]. With the user forward motion (i.e., reference point) generated by an agent-based simulation, the mobility model is used as an input to a ray-tracer for dynamic on-, off- and body-to-body channel simulations.

In summary, the following can be concluded from previous works. Mobility models based on MoCap data are limited by their resolution and size, while the required data storage and involved calculations considerably add to the complexity of a simulator [28], [32]. While being acceptable when the skeleton-based model is also used to modify posture of the body phantom in full-wave on-body channel simulations [20], [22], this complexity is beyond the required one if only antenna’s position and orientation are needed, e.g., in GBSC channel models [33], [34]. Most of the available models consider only the antenna’s position, and its orientation is considered only by a few authors [26], [28], [32]. Moreover, the models for wearable antenna rotations in [26] and [32] are not complete. Since the authors in [26] consider only the vector normal to the patch antenna plane for its orientation, the rotation around this axis is neglected. Similarly, due to limitations of the used MoCap data and of the method used to obtain the orientation vectors, the rotation about the vertical axis of the antenna is neglected in [32]. However, these two rotations can have an important impact on the channel, where the former can yield significant depolarisation loss and the latter variations in the antenna gain and Cross-Polarisation Isolation (XPI) in directions associated with the arriving MPCs.

The main contribution of this work is the proposed analytical mobility model for wearable antennas in BANs with dynamic users. The model is based on Fourier series whose parameters are calculated from MoCap data. Therefore, it provides a realistic motion as skeleton-based models, while being relieved of their inherent complexity. The mobility model provides the position and orientation of an antenna for 14 different on-body placements, for user walking and running motions. It is suitable for use with a variety of propagation channel models, and can allow for analytical inference in simplified scenarios. A GBSC model is used for the purpose of the work presented in this paper.

The rest of the paper is structured as follows. The adopted propagation model is described in Section II, and the mobility model for wearable antennas is presented in the following Section III. The off-body BAN communications scenarios simulated for model demonstration are described in Section IV, and results are discussed in Section V. The paper is concluded in Section VI.

II. OFF-BODY CHANNEL MODEL

In off-body communications, one of the antennas is assumed to be worn by the user and the other is fixed somewhere in the surrounding environment. Considering multipath propagation, the complex baseband amplitude of the Rx signal can be represented as a phasor sum of the arriving MPCs [14]:

\[ A_r = \sum_{n=1}^{N_m} A_n e^{-j \frac{2\pi}{\lambda} r_n} \]  

(1)

where:
- \( \lambda \): wavelength;
- \( N_m \): number of MPCs;
- \( A_n \): amplitude of the \( n \)-th MPC;
- \( r_n \): \( n \)-th MPC’s path length.

The Rx amplitude of an MPC depends on the involved propagation mechanism, with the general expression:

\[ A_n = \frac{\lambda}{4\pi r_n} \sqrt{G_r(\phi_{n/r}, \psi_{n/r})G_t(\phi_{n/t}, \psi_{n/t})P_t} \]  

(2)

where:
- \( P_t \): transmitter (Tx) power;
- \( G_{t/r} \): Tx/Rx antenna gain;
- \( \phi_{n/r} \): azimuth angle of departure/arrival (AAoD/AAoA);
- \( \psi_{n/r} \): elevation angle of departure/arrival (EAoD/EAoA);
- \( \Gamma_{r/d} \): reflection/diffraction loss (omitted for the LoS component).

The Rx signal power is obtained from (1), according to:

\[ P_r = \frac{1}{2} |A_r|^2 \]  

(3)

For the sake of simplicity, this work considers LoS and single-reflected components only. However, the model is
easily extendible to include other propagation mechanisms and/or higher-order MPCs. Moreover, the model can account for shadowing by the user, if the employed radiation patterns are obtained for antennas on the body. However, a detailed consideration of the body-shadowing effect is beyond the scope of this work. One should also note that the polarisation aspect of the channel is not considered in this work. The polarisations of the Rx antenna and of the arriving MPCs are assumed to be perfectly matched, and the reflection loss in (2) is calculated by assuming equal powers in polarisations parallel and perpendicular to the plane of incidence.

The antenna gains in (2) account for the radiation properties of the Tx and Rx antennas in the directions of departure/arrival (DoD/DoA) of MPCs. These directions are given by the azimuth and elevation angles obtained according to (the upper/lower sign corresponds to DoD/DoA, i.e. index $t/r$):

$$\phi^t_r = \arctan\left(\pm k^t_r \cdot u_y^a\right)$$

$$\psi^t_r = \arcsin\left(\pm k^t_r \cdot u_z^a\right)$$

(4)

(5)

where:

- $k^t_r$: DoD/DoA unit vector;
- $u_{x/y/z}^a$: unit vector(s) along the $x/y/z$ axis of the antenna coordinate system.

Fig. 1 illustrates the terms in (4) and (5) for a patch antenna, shown as a dark grey rectangle, whose plane lies within the Y-Z plane of the associated local coordinate system, i.e. defined by vectors $u_y^a$ and $u_z^a$.

![FIGURE 1: AAoD and EAoD in the antenna coordinate system.](image_url)

The motion of the antenna has a two-fold influence on (4) and (5). The displacement of the antenna hinges the multipath geometry, thus affecting the DoD/DoA vectors ($k^t_r$), and the rotation changes the orientation of vectors $u_x^a$, $u_y^a$, and $u_z^a$. While the former yields variations in the antenna gain, the latter is additionally responsible for polarisation mismatch, which can yield poor channel conditions, even in the case of a clear LoS. In order to account for the dynamic changes in the antenna’s position and orientation for a dynamic user, a mobility model for wearable antennas in BANs is developed and presented in the following section.

III. ANTENNA MOBILITY MODEL

A. POSITION AND ORIENTATION OF THE ANTENNA

The uniform motion of a person walking and running is distinctively cyclic, and can be represented as the composition of two components: forward motion at a constant velocity, and a periodic component corresponding to the change in body posture during a motion cycle. Considering the position of an on-body antenna, the former translates into a linear component common to all on-body antennas, describing the position of a reference point associated with the body, while the latter corresponds to the relative motion of the antenna with respect to this reference. Hence, the position of the antenna over time ($t$) can be represented as:

$$r_{[m]}(t) = r_{0[m]} + v_{u[m/s]}t[s]u_v + \Delta r_{[m]}(t)$$

(6)

where:

- $v_u$: user’s velocity;
- $r_0$: starting point, i.e. $r_0 = (r_{0,x}, r_{0,y}, 0)$

- $u_v$: unit direction vector, i.e. $u_v = (\cos\phi_u, \sin\phi_u, 0)$

- $\Delta r$: periodic component.

The terms in (6) are illustrated in Fig. 2. In order to allow for the highest level of flexibility and the most straightforward modification of motion for an arbitrary path (Appendix A), model parameters are calculated for the reference case in which the user starts at the origin and moves in the positive $x$-axis direction, i.e. $r_{0,x/y} = 0$ m and $\phi_u = 0^\circ$.

![FIGURE 2: Illustration of the model for antenna position.](image_url)
Fourier series for each coordinate, i.e. $\Delta r_x$, $\Delta r_y$, and $\Delta r_z$, which can be expressed in a vector form by:

$$\Delta \mathbf{r}(t) = \mathbf{a}_0 + \sum_{n=1}^{N_h} \left[ a_{n}^c \cos \left( \frac{2\pi}{T} t \right) + a_{n}^s \sin \left( \frac{2\pi}{T} t \right) \right]$$

where:
- $N_h$: number of harmonics;
- $T$: motion cycle period;
- $a_0$: mean values of position coordinates;
- $a_{n}^c$: amplitudes of $n$-th harmonic’s cosine component;
- $a_{n}^s$: amplitudes of $n$-th harmonic’s sine component.

This approach yields a unified model for all on-body antennas and user motions, where only the values of the parameters change; the period ($T$) is fixed for a particular user motion, while amplitude parameters $a_0$, $a_{n}^c$, and $a_{n}^s$ vary for antenna’s placements and motions. The number of harmonics can be chosen separately for each component, depending on its variability, i.e. by choosing the appropriate $N_h$ considering all coordinate components, and by setting the higher harmonics’ amplitude parameters to zero for the less variable ones. One should note that $a_0$ obtained for a walking user corresponds to the antenna position for the user static standing posture, hence, it can be used for static off-body channel considerations.

The antenna orientation can be represented as a rotation of the local coordinate system relative to the global one (i.e., $\mathbf{u}_x$, $\mathbf{u}_y$ and $\mathbf{u}_z$), which in turn can be represented by a sequence of Euler rotations [36]. With a chosen axis rotation sequence Z-Y-Z, the antenna orientation is represented by three (proper) Euler angles $\gamma_1$, $\gamma_2$, and $\gamma_3$, corresponding to the successive elementary rotations around the $z$-, $y$- and $z$-axes of the associated local coordinate system, respectively. The antenna orientation vectors at the end of the rotation sequence are obtained in the columns/rows of the composite rotation matrix (considering column/row-vector representation) [36], where one has:

$$\mathbf{u}_x^e = (\cos \gamma_1 \cos \gamma_2 \cos \gamma_3 - \sin \gamma_1 \sin \gamma_3, \\ \sin \gamma_1 \cos \gamma_2 \cos \gamma_3 + \cos \gamma_1 \sin \gamma_3, \\ - \sin \gamma_2 \cos \gamma_3)$$  \hspace{1cm} (10)$$

$$\mathbf{u}_y^e = (-\cos \gamma_1 \cos \gamma_2 \sin \gamma_3 - \sin \gamma_1 \cos \gamma_3, \\ - \sin \gamma_1 \cos \gamma_2 \sin \gamma_3 + \cos \gamma_1 \cos \gamma_3, \\ \sin \gamma_2 \cos \gamma_3)$$  \hspace{1cm} (11)$$

$$\mathbf{u}_z^e = (\cos \gamma_1 \sin \gamma_2, \sin \gamma_1 \sin \gamma_2, \cos \gamma_2)$$  \hspace{1cm} (12)$$

With the chosen rotation sequence Z-Y-Z, the first two Euler angles specify the antenna tilt; $\gamma_1$ is the azimuth direction in which the antenna is tilted and $\gamma_2$ is the tilt angle. The last angle in the sequence, i.e. $\gamma_3$, determines the final pointing direction of the antenna.

For the periodic character of the antenna rotation imposed by the walking and running motions, Euler angles exhibit periodic variations, hence, they can be modelled via a Fourier series given as:

$$\gamma_i(t) = b_{0,i} + \sum_{n=1}^{N_h} \left[ b_{n,i}^c \cos \left( \frac{2\pi}{T} t \right) + b_{n,i}^s \sin \left( \frac{2\pi}{T} t \right) \right]$$

where:
- $b_{0,i}$: mean value for angle $\gamma_i$;
- $b_{n,i}^c$: amplitude of $n$-th harmonic’s cosine component;
- $b_{n,i}^s$: amplitude of $n$-th harmonic’s sine component.

The period of the series for Euler angles (13) is the same as that for antenna position (9), for each user motion.

### B. ESTIMATION OF MODEL PARAMETERS

In order to obtain realistic motion, the calculation of the model parameters is based on MoCap data [37]. While these data are provided for the human body, the motion of the attached on-body antennas can be obtained by using the methods from computer animation. To do so, one should consider that MoCap data are provided for a skeleton model that represents the body as a set of bones and connecting joints [36]. The skeleton’s motion is provided in terms of the position of an associated reference point and a set of rotations for each joint; the former specifies the global position of the body, and the latter sets the orientations of the associated bones and posture of the body, altogether.

In a way similar to the one used to drive the motion of a character in computer animation, the skeleton with its associated MoCap data can be used to drive the motion of an on-body antenna. This is achieved by associating the antenna with a bone in the skeleton based on the on-body placement, i.e. by defining its position and orientation relative to the bone, and inheriting its motion. Fig. 3 shows this association for several on-body antenna placements: front and back sides of the torso (To_F/B), left and right sides of the waist (Wa_L/R), left and right sides of the head (He_L/R), left and right upper arms (AU_L/R), left and right hand wrists (AL_L/R), left and right upper legs (LU_L/R), and left and right lower legs (LL_L/R). These antenna placements are chosen to represent popular BAN applications, such as smart watch, smart glasses, and chest band cardio monitor, among others [1].

With the established antenna-bone association, the antenna motion is obtained using the MoCap toolbox in Matlab [38], [39] and the data available in the CMU Graphics Lab Database [37], namely, motions 33 (walking) and 26 (running) for subject 35. A simple linear transformation is applied to the data to obtain the motion with a user moving in the positive $x$-axis direction, starting at the origin. Then, the data corresponding to a single motion cycle period are extracted based on a gait analysis [36]. The parameters of the forward motion component in (6) are first calculated by fitting a linear model to the $x$-axis coordinate of the extracted antenna.
The evident symmetries characterising the human body and its motion allow for a considerable simplification of the model. Namely, for the on-body antenna placements shown in Fig. 3, it is sufficient to provide the parameters for those marked with a star. One can show that the positions of the two antennas on symmetric placements on the left and right sides of the body are related according to (Appendix B):

\[
\Delta r_{x/z}^R(t) = \Delta r_{x/z}^L(t - T/2) \quad (14)
\]

\[
\Delta r_{y}^R(t) = -\Delta r_{y}^L(t - T/2) \quad (15)
\]

where superscripts \( L/R \) indicate the left/right sides of the body. At the same time, the corresponding relations for the Euler angles can be written as (Appendix B):

\[
\gamma_i^R(t) = (-1)^i \gamma_i^L(t - T/2), \quad i = 1, 2, 3 \quad (16)
\]

These relations do not hold for antennas on the waist and the head. While their positions are related according to (14) and (15), the \( Wa_L \) and \( Wa_R \) antennas have the same orientation as they share the common vertical rotation axis (i.e. \( u^z \)) and face the same side of the body. The \( He_L \) and \( He_R \) antennas also share the vertical axis, i.e. the one of the head, but face opposite directions. This also means that their orientations are directly related, i.e. without a time offset of \( T/2 \); one straightforwardly has:

\[
\gamma_1^R(t) = \gamma_1^L(t) \quad (17)
\]

\[
\gamma_3^R(t) = \gamma_3^L(t) + 180^\circ \quad (18)
\]

By assuming their placement on exactly opposite sides of the head, the distance between the \( He_L \) and \( He_R \) antennas is equal to the head’s diameter, \( D_H \) (e.g. 18 cm [28]), but in the direction that varies over a motion cycle, hence:

\[
\Delta r_{[cm]}^R(t) = \Delta r_{[cm]}^L(t) - D_H [cm] \cdot u^z \quad (19)
\]

The case for the \( To_F \) and \( To_B \) antennas is essentially the same as for the \( He_L \) and \( He_R \) ones, while the common vertical axis is now the one of the torso. Therefore, (17) and (18) also hold for the \( To_F \) and \( To_B \) antennas, where superscripts \( L/R \) are replaced by \( F/B \). However, the diameter of the torso, \( D_T \) (e.g. 26 cm [28]), should be used in (19) instead of the one of the head.

D. MODEL PARAMETERS

Following the procedure described in Section III-B, the model parameters were calculated from MoCap data for walking and running motions [37] (subject 35, motions 33 and 26, respectively). User’s velocity is estimated to be 1.307 m/s and the motion cycle period is 1.142 s for the former, while the respective values are 3.551 m/s and 0.717 s for the latter. As discussed in Section III-C, the parameters of the Fourier series representation of the periodic components are calculated for the antenna placements indicated by a star in Fig. 3. These values are summarised in Table 1a for the position coordinates, and in Table 1b for the Euler angles representing orientation. For the antenna position (Table 1a), a single harmonic in the Fourier series is typically sufficient, two being required only for a few components in the case of the walking motion, while two harmonics are also mostly required for the running case. On the other hand, the orientation angles in most cases can be represented by a single harmonic and only a few components require two, for both
walking and running. It is noted that the parameters in Table 1 correspond to walking and running motions of a typical person, where variations across different people are expected to be insignificant for channel modelling purposes. However, the user motion velocity can be adjusted as described in Appendix A.

E. MODEL ACCURACY

In order to analyse the error relative to the realistic motion obtained from the skeleton-based model with MoCap data, two comparative metrics are considered, namely, the maximum distance between antenna positions, \(\epsilon_{\Delta r}\), and the maximum error considering the relative rotation (angle) between orientations obtained from the proposed model and MoCap data, \(\gamma\). These metrics, respectively, provide a measure of the error in antenna’s position and orientation:

\[
\epsilon_{\Delta r} = \max_t \|\Delta r(t) - \Delta r_{MC}(t)\| \quad (20)
\]

\[
\gamma = \max_t |\Delta \gamma(t)| \quad (21)
\]

where:
- \(r_{MC}\): periodic component of the antenna’s position, obtained from MoCap data;
- \(\Delta \gamma\): relative rotation angle between orientations given by the model and MoCap data.

One should note that (20) considers 3D distances, rather than the individual coordinates. The relative rotation angle \((\Delta \gamma)\) in (21) is obtained from the axis-angle representation of rotation, according to Euler’s theorem [36]. The values obtained for the considered antenna placements and user motions are shown in Fig. 4. It should be noticed that the index in the acronyms for antenna placements is dropped, as the error applies to two symmetric antenna placements, i.e. L/R or F/B (Section III-C).

One can observe that the error obtained for the antenna position is below 2 cm in all cases, except for the wrist antenna (AL) on a running user, for which the maximum distance error is 3.2 cm. Furthermore, the error is similar across antenna placements and motions. Hence, the error is uniform and always within the tolerance, i.e. 5 cm (Section III-B). One should note that the maximum orientation error is found to be 9°, at most, being obtained for the lower leg antenna (LL) on a walking user. In this case, the error is not uniform across different antenna placements; the somewhat higher values are observed for more dynamic on-body antenna placements, i.e. AL, LU and LL. However, it should be pointed out that the higher error maxima for the aforementioned three antenna placements are observed at the end of a motion period. The imperfect periodicity of the human motion yields mismatched on-body antenna orientation at the beginning and the end of a motion period, with this mismatch being more emphasised for the antenna placements on the arms and legs. Therefore, the observed maximum error is actually due to motion cyclification imposed by the mobility model. It should be pointed out that, if only the inner part of the motion period is considered, the orientation error for these placements is always below 6°, being well within the 10° tolerance (Section III-B). Moreover, the Root Mean Square Error over the motion period is below 5° for all antennas.

While the error considered in this section is that in between the model and the MoCap data from which its parameters were estimated, one could argue that the analysis should be performed for several different subjects and motions. Such a reasoning would then require a comparison for subjects of different gender, age and size, but also variations in the exact antenna placement on the same body part. However, the main goal of this work is to provide a simple parametrisation mobility model, which captures the principal characteristics of the human motion. Therefore, the MoCap data used to calculate the parameters were chosen for their high quality, while being representative of an average person.

F. MODEL COMPLEXITY

Following the error analysis, a few notes should be made on model complexity compared to the skeleton-based models with MoCap data. It is easy to notice that the proposed model is superior to the latter in this regard. Considering memory requirements, skeleton-based models require the storage of MoCap data, which contain a number of channels (components) needed to represent the body’s position and posture. These channels contain samples for all body postures over a motion period, where the number of samples depends on the resolution of data, i.e. frame rate. On the other hand, the memory requirements of the proposed model do not depend on the sampling resolution, and only the motion period is considered, the orientation error for these placements is always below 6°, being well within the 10° tolerance (Section III-B). Moreover, the Root Mean Square Error over the motion period is below 5° for all antennas.

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### TABLE 1: ESTIMATED PARAMETERS FOR PERIODIC MOTION COMPONENTS, FOR WALKING AND RUNNING.

#### (a) Antenna position (periodic component).

<table>
<thead>
<tr>
<th>Ant.</th>
<th>Comp.</th>
<th>Walking, $T = 1.142$ s</th>
<th>Running, $T = 0.717$ s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$a_0$ [cm]</td>
<td>$a_1$ [cm]</td>
</tr>
<tr>
<td>To_F</td>
<td>$\Delta r_x$</td>
<td>10.1</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>$\Delta r_y$</td>
<td>0.1</td>
<td>-0.5</td>
</tr>
<tr>
<td></td>
<td>$\Delta r_z$</td>
<td>135.5</td>
<td>0.1</td>
</tr>
<tr>
<td>He_L</td>
<td>$\Delta r_x$</td>
<td>5.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>$\Delta r_y$</td>
<td>9.1</td>
<td>-0.3</td>
</tr>
<tr>
<td></td>
<td>$\Delta r_z$</td>
<td>165.1</td>
<td>-0.2</td>
</tr>
<tr>
<td>Wa_L</td>
<td>$\Delta r_x$</td>
<td>8.5</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>$\Delta r_y$</td>
<td>11.9</td>
<td>-2.3</td>
</tr>
<tr>
<td></td>
<td>$\Delta r_z$</td>
<td>90.9</td>
<td>-1.0</td>
</tr>
<tr>
<td>AU_L</td>
<td>$\Delta r_x$</td>
<td>-0.3</td>
<td>-3.4</td>
</tr>
<tr>
<td></td>
<td>$\Delta r_y$</td>
<td>22.9</td>
<td>-2.5</td>
</tr>
<tr>
<td></td>
<td>$\Delta r_z$</td>
<td>128.7</td>
<td>-0.5</td>
</tr>
<tr>
<td>AL_L</td>
<td>$\Delta r_x$</td>
<td>10.1</td>
<td>-11.3</td>
</tr>
<tr>
<td></td>
<td>$\Delta r_y$</td>
<td>27.1</td>
<td>-4.8</td>
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<td></td>
<td>$\Delta r_z$</td>
<td>87.0</td>
<td>-3.1</td>
</tr>
<tr>
<td>LU_L</td>
<td>$\Delta r_x$</td>
<td>7.9</td>
<td>8.9</td>
</tr>
<tr>
<td></td>
<td>$\Delta r_y$</td>
<td>13.6</td>
<td>-1.4</td>
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<tr>
<td></td>
<td>$\Delta r_z$</td>
<td>71.1</td>
<td>0.8</td>
</tr>
<tr>
<td>LL_L</td>
<td>$\Delta r_x$</td>
<td>4.2</td>
<td>23.8</td>
</tr>
<tr>
<td></td>
<td>$\Delta r_y$</td>
<td>10.3</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>$\Delta r_z$</td>
<td>32.2</td>
<td>0.3</td>
</tr>
</tbody>
</table>

#### (b) Antenna orientation (Euler angles, for rotation sequence Z-Y-Z).

<table>
<thead>
<tr>
<th>Ant.</th>
<th>Comp.</th>
<th>Walking, $T = 1.142$ s</th>
<th>Running, $T = 0.717$ s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$b_0$ [deg]</td>
<td>$b_1$ [deg]</td>
</tr>
<tr>
<td>To_F</td>
<td>$\gamma_1$</td>
<td>-23.9</td>
<td>24.1</td>
</tr>
<tr>
<td></td>
<td>$\gamma_2$</td>
<td>3.9</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$\gamma_3$</td>
<td>22.8</td>
<td>-19.8</td>
</tr>
<tr>
<td>He_L</td>
<td>$\gamma_1$</td>
<td>-10.0</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td>$\gamma_2$</td>
<td>14.8</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$\gamma_3$</td>
<td>93.1</td>
<td>-5.2</td>
</tr>
<tr>
<td>Wa_L</td>
<td>$\gamma_1$</td>
<td>-24.4</td>
<td>-66.3</td>
</tr>
<tr>
<td></td>
<td>$\gamma_2$</td>
<td>-4.9</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$\gamma_3$</td>
<td>22.8</td>
<td>62.8</td>
</tr>
<tr>
<td>AU_L</td>
<td>$\gamma_1$</td>
<td>124.8</td>
<td>45.5</td>
</tr>
<tr>
<td></td>
<td>$\gamma_2$</td>
<td>-12.6</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$\gamma_3$</td>
<td>-16.1</td>
<td>-37.8</td>
</tr>
<tr>
<td>AL_L</td>
<td>$\gamma_1$</td>
<td>24.8</td>
<td>7.8</td>
</tr>
<tr>
<td></td>
<td>$\gamma_2$</td>
<td>-23.8</td>
<td>12.2</td>
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<tr>
<td></td>
<td>$\gamma_3$</td>
<td>41.8</td>
<td>-2.2</td>
</tr>
<tr>
<td>LU_L</td>
<td>$\gamma_1$</td>
<td>2.0</td>
<td>-5.4</td>
</tr>
<tr>
<td></td>
<td>$\gamma_2$</td>
<td>-11.7</td>
<td>-22.5</td>
</tr>
<tr>
<td></td>
<td>$\gamma_3$</td>
<td>83.8</td>
<td>2.1</td>
</tr>
<tr>
<td>LL_L</td>
<td>$\gamma_1$</td>
<td>3.1</td>
<td>-5.3</td>
</tr>
<tr>
<td></td>
<td>$\gamma_2$</td>
<td>21.2</td>
<td>-19.8</td>
</tr>
<tr>
<td></td>
<td>$\gamma_3$</td>
<td>82.6</td>
<td>1.4</td>
</tr>
</tbody>
</table>
period length, average velocity and parameters of the Fourier series (Table 1) have to be stored.

The superiority of the proposed model is even more significant when the computational complexity involved in obtaining the antenna’s position and orientation at a given time is considered. For skeleton-based models, this requires a chain of recursively applied rotations and offsets through the skeleton hierarchy, in order to obtain the final position and orientation from the relative ones between the parent-child nodes [36]. For the proposed model, the antenna orientation is obtained by evaluating the Fourier series (13) for the corresponding parameters in Table 1, whereas the orientation vectors are obtained according to (10) - (12). Similarly, the position is obtained by first evaluating (9) and then (6).

For a quantitative reference, the two models can be compared in terms of the number of scalar operations, i.e. multiplication and addition, required to obtain the antenna’s position and orientation at a given time. The proposed model requires in total 24 scalar multiplications and 18 additions, as it follows from (9) and (13), with two harmonics being used in the model (Section III-D). On the other hand, the number of operations required for the skeleton-based model depends on the antenna placement (Fig. 3). The position and orientation of the associated node in the skeleton structure is obtained through recursive multiplications of $4 \times 4$ matrices for each node along the branch [36, Ch. 5]. For the skeleton-based model from [37] (Section III-B), the most demanding case is the wrist antenna (AL_L/R), which requires 8 such multiplications, i.e. 128 scalar multiplications and 96 additions.

Therefore, the proposed model can reduce the number of required multiplications and additions by more than 5 times. One should note that this number does not take the calculations in (10) - (12) into account. While being performed only once in the proposed model, in the skeleton-based one they are needed to obtain the transformation matrices from Euler angles in the MoCap data for each node, i.e. 8 times for the wrist antenna. Since these involve cumbersome evaluations of trigonometric functions, the achieved reduction in the computation complexity is apparently much greater.

While the proposed model will certainly reduce the simulation time, its main advantage is a simple mathematical formulation. As such, it should allow for an analytical analysis of some canonical scenarios.

IV. SIMULATION SCENARIOS

In order to demonstrate the model, three scenarios illustrated in Fig. 5 were simulated. The proposed model is first compared with other common approaches for BAN user mobility, in Scenario 1. It is then employed to analyse the effect of user dynamics on the off-body channel, in Scenarios 2 and 3. Wearable antenna placements on the chest (To_F), wrist (AL_L) and lower leg (LL_L) were considered for their different motion dynamics (Fig. 3), while the simulation was repeated for walking and running motions. In all scenarios, the on-body antenna is transmitting 100 mW, at 2.45 GHz. A patch antenna with a gain of 6.7 dBi and the radiation pattern shown in Fig. 6 was considered for all on-body placements. One should notice that the azimuth and elevation angles in Fig. 6 are defined with respect to the local coordinate system of the wearable antenna (Fig. 1), whose orientation relative to the global reference in Fig. 5 is changing over time, due to the user’s motion. The Rx off-body antenna was an ideal vertical dipole, with a fixed position and height of 1.4 m.

In Scenario 1, the user is moving towards the off-body antenna over a straight line, starting at a 6 m distance and stopping at 1 m. The simulation was repeated for the antenna motion obtained from the skeleton-based model with MoCap data (Section III-B), and for the case when only the linear forward motion of the user is considered. In the latter, the periodic component in (6) is replaced by a fixed vector of coordinate averages for the walking motion, i.e. the corresponding values of $a_0$ in Table 1a. The ideal vertical alignment of the antennas is considered in this case (i.e. $u_3 = u_z$), while the facing direction depends on the antenna placement, taking $u_2 = u_x$ for To_F and $u_2 = u_y$ for AL_L and LL_L antennas (Fig. 5). Free-space propagation is assumed as the user dynamics’ effect is most evident on the LoS component, but one should note that all MPCs are affected in a similar way.

To further isolate the influence of user’s motion, Scenario 2 considers the case where the user is at a fixed distance of 4 m from the off-body antenna (Fig. 5), walking and running in place as levitating above the ground or being on a treadmill. Hence, the forward motion of the user in (6) is omitted.

FIGURE 5: Simulation scenarios.

FIGURE 6: Generalised gain of the on-body patch antenna (the dashed rectangle corresponds to the area shown in Fig. 9a).
Only a single motion period is simulated, as the effects of user dynamics on the channel repeat over consecutive motion cycles. For each on-body placement, the user is oriented so that the wearable antenna is facing towards the off-body one. Therefore, the user faces in the direction indicated by $\varphi_1$ in Fig. 5 for the To_F antenna, and $\varphi_2$ for the AL_L and LL_L ones. For reference, the simulation was repeated for the static user. Average coordinates are used for the positions of the antennas, while the fixed antennas’ orientations match the global coordinate system (Fig. 5) for all on-body placements in this scenario. Again, only LoS propagation is considered.

Scenario 3 has the same setting as the previous one, but the single-reflected MPCs arriving at the Rx are considered instead of the LoS component. Adopting the common approach from the GBSC models [40], scatterers are assumed to be distributed over a cylinder with a 2 m radius, centred around the user. The EM properties of the scatterers are assumed to be those of concrete/glass ($\varepsilon_r = 4.11$), and their orientation such that the (Snell’s) law of reflection is satisfied [14]. A uniform distribution over $[0, 2.5]$ m is assumed for the scatterers’ heights, while the corresponding azimuth angles follow the Von Misses Distribution with the mean ($\mu_v$) of $90^\circ$ and the spread parameter ($\kappa_v$) being 5. This yields scatterers concentrated over the area indicated by a thick dashed line in Fig. 5. It is important to note that the scatterers’ positions are generated once and kept fixed during simulation.

V. SIMULATION RESULTS

This section presents the analysis of the simulation results, intending to provide a comparison between the proposed mobility model for wearable antennas with other common approaches, and also to investigate the mechanisms through which the antenna motion affects the off-body channel.

Fig. 7 shows the Rx power obtained in Scenario 1, for the three considered mobility models. For its realistic motion, the skeleton-based model with MoCap data can be used as a reference for the evaluation of the two mobility models. Table 2 summarises the maximum differences between the Rx power obtained from MoCap data and the two considered mobility models, i.e.

$$\Delta P_{\text{max}} = \max_{r \in [0,T]} \left| P_r^{\text{MoCap}}(t) - P_r^{\text{lin./mod.}}(t) \right|$$  

(22)

where:

- $P_r^{\text{MoCap}}$: Rx power obtained for MoCap data;
- $P_r^{\text{lin./mod.}}$: Rx power for the linear/proposed model.

As seen in Fig. 7, the linear mobility model fails to capture the characteristic motion pattern observed when the skeleton-based model with MoCap data is used, and yields only a slow change in Rx power due to the decreasing propagation loss as the user approaches the off-body antenna. The difference in both dynamics and range of Rx power variation observed between the two models highlights the importance of using an appropriate mobility model. The availability of such a model is more important as more dynamic the antenna motion is. The obtained difference is less than 1 dB for the To_F antenna, while it is typically greater than 5 dB for the AL_L and LL_L ones (Table 2); the exception is the case with the AL_L antenna and user walking motion, for which the maximum difference is 3.7 dB. This result is expected, since the torso is fairly static during walking and running motions, while the arms and legs are considerably more dynamic, especially for running. On the other hand, an excellent match is observed between the results obtained for the developed mobility model and the one based on MoCap data. The difference between the corresponding Rx powers is less than 1 dB in all considered cases.

The results obtained for Scenario 2 are shown in Figs. 8 and 9. The former shows the Rx power over a motion period,
while the latter shows the corresponding variation in the DoD (Fig. 9a) and the associated on-body antenna gain (Fig. 9b), i.e., in direction of the off-body antenna (LoS). In addition to the results for the walking and running motions, those obtained for the static user are also shown to serve as a reference. These constant values are indicated by dashed grid lines and empty markers associated with the considered wearable antenna placements on the right-hand side y-axis in the figures. Additionally, the range of values for the Rx power, the on-body antenna gain and the DoD angles are summarised in Table 3. With the same definition of the range being used in all cases, for the Rx power one has:

$$\Delta P_r [\text{dB}] = \max_{t \in [0,T]} P_r [\text{dBm}] (t) - \min_{t \in [0,T]} P_r [\text{dBm}] (t)$$

(23)

![Figure 8: LoS component Rx power in Scenario 2.](image)

The influence of antenna placement and user dynamics on the channel is apparent in Fig. 8. Expectedly, the walking motion yields generally small variations (<1.7 dB) in the considered scenario, while variations of up to 6.2 dB are observed for the user running motion (Table 3). Similarly, the least varying power levels are observed for the low dynamic To_F antenna placement (<0.9 dB), while the highly dynamic motion exhibited by antennas on AL_L and LL_L yields variations up to 6 dB. The highest variability of the Rx signal is observed for the wrist antenna on a running user. This can be explained by the particular posture of the user’s arms, yielding the LoS direction far from that of the maximum antenna radiation, as discussed later.

In order to identify the exact mechanisms responsible for the observed Rx power variations, it is useful to analyse the LoS direction trajectories in the on-body Tx antenna spherical coordinates shown in Fig. 9a; the area shown in this figure corresponds to the dashed rectangle in Fig. 6. It is convenient first to consider the static user case, for which the DoDs are fixed points, indicated by empty markers in Fig. 9a. The positions of these points in the figure can be directly explained by the corresponding antenna placements. The azimuth angle indicates the horizontal distance in between the wearable antenna and a plane containing the off-body one and the vertical axis of the user. Thereby, the 0° azimuth obtained for To_F expectedly implies the antenna is on this plane, while the deviations of the angles obtained for AL_L and LL_L reflect the fact that the arms of a standing user are further away from the vertical body axis than the legs are. In a similar way, the elevation angles relate to the antennas’ heights. Therefore, the low value (<1°) obtained for To_F antenna implies its height is similar to that of the off-body antenna, i.e., the difference being approximately 5 cm, while higher values obtained for AL_L and LL_L antennas relate to their lower heights; the difference in this case being 53 cm and 108 cm, respectively. It should be noted that the on-body antenna heights for a static user can be read from Table 1a, i.e. values of $a_0$ for $\Delta r_z$ component.

![Figure 9: LoS component DoD and the corresponding Tx antenna gain variation in Scenario 2.](image)

**TABLE 3: RANGE OF VALUES FOR THE RX POWER, TX ANTENNA GAIN AND LOŚ DIRECTION ANGLES IN SCENARIO 2.**

<table>
<thead>
<tr>
<th>Motion</th>
<th>Walking</th>
<th>Running</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna</td>
<td>To_F</td>
<td>AL_L</td>
</tr>
<tr>
<td>$\Delta P_r [\text{dB}]$</td>
<td>0.3</td>
<td>0.6</td>
</tr>
<tr>
<td>$\Delta G_r [\text{dBi}]$</td>
<td>0.3</td>
<td>0.7</td>
</tr>
<tr>
<td>$\Delta \phi_r [\text{deg}]$</td>
<td>11.6</td>
<td>22.1</td>
</tr>
<tr>
<td>$\Delta \psi_r [\text{deg}]$</td>
<td>1.5</td>
<td>7.1</td>
</tr>
</tbody>
</table>

On the other hand, for the dynamic user case, the DoDs trace trajectories during a motion cycle. These trajectories...
reveal the geometric aspect of this effect, regardless of the radiation characteristics of the antenna. The size and shape of the trajectory reflect the principal characteristics and dynamics of the motion for each considered antenna. The wide and short area occupied by the trajectory for the To_F antenna on a walking user implies that the LoS direction varies due to the antenna rotation about the vertical axis of the torso, while there is little effect from the periodic tilt in the posture of a walking user. The trajectory obtained for the AL_L antenna expectedly suggests its more dynamic motion. The 22.1° variation in the azimuth angle ($\phi_t$) observed for this antenna in Fig. 9a is primarily due to its rotation about the vertical axis of the lower arm, considering the user is turned sideways (left) towards the off-body antenna. The small variation in the elevation ($\psi_t$) is because of the periodic tilt of the antenna as the hand moves closer and farther from the body during a walking cycle. For the LL_L antenna, one observes larger elevation angles due to the low antenna height. Interestingly, the DoD variation is less severe in this case than for the AL_L antenna, because the lower leg placement dominantly yields rotation of the antenna about the axis normal to its plane. For the setting in Scenario 2, this axis is close to the LoS direction and thereby the rotation has a minor effect on the DoD.

While a similar behaviour across the considered antenna placements is observed for the user running motion, the LoS DoD is generally exhibiting more dynamic variations in this case. Two interesting differences compared to the walking motion can be noticed. First, the DoD trajectory of the To_F antenna is shifted upwards due to notable forward lean in the posture of a running person. Second, the trajectory of the AL_L antenna is in a different region, i.e. rotated and translated, but of somewhat similar shape. This is attributed to the aforementioned horizontal position of the running person’s arms. The large elevation angle variation of 35.2° (Table 3) can be related to the high antenna gain variation over the motion period.

Fig. 9b shows the on-body patch antenna gain value for the LoS direction, as it changes according to the DoD trajectories in Fig. 9a. From this figure and the corresponding values in Table 3, it is observed that the Tx gain variations exactly explain those of the Rx power in Fig. 8. The impact of the propagation loss due to the variable distance between the on- and off-body antennas during motion is negligible. While gain variations are relatively small for the specific setting of Scenario 2 (<6.1 dB), namely LoS is always in the forward radiation direction of the on-body antenna, where its gain exhibits the slowest change with DoD, one can expect much greater variations in a general case.

For illustration, Fig. 10 shows the maximum antenna gain variations over the motion period, for fixed directions in space, given by its azimuth ($\phi$) and elevation ($\psi$) angles in the global coordinate system (Fig. 5). All figures correspond to the user facing in direction of the $x$-axis. The same scale is used in all figures for comparison, while the maximum value in each particular case is indicated in the caption. The magnitude of the gain variations and the number of affected directions are observed to increase with dynamics of the antenna motion. The highest maximum variation is obtained for the wrist antenna and the user running motion (Fig. 10c), where a significant area in $\phi$-$\psi$ plane exhibits gain variations higher than 10 dB. Therefore, the channel quality can be severely affected should the LoS direction fall in this area.

It should be mentioned that the off-body antenna gain has a negligible effect on Rx power variations in the considered scenario. More specifically, a maximum Rx gain variation in the LoS direction of 0.15 dB is observed for the LL_L antenna and the user running case, while being below 0.1 dB in all other cases. However, these variations can be quite significant in other scenarios, e.g. the user passing by the off-body antenna in its close vicinity.

One should also notice that the polarisation aspect is not considered in this work, i.e. the polarisations of the Rx antenna and the impinging EM wave are assumed to be perfectly matched. Therefore, the polarisation mismatch loss due to physical misalignment between the antennas is neglected, although its significant effect on the Rx power can be anticipated [11].

Finally, the results obtained in Scenario 3 are presented in Fig. 11 and Table 4; the former shows the Rx power over a motion period, while the range of its variations for the considered antenna placements and motions of the user are summarised in the latter. Similarly to the LoS component in Scenario 2, the user’s motion has an evident influence on the Rx signal resulting from the arriving MPCs. Again, the strong correlation between the dynamics of the motion exhibited by the antenna for the particular placement and severity of the obtained Rx power variations is observed. The least variable signal is obtained for the To_F antenna (<7 dB), while the variations are considerably more severe for the AL_L and LL_L ones, being up to 28 dB for the latter. Considering a particular antenna placement, the running motion yields faster and more significant changes in the Rx power than the walking one.

**TABLE 4: RANGE OF RX POWER IN SCENARIO 3.**

<table>
<thead>
<tr>
<th>Motion</th>
<th>Walking</th>
<th>Running</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna</td>
<td>To_F</td>
<td>AL_L</td>
</tr>
<tr>
<td>$\Delta P_r$ [dB]</td>
<td>1.7</td>
<td>19.0</td>
</tr>
</tbody>
</table>

It should be noticed that the low average Rx power obtained for the To_F antenna compared with the other two placements is due to the particular distribution of scatterers and user’s orientation in Scenario 2. While MPCs are arriving to the AL_L and LL_L antennas from the forward direction, for the To_F antenna these arrivals are from the side and the back directions, for which the antenna gain is lower.

**VI. CONCLUSIONS**

With the recent advancements in electronics and wireless communications, BANs are becoming increasingly popular. Since the performance of these systems highly relies on communication, the availability of an accurate channel model...
A Mobility Model for Wearable Antennas on Dynamic Users

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Turbic et al.: A Mobility Model for Wearable Antennas on Dynamic Users

is of a key importance for an optimised system design. Such a model has to account for the motion of wearable antennas, imposed by users activity. The periodic antenna displacement and rotation due to changing posture of a dynamic user are important aspect of this motion, which is typically neglected or exceedingly complex models are used for its representation.

This paper presents a mobility model for wearable antennas on dynamic users, considering user walking and running motions. The novelty of the presented work is the mobility model developed for wearable antennas in BANs. This model fits the general RPGM framework, where group mobility associated with the forward motion of the user is represented by a linear model, and Fourier series with at most two harmonics are used to model periodic changes in the individual antenna’s position and orientation. The calculation of model parameters is based on the skeleton-driven body motion model and MoCap data, hence, a realistic motion of the antennas is obtained. However, the main advantage of the presented mobility model is in its simplicity, which allows for it to be used in BAN channel simulators, e.g., based on ray-tracing and GBSC models, and also for the analytical inference in simplified scenarios. As such, the model is unique and fills in an important gap in the literature.

Three simple off-body communication scenarios were simulated in order to demonstrate the model and compare it with other common approaches in mobility modelling for BANs. Simulation results show that the Rx power obtained for the developed mobility model matches those for the skeleton-based model with MoCap data; the error is typically less than 0.6 dB, 1 dB being the worst case. Both free-space and multipath propagation scenarios are considered, where the user motion is observed to affect the channel primarily by yielding variable antenna gain in directions of LoS and arriving MPCs. While Rx power variations of less than 6.2 dB are observed for the LoS component in the considered scenario, yielding variations up to 28 dB are observed.

Considering multipath propagation without LoS, Rx power variations up to 28 dB are observed.

It should be pointed out that signal polarisation is not considered in this paper, and that channel variations observed in Section V are primarily due to gain variations. The polarisation mismatch loss imposed by the wearable antenna rotation during motion is neglected, although significant values are anticipated in the general case. Therefore, future work has a goal to expand the channel model to account for the depolarisation effect. Moreover, this model should be compared against measurements, obtained in a dedicated measurement campaign.

FIGURE 10: Wearable antenna gain variation due to rotation.

FIGURE 11: Rx power from MPCs in Scenario 3.
APPENDIX A

The motion specified by the parameters provided in Section III-D can be easily modified for user arbitrary path and velocity. For a straight motion path specified by its end points, the direction vector in (6) is obtained according to:

\[ \mathbf{u}_v = \frac{\mathbf{r}_d - \mathbf{r}_0}{\|\mathbf{r}_d - \mathbf{r}_0\|} \] (24)

where:
- \( \mathbf{r}_d \) : destination point.

The azimuth angle of the motion direction is obtained as:

\[ \phi_m = \arctan \left( \frac{\mathbf{u}_{x} \cdot \mathbf{u}_y}{\mathbf{u}_{x} \cdot \mathbf{u}_z} \right) \] (25)

Since the model parameters provided in Section III-D correspond to the motion in the direction of the positive \( x \)-axis, an additional rotation about the \( z \)-axis for angle \( \phi_n \) has to be applied to the periodic component in (6) and orientation vectors (10) - (12). Considering that Euler rotations are equivalent to the ones about the global (fixed) axis in the reverse order [36, Ch. 2], the latter is equivalent to adding angle \( \phi_n \) to the Euler angle \( \gamma_1 \) (i.e. for all antennas). In a general case, the direction vector and the corresponding azimuth angle change over time. An arbitrary motion path can represented by a parametric curve [36, Ch. 3], whose (normalised) first derivative in each point then represents the direction vector. If the path curve has a simple analytical expression for the first derivative, the mobility model should remain fairly simple.

Motion velocity can be modified by directly providing a value for the forward motion component in (6), and appropriately changing the period of the Fourier series representing the periodic component. For a given velocity \( \langle \mathbf{v}_u \rangle \), the corresponding motion period is obtained according to:

\[ T = \frac{\mathbf{v}_u}{\langle \mathbf{v}_u \rangle} \] (26)

where the hat indicates the parameters of the new modified motion, and the original values are provided in Section III-D. It is noteworthy that one has to be careful when modifying the velocity, since values far from the original one estimated from the MoCap data (Section III-D) may yield unnatural motion.

Finally, it should be noticed that the starting posture of the user can be changed as well. This is achieved by setting a common initial phase to all periodic components.

APPENDIX B

This appendix explains the derivation of expressions (14) - (16) in Section III-C, for which the perfect symmetry of the body and its motion is assumed. One starts by observing that the walking and running motions are characterised by periodic changes in the posture of a person, which yield symmetric movement of the left and right sides of the body, but with an offset of a half the motion period. Hence, exhibited rotations and trajectories traced by two symmetrically placed antennas are images of each other. Assuming that the user is aligned with the \( z \)-axis and faces the positive \( x \)-axis direction (as in Section III-D), the plane of this symmetry is the X-Z plane. Since the reflection of a point about the X-Z plane is essentially obtained by changing the sign of the \( y \)-coordinate, the relations for the antenna position, i.e. (14) and (15), follow straightforwardly.

The orientations of these wearable antennas exhibit states that are also mirrored images of one another, with the matching orientations occurring with half the motion period offset between the two antennas. In order to obtain the symmetry relations for the Euler angles (16), one should consider the orientation of the antenna over time as a rotation by an angle \( \gamma_3 \), about the axis established by the sequence of elementary rotations \( (\gamma_1, \gamma_2) \). This axis corresponds to the vector \( \mathbf{u}_z \) of the antenna’s local coordinate system, which is aligned with that of the arm or the leg it is attached to. For symmetric wearable antenna placements, the corresponding vectors \( \mathbf{u}_z \) are reflections of one another with respect X-Z plane, and the rotations about these axis are reversed in sense. While the opposite sign relation for \( \gamma_3 \) in (12) directly follows from the latter, the former and (12) yield:

\[ \cos \gamma_1 R \sin \gamma_2 = \cos \gamma_1^L \sin \gamma_2^L \] (27)

\[ \sin \gamma_1 R \sin \gamma_2 = -\sin \gamma_1^L \sin \gamma_2^L \] (28)

from which, in turn, the relations for \( \gamma_1 \) and \( \gamma_2 \) follow.

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LUIS M. CORREIA was born in Portugal, in 1958. He received the Ph.D. in Electrical and Computer Engineering from IST (University of Lisbon) in 1991, where he is currently a Professor in Telecommunications, with his work focused in Wireless/Mobile Communications in the areas of propagation, channel characterisation, radio networks, traffic, and applications, with the research activities developed in the INESC-ID institute. He has acted as a consultant for Portuguese communications operators and the telecommunications regulator, besides other public and private entities, and has been in the Board of Directors of a telecommunications company. Besides being responsible for research projects at the national level, he has participated in 31 projects within European frameworks, having coordinated 5 of them and taken leadership responsibilities at various levels in many others. He has supervised more than 200 M.Sc./Ph.D. students, contribute to European strategic documents, and authored more than 450 papers in international and national journals and conferences, for which served also as a reviewer, editor, and board member. Internationally, he was part of 33 Ph.D. juries, and 52 research projects and institutions evaluation committees for funding agencies in 10 countries and the European Commission. He has been the Chairman of Conference, of the Technical Programme Committee and of the Steering Committee of several major conferences, besides other several duties. He was a National Delegate to the COST Domain Committee on ICT. He was active in the European Net!Works platform, by being an elected member of its Expert Advisory Group and of its Steering Board, and the Chairman of its Working Group on Applications, and was also elected to the European 5G PPP Association.

MARKO BEKO was born in Belgrade, Serbia, on November 11, 1977. He received the Dipl. Eng. degree from the University of Belgrade, Belgrade, Serbia, in 2001 and the PhD degree in electrical and computer engineering from Instituto Superior Tecnico, Lisbon, Portugal, in 2008. Currently, he is a Professor at the Universidade Lusófona de Humanidades e Tecnologias, Portugal. He is also a Researcher at the UNINOVA, Campus da FCT/UNL, Monte de Caparica, Portugal. His current research interests are in the area of signal processing for wireless communications. He serves as an Associate Editor for the IEEE Access Journal and Elsevier Journal on Physical Communication. He was awarded a Starting Grant under the Investigador FCT programme of the Portuguese Science and Technology Foundation in 2016. He is the winner of the 2008 IBM Portugal Scientific Award.

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